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(54) Title: COMPOSITIONS COMPRISING BACTERIAL STRAINS

(57) Abstract: The invention provides compositions comprising commensal bacterial strains and organic acids and the uses thereof in the treatment of diseases.

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COMPOSITIONS COMPRISING BACTERIAL STRAINS

TECHNICAL FIELD

This invention is in the field of compositions comprising bacterial strains isolated from the mammalian digestive tract and the use of such compositions in the treatment of disease.

BACKGROUND TO THE INVENTION

The human intestine is thought to be sterile *in utero*, but it is exposed to a large variety of maternal and environmental microbes immediately after birth. Thereafter, a dynamic period of microbial colonization and succession occurs, which is influenced by factors such as delivery mode, environment, diet and host genotype, all of which impact upon the composition of the gut microbiota, particularly during early life. Subsequently, the microbiota stabilizes and becomes adult-like [1]. The human gut microbiota contains more than 500-1000 different phylotypes belonging essentially to two major bacterial divisions, the Bacteroidetes and the Firmicutes [2]. The successful symbiotic relationships arising from bacterial colonization of the human gut have yielded a wide variety of metabolic, structural, protective and other beneficial functions. The enhanced metabolic activities of the colonized gut ensure that otherwise indigestible dietary components are degraded with release of by-products providing an important nutrient source for the host. Similarly, the immunological importance of the gut microbiota is well-recognized and is exemplified in germfree animals which have an impaired immune system that is functionally reconstituted following the introduction of commensal bacteria [3-5].

Dramatic changes in microbiota composition have been documented in gastrointestinal disorders such as inflammatory bowel disease (IBD). For example, the levels of *Clostridium* cluster XIVa bacteria are reduced in IBD patients whilst numbers of *E. coli* are increased, suggesting a shift in the balance of symbionts and pathobionts within the gut [6-9].

In recognition of the potential positive effect that certain bacterial strains may have on the animal gut, various strains have been proposed for use in the treatment of various diseases (see, for example, [10-13]). Also, certain strains, including mostly *Lactobacillus* and *Bifidobacterium* strains, have been proposed for use in treating various inflammatory and autoimmune diseases that are not directly linked to the intestines (see [14] and [15] for reviews). However, the relationship between different diseases and different bacterial strains, and the precise effects of particular bacterial strains on the gut and at a systemic level and on any particular types of diseases are poorly characterised, particularly for neurodegenerative disorders.

Recently, there has been increased interest in the art regarding alterations in the gut microbiome that may play a pathophysiological role in human brain diseases [16]. Preclinical and clinical evidence are strongly suggesting a link between brain development and microbiota [17]. A growing body of preclinical literature has demonstrated bidirectional signalling between the brain and the gut microbiome, involving multiple neurocrine and endocrine signalling systems. Indeed, increased levels

of *Clostridium* species in the microbiome have been linked to brain disorders [18], and an imbalance of the *Bacteroidetes* and *Firmicutes* phyla has also been implicated in brain development disorders [19]. Suggestions that altered levels of gut commensals, including those of *Bifidobacterium*, *Lactobacillus*, *Sutterella*, *Prevotella* and *Ruminococcus* genera and of the *Alcaligenaceae* family are involved in immune-mediated central nervous system (CNS) disorders, are questioned by studies suggesting a lack of alteration in the microbiota between patients and healthy subjects [19]. There have also been suggestions that the administration of probiotics may be beneficial in the treatment of neurological disorders. However, these studies failed to conclude that probiotic compositions *per se* can achieve therapeutic benefits with respect to the treatment of neurodegeneration and did not show any useful effects for any particular bacteria [20, 21]. This indicates that, at present, the practical effect of the link between the microbiome and human brain diseases is poorly characterised. Accordingly, more direct analytical studies are required to identify the therapeutic impact of altering the microbiome on neurodegenerative disorders.

There is a requirement in the art for new methods of treating neurodegenerative disorders. There is also a requirement for the potential effects of gut bacteria to be characterised so that new therapies using gut bacteria can be developed.

SUMMARY OF THE INVENTION

The inventors have developed new therapies for treating and preventing neurodegenerative disorders. In particular, the inventors have identified that commensal bacteria that produce certain organic acids have neuroprotective activities and may be effective for treating neurodegenerative disease. Related to this, the inventors have also identified that adding organic acids to compositions comprising commensal bacteria, or using organic acids in combination with commensal bacteria, may provide enhanced therapeutic effects, in particular in the treatment of neurodegenerative disorders.

The inventors have identified that commensal bacterial strains that produce one or more organic acids with the formula R^x-COOH, wherein R^x comprises an alkyl group comprising in the range of 4 to 11 carbons, or wherein R^x comprises a phenyl group with a substituent hydroxyl group, wherein optionally the hydroxyl group is at position 4, may be effective for treating neurodegenerative diseases. In another aspect of the invention, the inventors have found that a combination of a commensal bacterial strain and an organic acid may be effective for treating or preventing neurodegenerative diseases. As used herein, the terms “the combination of the invention”, “the therapeutic combination of the invention” and “the therapeutic combination” may be used interchangeably and refer to a therapeutic combination of: (a) a composition comprising a commensal bacterial strain; and (b) a composition comprising an organic acid. It is to be understood that the term “combination” in the context of the therapeutic combination does not refer to components (a) and (b) of the combination necessarily being in the same composition and/or administered at the same time.

As described in the examples, administration of compositions comprising *Megasphaera massiliensis* can protect against reactive oxygen species and prevent inflammation, thus actingas a neuroprotectant. The inventors have identified that *Megasphaera massiliensis* produces certain organic acids including hexanoic acid, valeric acid and 4-hydroxyphenylacetic acid. The inventors have also identified that treatment with *Megasphaera massiliensis* can reduce the activation of proinflammatory molecules, such as NFκB and IL-6, by LPS and mutant α-synuclein. The inventors have also found that *Megasphaera massiliensis* can increase the activation of the pro-inflammatory cytokine IL-8, which can help to promote neuron myelination. The inventors have also identified that treatment with a combination of *Megasphaera massiliensis* and retinoic acid can increase the secretion of brain-derived neurotrophic factor (BDNF), which can help promote neurogenesis and neuritogenesis and/or prevent cell death. The inventors have identified that treatment with *Megasphaera massiliensis* can attenuate oxidative stress, reduce histone deacetylation activity and lipid peroxidation *in vitro*, which can help to reduce cell death and apoptosis. In particular, the inventors have identified that treatment with *Megasphaera massiliensis*, which can produce valeric acid, can reduce histone deacetylation, which can help to reduce cell death and apoptosis. The inventors have also identified that *Megasphaera massiliensis* can produce indole that can attenuate inflammation and oxidative stress. The inventors have also demonstrated that treatment with *Megasphaera massiliensis* can increase kynurenine levels. Furthermore, the inventors have also found that *Megasphaera massiliensis* can produce hexanoic acid, which can be neuroprotective or neurorestorative, for example by promoting neurite outgrowth. The inventors have found that *Megasphaera massiliensis* that can produce hexanoic acid increase the expression of MAP2 (Microtubule –associated protein 2), which is thought to be essential for microtubule formation in neuritogenesis. Therefore, the inventors have found that *Megasphaera massiliensis* that can produce hexanoic acid can be used to promote neurite outgrowth. *Megasphaera massiliensis* and other bacteria that produce organic acids like hexanoic acid, valeric acid and 4-hydroxyphenylacetic acid may therefore be useful for treating neurodegenerative disorders.

Thus, in a first aspect, the invention describes a composition comprising a commensal bacterial strain for use in a method of treating or preventing a neurodegenerative disorder, wherein the strain produces one or more organic acids each having the following formula: R^x-COOH, wherein R^x comprises an alkyl group comprising at least 4 carbons, or wherein R^x comprises a phenyl group with a substituent hydroxyl group, wherein optionally the hydroxyl group is at position 4.

In a second aspect, the invention provides a composition comprising a commensal bacterial strain and one or more organic acids having the formula R^n-COOH or pharmaceutically acceptable salts or esters thereof. In preferred embodiments, the composition comprises one or more of the organic acids valproic acid, valeric acid, hexanoic acid, retinoic acid, and 4-hydroxyphenylacetic acid or pharmaceutically acceptable salts or esters thereof. The examples demonstrate that such combinations have therapeutic benefits.

In some embodiments, the invention describes a composition comprising a commensal bacterial strain for use in a method of treating or preventing a disease in a subject, wherein the composition is to be administered in combination with one or more organic acids or pharmaceutically acceptable salts or esters thereof. The examples demonstrate that such combinations may be particularly effective.

In some embodiments, the invention describes a composition comprising one or more organic acids or pharmaceutically acceptable salts or esters thereof for use in a method of treating or preventing a disease in a subject, wherein the composition is to be administered in combination with a commensal bacterial strain. The examples demonstrate that such combinations may be particularly effective.

Preferred embodiments of both aspects of the invention are discussed below and throughout the application.

In some embodiments, the commensal bacterial strain produces a short chain fatty acid. Preferably, the short chain fatty acid is butyric acid. Butyrate may contribute to reducing impermeability of the blood brain barrier, which has a neuroprotective effect.

In some embodiments, the composition is for use in a method of treating or preventing disease.

In some embodiments, the compositions are for use in a method of treating or preventing a neurodegenerative disorder.

In particular embodiments, the compositions are for use in a method of treating or preventing a disease or condition selected from the group consisting of: Parkinson's disease, including progressive supranuclear palsy, progressive supranuclear palsy, Steele-Richardson-Olszewski syndrome, normal pressure hydrocephalus, vascular or arteriosclerotic parkinsonism and drug-induced parkinsonism; Alzheimer's disease, including Benson's syndrome; multiple sclerosis; Huntington's disease; amyotrophic lateral sclerosis; Lou Gehrig's disease; motor neurone disease; prion disease; spinocerebellar ataxia; spinal muscular atrophy; dementia, including Lewy body, vascular and frontotemporal dementia; primary progressive aphasia; mild cognitive impairment; HIV-related cognitive impairment, progressive inflammatory neuropathy, and corticobasal degeneration.

In preferred embodiments, the compositions of the invention are for use in a method of treating or preventing Parkinson's disease, such as environmental, familial or Parkinson's associated with general inflammatory status. The inventors have identified that treatment with the compositions of the invention can reduce the activation of proinflammatory molecules, such as NFκB and IL-6, by LPS and mutant α-synuclein in *in vitro* models of environmental and familial Parkinson's.

In some embodiments, the compositions of the invention are for use in a method of treating or preventing early-onset neurodegenerative disease. In some embodiments, the compositions of the invention are for use in a method of preventing or delaying onset or progression of a neurodegenerative disorder.

In preferred embodiments, the invention provides a combination comprising a bacterial strain of the species *Megasphaera massiliensis,* and an organic acid selected from the list consisting of hexanoic acid, valeric acid, valproic acid, retinoic acid or 4-hydroxyphenylacetic acid for use in the treatment of Parkinson's disease. Combinations using *Megasphaera massiliensis* and hexanoic acid may be particularly effective for use in a method of treating neurodegenerative diseases, in particular Parkinson's. Preferred compositions of the invention comprise a commensal bacteria and retinoic acid. Further preferred compositions of the invention comprise a commensal bacteria and hexanoic acid. Further preferred compositions of the invention comprise a commensal bacteria and valeric acid

In some embodiments of the invention, the commensal bacterial strain is from the genus selected from the list consisting of *Bacteroides, Enterococcus, Escherichia, Klebsiella, Bifidobacterium, Staphylococcus, Lactobacillus, Megasphaera, Clostridium, Proteus, Pseudomonas, Salmonella, Faecalibacterium, Peptostreptococcus or Peptococcus,* or a combination thereof. In some embodiments, the commensal bacterial strain is from the genus *Megasphaera*. In some preferred embodiments the strain is of the species *Megasphaera massiliensis*. Closely related strains may also be used, such as bacterial strains that have a 16S rRNA sequence that is at least 95%, 96%, 97%, 98%, 99%, 99.5% or 99.9% identical to the 16S rRNA sequence of a bacterial strain of *Megasphaera massiliensis*. Preferably, the bacterial strain has a 16S rRNA sequence that is at least 95%, 96%, 97%, 98%, 99%, 99.5% or 99.9% identical to SEQ ID NO: 2. Preferably, the bacterial strain for use in the invention has the 16S rRNA sequence represented by SEQ ID NO:2.

In preferred embodiments, the strain for use in the invention produces one or more organic acids each having the following formula: R^x-COOH, wherein R^x comprises an alkyl group comprising at least 4 carbons, or wherein R^x comprises a phenyl group with a substituent hydroxyl group, wherein optionally the hydroxyl group is at position 4, wherein the organic acid is effective in the treatment or prevention of a neurodegenerative disorder. In some embodiments, the strain for use in the invention produces an organic acid selected from the list consisting of hexanoic acid, valeric acid, valproic acid, retinoic acid or 4-hydroxyphenylacetic acid. Preferably, strains of the invention are capable of increasing the activation of IL-8 and reducing the activation of IL-6.

In some embodiments of the invention, the commensal bacterial strain of the composition is engineered to produce the organic acid of the invention.

In some embodiments, the compositions of the invention are for oral administration. Oral administration of the strains of the invention and where applicable the organic acid of the invention can be effective for neurodegenerative disorders. Also, oral administration is convenient for patients and practitioners and allows delivery to and / or partial or total colonisation of the intestine.

In certain embodiments, the composition of the invention comprises one or more pharmaceutically acceptable excipients or carriers.

In certain embodiments, the composition of the invention comprises a commensal bacterial strain that has been lyophilised. Lyophilisation is an effective and convenient technique for preparing stable compositions that allow delivery of bacteria.

In certain embodiments, the invention provides a food product comprising any of the compositions as described above.

In certain embodiments, the invention provides a vaccine composition comprising the composition as described above.

Additionally, the invention provides a method of treating or preventing neurodegenerative diseases, comprising administering a composition comprising a commensal bacterial strain that produces one or more organic acids each having the following formula: R^x-COOH, wherein R^x comprises an alkyl group comprising at least 4 carbons, or wherein R^x comprises a phenyl group with a substituent hydroxyl group, wherein optionally the hydroxyl group is at position 4.

The invention also provides a method of treating or prevention neurodegenerative diseases comprising administering a combination of a commensal bacterial strain and an organic acid or a pharmaceutically acceptable salt or ester thereof.

In developing the above invention, the inventors have identified and characterised a bacterial strain that is particularly useful for therapy. The *Megasphaera massiliensis* strain of the invention is shown to be effective for treating the diseases described herein, such as neurodegenerative diseases. Therefore, in another aspect, the invention provides a cell of the *Megasphaera massiliensis* strain deposited under accession number NCIMB 42787, or a derivative thereof. The invention also provides compositions comprising such cells, or biologically pure cultures of such cells. The invention also provides a cell of the *Megasphaera massiliensis* strain deposited under accession number NCIMB 42787, or a derivative thereof, for use in therapy, in particular for the diseases described herein.

In certain embodiments of either aspect of the invention, the composition is for use in treating brain injury. The neuroprotective activity of the compositions of the invention and their ability to reduce levels of histone deacetylase activity (HDAC) may make them useful for treating brain injury. In preferred embodiments, the compositions of the invention are for use in treating stroke, such as treating brain injury resulting from a stroke.

BRIEF DESCRIPTION OF DRAWINGS

Figure 1: Cell viability of neuroblastoma cells

Figure 2: Downregulation of IL-6 secretion

Figure 3: Secretion of IL-8

Figure 4: Inhibition of α- synuclein IL-6 and IL-8 secretion

Figure 5: Inhibition of α- synuclein induced NFκB promoter activation

Figure 6: Inhibition of LPS induced NFκB promoter activation

Figure 7: Promoting neurite outgrowth: light microscopy and MAP2 gene expression (Figure 7A), Phalloidin immunofluorescence microscopy (Figure 7B)

Figure 8: Change in antioxidant capacity

Figure 9: Change in total anti-oxidant capacity (lipid oxidation)

Figure 10: Change in ROS levels in (a) U373 cells and (b) SHSY-5Y cells

Figure 11: Neuroprotection – cell viability. Figure 11 shows the same data as Figure 1.

Figure 12: Change in histone deacetylase (HDAC) activity

Figure 13 Strain-induced changes in whole cell and cell lysate histone deacetylase activity (Figure 13A), acid-induced changes in histone deacetylase activity (Figure 13B), metabolite production by strains (Figuure 13C)

Figure 14 HDAC1 inhibition (Figure 14A), HDAC2 inhibition (Figure 14B), HDAC3 inhibition (Figure 14C)

Figure 15 Inhibition of Class I HDACs (Figure 15A); inhibition of HDAC1 (Figure 15B); inhibition of HDAC2 (Figure 15C); inhibition of HDAC3 (Figure 15D)

Figure 16: Level of Indole production

Figure 17: Level of Kyrunenine production

Figure 18: Level of BDNF production

Figure 19: Levels of metabolite production – neurotransmitters in the brain

Figure 20: Levels of metabolite production – organic acids in the supernatant

Figure 21: Mean Dopamine (DA) levels (Figure 21A), DOPAC levels (Figure 21B) and HVA levels (Figure 21C) in striatum. Data is displayed as Mean + SEM.

Figure 22: Effect on intestinal barrier function.

Figure 23: Production of neurotransmitters in the brain

Figure 24: Changes in Hippocampal Receptor Expression – A) Oxytocin Receptor, B) Vasopressin Receptor, C) Glucocorticoid Receptor and D) Mineralocorticoid Receptor

Figure 25: Changes in Hippocampal Expression of A) Corticotropin-Releasing Hormone (CRH), B) BDNF Expression and C) TLR4

Figure 26: A) Changes in Hippocampal Corticotropin Releasing Hormone Receptor 1 (CRFR1) Expression and B) Corticotropin Releasing Hormone Receptor 2 (CRFR2) Expression

Figure 27: Changes in Hippocampal Expression of A) Tumour Necrosis Factor, B) Interleukin 1b and C) IL-6

Figure 28: A) Changes in Hippocampal Integrin Alpha M (CD11b) Expression and B) Changes in Hippocampal Serotonin 1A Receptor (5-HT1A receptor) Expression

Figure 29: A) Changes in Hippocampal Glutamate Ionotropic Receptor NMDA Type Subunit 2A (Grin2A) and B) Glutamate Ionotropic Receptor NMDA Type Subunit 2B (Grin2B) expression

Figure 30: Changes in Hippocampal Expression of A) Gamma-Aminobutyric Acid A Receptor 2 (GABA A2), B) Gamma-Aminobutyric Acid B Receptor 1 (GABA BR1) and C) Dopamine Receptor 1 (DRD1)

Figure 31: Changes in Amygdala Receptor Expression – A) Oxytocin Receptor, B) Vasopressin Receptor, C) Glucocorticoid Receptor and D) Mineralocorticoid Receptor

Figure 32: Changes in Amygdala Expression of A) Brain Derived Neurotrophic Factor (BDNF), B) Toll-like Receptor 4 (TLR-4), C) Corticotropin Releasing Hormone Receptor 1 (CRFR1) and D) Corticotropin Releasing Hormone Receptor 2 (CRFR2)

Figure 33: Changes in Amygdala Expression of A) Integrin Alpha M (CD11b), B) Interleukin-6 (IL-6), C) Glutamate Ionotropic Receptor NMDA Type Subunit 2A (Grin2A) and D) Glutamate Ionotropic Receptor NMDA Type Subunit 2B (Grin2B)

Figure 34: Changes in Amygdala Expression of A) GABA-A Receptor Alpha 2 Subunit (GABRA2), B) GABA-A Type B Receptor 1 Subunit (GABBR1) and C) Dopamine Receptor 1 (DRD1)

Figure 35: Changes in Prefrontal Cortex Expression of A) Oxytocin Receptor, B) Brain Derived Neurotrophic Factor (BDNF), C) Mineralocorticoid Receptor and D) Glucocorticoid Receptor

Figure 36: Changes in Prefrontal Cortex Expression of A) Toll-like Receptor 4 (TLR-4), B) Corticotropin Releasing Hormone Receptor 1 (CRFR1), C) Corticotropin Releasing Hormone Receptor 2 (CRFR2) and D) Integrin Alpha M (CD11b)

Figure 37: Changes in Prefrontal Cortex Expression of A) Interleukin-6 (IL-6), B) Glutamate Ionotropic Receptor NMDA Type Subunit 2A (Grin2A), C) Glutamate Ionotropic Receptor NMDA Type Subunit 2B (Grin2B) and D) GABA-A Receptor Alpha 2 Subunit (GABRA2)

Figure 38: Changes in Prefrontal Cortex Expression of A) GABA-A Receptor Type B Receptor Subunit 1 (GABBR1) and B) Dopamine Receptor 1 (DRD1)

Figure 39: Changes in Colon Expression of A) Tryptophan Hydroxylase-1 (Tph1) and B) Indoleamine2,3-Dioxygenase-1 (IDO1)

Figure 40: Changes in Ileum Expression of A) Tryptophan Hydroxylase-1 (Tph1) and B) Indoleamine2,3-Dioxygenase-1 (IDO1)

Figure 41: Changes in Circulating Tryptophan Metabolite Levels A) Kynurenine, B) Tryptophan and C) Kynurenine/ Tryptophan Index of metabolism

Figure 42: Effect on Interferon-γ Production from from mouse Splenocytes from mice fed with MRx0029

Figure 43: Effect on Interleukin-1β Production from Splenocytes

Figure 44: Effect on Interleukin-6 Production from Splenocytes

Figure 45: Effect on Tumour Necrosis Factor Production from Splenocytes

Figure 46: Effect on Interleukin-10 Production from Splenocytes

Figure 47: Effect on Chemoattractant CXCL1 Production from Splenocytes

Figure 48: Changes in Caecal Short Chain Fatty Acid Levels

Figure 49: MRx0029 and MRX005-induced changes in gene expression levels of Actin, Villin, Occludin TJP1, TJP2, MAP2, DRD2, GABRB3, SYP, PINK1, PARK7 and NSE.

Figure 50: SHSY5Y cell differentiation induced by MRx0005 and MRx0029. (A-C) Representative images of immuno labelled cells with Phalloidin and MAP2. (D—F) images of A-C merged with DAPI images. (G—I) β3 tubulin immunolabelled cells. (J-L) merged with DAPI images. Magnification x630. Western blot analysis of effects of MRx0005 and MRx0029 treatment on SHSY5Y cells. Western blot membranes were probed with antibodies to MAP2 (M) and b3 tubulin (N). Actin was used as a loading control. Lower panels: representative blots from one of six separate experiments; upper panels: relative densitometric intensity.

DISCLOSURE OF THE INVENTION

Bacterial strains

The compositions of the invention comprise a commensal bacterial strain useful for treating or preventing diseases. In a first aspect, the commensal bacterial strains of the invention produce one or more organic acids each having the following formula: R^x-COOH, wherein R^x comprises an alkyl group comprising at least 4 carbons, or wherein R^x comprises a phenyl group with a substituent

hydroxyl group, wherein optionally the hydroxyl group is at position 4. In a second aspect, the invention provides compositions comprising a commensal bacterial strain and one or more organic acids having the formula R-COOH, or pharmaceutically acceptable salts or esters thereof. The commensal bacterial strain of the second aspect may or may not produce an organic acid according to the invention.

The inventors have found that certain commensal bacterial strains reduce the activation of inflammatory cytokines such as IL-6 and increase the activation of the inflammatory cytokine IL-8. IL-8 has been implicated in myelin sheath formation. Chronic inflammation induced by IL-6 can ultimately lead to cell death. Therefore, the commensal bacterial strains of the invention are particularly useful in the treatment or prevention of neurodegenerative disorders. In some embodiments, the commensal bacterial species are useful in the treatment of conditions characterised by the enhanced activation of IL-6. In some embodiments, the compositions of the invention are for use in the treatment or prevention of neurodegenerative diseases characterised by demyelination. Many neurodegenerative diseases are characterised by demyelination. Demyelination impedes the propagation of action potentials within neurons, impairing effective communication within the nervous system. IL-8 has been shown to contribute positively to myelin sheath formation and repair [22]. Therefore, the compositions of the invention are particularly beneficial in the treatment or prevention of neurodegenerative disorders characterised by demyelination, such as Multiple Sclerosis.

The inventors have found that the commensal bacteria of the invention alleviate symptoms of neurodegenerative diseases in models of the disease. For example, the inventors have found that the particular commensal bacteria strains promote neurite outgrowth *in vitro*, and may therefore be used in promoting neuron restoration for the treatment or prevention of neurodegenerative diseases. Thus, commensal bacterial strains of the invention are for use in the treatment or prevention of neurodegenerative diseases.

The commensal bacterial strain of the first aspect of the invention may produce one or more of the organic acids of the invention and be administered in combination with one or more of the organic acids of the invention.

Commensal bacterial strains of the second aspect that are beneficial for the treatment or prevention of neurodegenerative diseases may be administered in combination with an organic acid that has the neurorestorative or neuroprotective properties described herein.

The commensal bacterial strains of the first and second aspect of the invention comprise those that exhibit the beneficial effects across the IL-6/IL-8 axis, whether or not the commensal bacterial strain produces one or more of the organic acids according to the invention.

The inventors have also found that the commensal bacterial strains of invention increase the activation of BDNF. BDNF is a neurotrophic growth factor that has been shown to enhance neuron differentiation and survival. The effect is most prominently observed when a commensal bacterial strain is

administered in combination with the organic acid of the invention. Thus, the compositions of the invention can be used in a method of enhancing nerve cell survival in the treatment or prevention of neurodegenerative diseases.

As used herein, "increasing" or "decreasing" "activation" refers to enhancing or reducing the concentration of bio-active biomolecules available for performing physiological functions, preferably following administration to the gastrointestinal tract. In other words, "increasing" or "decreasing" refers to the modulating the level of a biomolecule such that a physiological response is appropriately modified. This may be achieved, for example, by modulating the expression or secretion of the biomolecule.

The compositions of the invention comprise a commensal bacterial strain. A commensal bacterial strain is a symbiont derived from the gastrointestinal tract of a mammal, such as a human. Examples of genera from which the commensal bacterial strain may be derived include *Bacteroides, Enterococcus, Escherichia, Klebsiella, Bifidobacterium, Staphylococcus, Lactobacillus, Megasphaera, Clostridium, Proteus, Pseudomonas, Salmonella, Faecalibacterium, Peptostreptococcus or Peptococcus*. In some embodiments, the commensal bacterial strain is of the genus *Megasphaera*. Preferrably, *Megasphaera* species for use in the invention include *Megasphaera elsdenii*, *Megasphaera cerevisiae*, *Megasphaera massiliensis, Megasphaera indica, Megasphaera paucivorans, Megasphaera sueciensis* and *Megasphaera micronuciformis*. A further example of a *Megasphaera* species for use in the invention is *Megasphaera hexanoica.* The *Megasphaera* are obligately anaerobic, lactate-fermenting, gastrointestinal microbe of ruminant and non-ruminant mammals, including humans. Preferably, the bacterial strain is derived from the species to which the composition is intended to be administered.

The type strain of *M. massiliensis* is NP3 (=CSUR P245=DSM 26228) [23]. The GenBank accession number for the 16S rRNA gene sequences of *M. massiliensis* strain NP3 is JX424772.1 (disclosed herein as SEQ ID NO:1).

The *Megasphaera massiliensis* bacterium tested in the Examples is referred to herein as strain MRx0029. MRX0029 and MRx0029 are used herein interchangeably. A 16S rRNA sequence for the MRx0029 strain that was tested is provided in SEQ ID NO:2. Preferably, the bacteria for use in the invention is of the species *Megasphaera massiliensis*, in particular the strain MRx0029.

Strain MRx0029 was deposited with the international depositary authority NCIMB, Ltd. (Ferguson Building, Aberdeen, AB21 9YA, Scotland) by 4D Pharma Research Ltd. (Life Sciences Innovation Building, Cornhill Road, Aberdeen, AB25 2ZS, Scotland) on 13th July 2017 as "*Megasphaera massiliensis* MRx0029" and was assigned accession number NCIMB 42787.

Commensal bacterial strains closely related to the strain tested in the examples are also expected to be effective for treating or preventing neurodegenerative diseases. In certain embodiments, the bacterial strain for use in the invention has a 16S rRNA sequence that is at least 95%, 96%, 97%, 98%, 99%,

99.5% or 99.9% identical to the 16S rRNA sequence of a bacterial strain of *Megasphaera massiliensis*. Preferably, the bacterial strain for use in the invention has a 16S rRNA sequence that is at least 95%, 96%, 97%, 98%, 99%, 99.5% or 99.9% identical to SEQ ID NO: 2. Preferably, the bacterial strain for use in the invention has the 16S rRNA sequence represented by SEQ ID NO:2.

Commensal bacterial strains that are biotypes of strains MRx0029 are also expected to be effective for treating or preventing neurodegenerative disorders. A biotype is a closely related strain that has the same or very similar physiological and biochemical characteristics.

Strains that are biotypes of MRx0029 and that are suitable for use in the invention may be identified by sequencing other nucleotide sequences for strains MRx0029. For example, substantially the whole genome may be sequenced and a biotype strain for use in the invention may have at least 95%, 96%, 97%, 98%, 99%, 99.5% or 99.9% sequence identity across at least 80% of its whole genome (e.g. across at least 85%, 90%, 95% or 99%, or across its whole genome). Other suitable sequences for use in identifying biotype strains may include hsp60 or repetitive sequences such as BOX, ERIC, $(GTG)_5$, or REP [24]. Biotype strains may have sequences with at least 95%, 96%, 97%, 98%, 99%, 99.5% or 99.9% sequence identity to the corresponding sequence of the strain MRx0029.

In some embodiments, a commensal bacterial strain useful in the invention is one that produces organic acids of the invention. Such biotypes may be identified by profiling the production of metabolites of a bacterial strain. Metabolite profiling can be used to identity candidate bacterial strains that produce the neurostimulatory organic acids of the invention. Metabolite profiling can be performed by mass spectrometry. Candidate strains that produce the organic acid and that are suitable for the uses described herein can then be identified by performing the methods and assays as set out in the examples.

Alternatively, suitable biotypes capable of producing an organic acid of the invention are those that contain metabolic pathways that produce the organic acids. Such strains can be identified by genomic analysis, for example by determining whether the bacterial strain encodes for enzymes required for the biosynthesis of the desired organic acids. For example, hexanoic acid production is a multistep catalytic process requiring the presence of multiple enzymes. A crucial step in the production of hexanoic acid is the condensation of acetyl-CoA and butyric-CoA to form a C6 acyl-CoA intermediate, such as 3-ketohexanoyl-CoA. Enyzmes required for the production of C4 and C2-CoA precursors are well known to a person skilled in the art. An example of a suitable enzyme for the condensation of C2 and C4 precursors is Beta-ketothiolase. Enzymatic pathways for the formation of C4 CoA are known to have activity with C6 substrates. Therefore, once the C6 intermediate has been formed, enzymes that catalyse the production C4 butryrl-CoA are also suitable for the generation of hexanoic acid. As such, suitable biotypes are those that encode C4-CoA and C2-CoA production- enzymes and an enzyme with beta-ketothiolase activity. Suitable strains may be identified using homology sequence searching

databases such as BLASTP or UNIPROT KB by using query sequences of well known enzymes involved in the production of hexanoic acid.

Listed below are bacteria that are known to produce organic acids of use according to the invention, together with supporting references. Using these lists and referenced documents, further strains and species useful for treating neurodegenerative disorders may be identified.

The following species and strains are known to produce hexanoic acid and so may be useful in the compositions of the invention. Preferably, the compositions of the invention comprise a bacterial strain of a species selected from: *Megasphaera hexanoica* [25], in particular strain *Megasphaera hexanoica* KFCC11466P (KR101745084B1); *Megasphaera sp.* MH [26]; *Megasphaera elsdenii* [27] and [28], in particular strain *Megasphaera elsdenii* NCIMB 702410 [29]; *Clostridium kluyveri* [30]; *Clostridium sp. BS-1* [31], CPB6 (*Ruminococcaceae bacterium*, Clostridium cluster IV) [32]; *Lactobacillus sanfranciscensis* CB1 [33]; *Pediococcus acidilactici* [34]; *Lysinibacillus spp.* Y20 [35] or *Eubacterium pyruvativorans* (I-6) [36].

Bacillus cereus is known to produce retinoic acid and so may be useful in the compositions of the invention [37]. In certain embodiments, the composition of the invention comprises a strain of the species *Bacillus cereus.*

The following genera, species and strains are known to produce (4)-hydroxyphenylacetic acid and so may be useful in the compositions of the invention. Preferably, the compositions of the invention comprise a bacterial strain of the genus *Clostridia* [38] and [39], preferably a bacterial strain of the species *C. difficile* [40] and [41], in particular strains *C. difficile* CDC A567 [42], *C. difficile* DSM 101085 [43], *C. difficile* DSM 102978 [43], *C. difficile* DSM 102860 [43], and *C. difficile* DSM 28666 [43]; *C. putrefaciens* [44]); *C. stricklandii* [44] and Great Plains Lab, Organic Acid Test, Nutritional and Metabolic Profile, Clostridia Bacterial Markers); *C. lituseburense* [44] and Great Plains Lab, Organic Acid Test, Nutritional and Metabolic Profile, Clostridia Bacterial Markers; *C. subterminale* [45], [46] and [44]; *C. propionicum* [44] [46]; *C. clostridiiforme* [46]; *C. cochlearium* [46]; *C. glycolicum* [46]; *C. hastiforme* [46]; *C. irregularis* [46]; *C. perfringens* [47]; or *C. botulinum* Type G [48] and [49]. Preferably, the compositions of the invention comprise a bacterial strain of a species selected from: *Bacteroides fragilis* [50] and [51]); *Bacteroides thetaiotaomicron* [51]; *Bacteroides eggerthii* [51]; *Bacteroides ovatus* [51]; *Parabacteroides distasonis* [51]; *Eubacterium hallii* [51]; *Clostridium bartlettii* [51]; *Porphyromonas* gingivalis [52]; *Flavobacterium sp.* [53]; *Desulfitobacterium dehalogenans* [54] and [55]; *Desulfitobacterium hafniense* DCB-2 [54]; or *Streptomyces sentonii* [56].

Commensal bacteria that have neuroprotective properties but do not produce organic acids in accordance with the first aspect of the invention may be useful in the second aspect of the invention, in compositions in combination with an organic acid. Bacteria which may be employed in the compositions of the second aspect of the present invention include those belonging to the genera

Roseburia (e.g. *Roseburia hominis*), *Bacteroides*, *Parabacteroides* (e.g. *Parabacteroides distasonis*), *Blautia* (e.g. *Blautia hydrogenotrophica, Blautia stercoris, Blautia wexlerae*), *Ruminococcus* (e.g. *Ruminococcus albus* [57]), *Clostridium* (e.g. *Clostridium butyricum* [58]), *Lactococcus* (e.g. *Lactococcus lactis, Lactococcus rhamnosus*), *Bifidobacterium* (e.g. *Bifidobacterium breve, Bifidobacterium longum, Bifidobacterium adolescentis, Bifidobacterium lactis, Bifidobacterium infantis*), *Lactobacillus* (e.g. *Lactobacillus paracasei, Lactobacillus delbrueckii, Lactobacillus brevis, Lactobacillus plantarum, Lactobacillus acidophilus*) or *Streptococcus* (e.g. *Streptococcus thermophilus*) ([59], [60]),

Alternatively, strains that are biotypes of strains MRX0029 and that are suitable for use in the invention may be identified by using strains MRX0029 and restriction fragment analysis and/or PCR analysis, for example by using fluorescent amplified fragment length polymorphism (FAFLP) and repetitive DNA element (rep)-PCR fingerprinting, or protein profiling, or partial 16S or 23S rDNA sequencing. In preferred embodiments, such techniques may be used to identify other *Megasphaera massiliensis* strains.

In certain embodiments, strains that are biotypes of strains MRX0029 and that are suitable for use in the invention are strains that provide the same pattern as strains MRX0029 when analysed by amplified ribosomal DNA restriction analysis (ARDRA), for example when using Sau3AI restriction enzyme (for exemplary methods and guidance see, for example, [61]). Alternatively, biotype strains are identified as strains that have the same carbohydrate fermentation patterns as strains MRX0029.

Other commensal bacterial strains that are useful in the compositions and methods of the invention, such as biotypes of MRX0029, may be identified using any appropriate method or strategy, including the assays described in the examples. For instance, strains for use in the invention may be identified by culturing with neuroblastoma cells and then assessing cytokine levels and levels of neuroprotection or neuroproliferation. In particular, bacterial strains that have similar growth patterns, metabolic type and/or surface antigens to MRX0029 may be useful in the invention. A useful strain will have comparable immune modulatory activity to MRX0029. In particular, a biotype strain will elicit comparable effects on the neurodegenerative disease models and comparable effects on cytokine levels to the effects shown in the Examples, which may be identified by using the culturing and administration protocols described in the Examples.

A particularly preferred strain of the invention is the *Megasphaera massiliensis* MRX0029 strain. This is the exemplary strain tested in the examples and shown to be effective for treating disease. Therefore, the invention provides a cell, such as an isolated cell, of the *Megasphaera massiliensis* strain MRX0029, or a derivative thereof. The invention also provides a composition comprising a cell of the *Megasphaera massiliensis* strain MRX0029, or a derivative thereof. The invention also provides a biologically pure culture of the *Megasphaera massiliensis* strain MRX0029. The invention also

provides a cell of the *Megasphaera massiliensis* strain MRX0029, or a derivative thereof, for use in therapy, in particular for the diseases described herein.

A particularly preferred strain of the invention is the *Megasphaera massiliensis* strain deposited under accession number NCIMB 42787. This is the exemplary MRx0029 strain tested in the examples and shown to be effective for treating disease. Therefore, the invention provides a cell, such as an isolated cell, of the *Megasphaera massiliensis* strain deposited under accession number NCIMB 42787, or a derivative thereof. The invention also provides a composition comprising a cell of the *Megasphaera massiliensis* strain deposited under accession number NCIMB 42787, or a derivative thereof. The invention also provides a biologically pure culture of the *Megasphaera massiliensis* strain deposited under accession number NCIMB 42787. The invention also provides a cell of the *Megasphaera massiliensis* strain deposited under accession number NCIMB 42787, or a derivative thereof, for use in therapy, in particular for the diseases described herein.

A derivative of the strain of the invention may be a daughter strain (progeny) or a strain cultured (subcloned) from the original. A derivative of a strain of the invention may be modified, for example at the genetic level, without ablating the biological activity. In particular, a derivative strain of the invention is therapeutically active. A derivative strain will have comparable therapeutic activity to the MRX0029 strain. In particular, a derivative strain will elicit comparable effects on the neurodegenerative disease models and comparable effects on cytokine levels to the effects shown in the Examples, which may be identified by using the culturing and administration protocols described in the Examples. A derivative of the MRX0029 strain will generally be a biotype of the MRX0029 strain.

References to cells of the *Megasphaera massiliensis* MRX0029 strain encompass any cells that have the same safety and therapeutic efficacy characteristics as the strain MRX0029, and such cells are encompassed by the invention.

In preferred embodiments, the bacterial strains in the compositions of the invention are viable and capable of partially or totally colonising the intestine.

A further commensal bacteria that may be used in the compositions of the invention is the species *Parabacteroides distasonis*. The examples demonstrate that *Parabacteroides distasonis* and *Megasphaera massiliensis* both have neuroprotective activities, but produce different metabolites and may have different mechanisms of action and specific neuroprotective activities. Therefore, these species may be particularly effective when used in combination. In preferred embodiments, the composition comprises a strain of the species *Parabacteroides distasonis* and a strain of the species *Megasphaera massiliensis*. The composition may also include an organic acid, as defined herein.

The *Parabacteroides distasonis* bacterium deposited under accession number NCIMB 42382 was tested in the Examples and is also referred to herein as strain MRx0005. MRX0005, MRX005, MRx005 and MRx0005 are used herein interchangeably. A 16S rRNA sequence for the MRx0005

strain that was tested is provided in SEQ ID NO:17. Strain MRx0005 was deposited with the international depositary authority NCIMB, Ltd. (Ferguson Building, Aberdeen, AB21 9YA, Scotland) by GT Biologics Ltd. (Life Sciences Innovation Building, Aberdeen, AB25 2ZS, Scotland) on 12th March 2015 as "*Parabacteroides sp* 755" and was assigned accession number NCIMB 42382. GT Biologics Ltd. Subsequently changed its name to 4D Pharma Research Limited.

In preferred embodiments, the invention provides a composition comprising the strain deposited at NCIMB under accession number NCIMB 42787, or a derivative or biotype thereof, and the strain deposited at NCIMB under accession number NCIMB 42382, or a derivative or biotype thereof, preferably for use in therapy, preferably for use in treating a neurodegenerative disease such as Parkinson's disease.

In certain embodiments, the composition of the invention does not comprise a bacterial strain of the genus *Megasphaera.* In certain embodiments, the composition of the invention does not comprise a bacterial strain of the species *Megasphaera massiliensis.* In certain embodiments, the composition of the invention does not comprise the *Megasphaera massiliensis* strain deposited under accession number NCIMB 42787.

Organic acids

As demonstrated in the Examples, one or more organic acids described herein have neuroprotective and/or neurorestorative properties. For example, the organic acids of the invention may promote neurite outgrowth. Neurite outgrowth is the process of neuritogenesis, which refers to the formation of axonal or dendritic projections from the cell body of a neuron. Axons and dendrites are responsible for receiving and transmitting action potentials. Thus, increasing neurite outgrowth can restore or preserve effective communication within neural networks within the nervous system. Therefore, in some embodiments, organic acids suitable for use in the invention are those capable of promoting neurite outgrowth. Such organic acids may be for use in a method of preventing disease. In some embodiments, the organic acids are for use in a method of treating or preventing a neurodegenerative disease.

The one or more organic acids comprise the following formula: R-COOH.

In some embodiments, R comprises an alkyl group. As referred to herein, an alkyl group is a linear, branched, or cyclic saturated hydrocarbon chain or any substituent derived therefrom. In some embodiments, R comprises an alkenyl group. As referred to herein, an alkenyl group is a linear, branched, or cyclic unsaturated hydrocarbon comprising at least one carbon-to-carbon double bond, or any substituent derived therefrom. In some embodiments, R comprises an alkynyl group. As referred to herein, an alkynyl group is a linear, branched, or cyclic unsaturated hydrocarbon comprising at least one carbon-carbon triple bond, or any substituent derived therefrom. In some embodiments, R comprises an aryl group. As referred to herein, an aryl group is a linear, branched or cyclic aromatic hydrocarbon, or any substituent derived therefrom.

As referred to herein, a substituent is an atom or group of atoms that replaces one or more hydrogens of the parent hydrocarbon chain. In some embodiments, R comprises one or more substituents. In some embodiments, the one or more substituents are selected from the list consisting of hydroxyl, carbonyl, aldehyde, haloformyl, carbonate ester, carboxylate, carboxyl, ester, methoxy, hydroperoxy, peroxy, ether, hemiacetal, hemiketal, acetal, ketal, orthoester, methylenedioxy, carboxamide, amine, imine, nitrate, nitrile, nitrite, pyridyl, sulfhydryl, sulphide, disulphide, sulfinyl, sulfonyl, sulfino, sulfo, carbonothioyl, catechol or a combination thereof.

In some embodiments, R comprises at least 4 carbon atoms. In some embodiments, R comprises at least 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18 or 19 carbon atoms. In some embodiments, R comprises in the range of 4 to 19 carbon atoms.

In some embodiments, R comprises in the range of 4 to 11 carbons. In some embodiments, R comprises an alkyl group consisting of 5 carbon atoms. In some embodiments, the one or more organic acids comprise hexanoic acid. The inventors have found that hexanoic acid and bacterial strains described herein that produce hexanoic acid enhance neurite outgrowth. As such, these organic acids can be used to promote neurite outgrowth. In some embodiments, these organic acids can be used to promote neurite outgrowth in the treatment or prevention of a neurodegenerative disease. Exemplary bacterial strains of the invention that produce hexanoic acid comprise those from the genus *Megasphaera*.

In some embodiments, R comprises an alkyl group consisting of 4 carbon atoms. In some embodiments, the one or more organic acids comprise valeric acid. Valeric acid and pentanoic acid are herein used interchangeably. The inventors have found that valeric acid and commensal bacterial strains described herein that produce valeric acid can reduce histone deacetylation. In particular the inventors have found that valeric acid histone deacetylase inhibitor. Histone deacetylases (HDACs) regulate gene expression by modulating chromatin acetylation. The overexpression of different isoforms of HDACs has been found in several types of cancer cells as well as in neurological and inflammatory pathologies. In humans, there are a total of 13 HDACs, which are categorised into four main classes - Class I (HDACs 1, 2, 3 and 8), Class IIa (HDACs 4,5,7 and 9) and Class IIb (HDACs 6 and 10), Class III (sirt1-sirt7) and class IV (HDAC 11). The inventors have found that valeric acid is a class 1 HDAC inhibitor.

In some embodiments, R comprises a branched alkyl group. In some embodiments, R comprises at least 5 carbon atoms. In some embodiments, R comprises in the range of 5 to 9 carbon atoms. In some embodiments, R comprises a butyric group. In some embodiments, R consists of a butyl group and a propyl group. In some embodiments, the one or more organic acids comprise valproic acid. The inventors have shown increases neurite outgrowth and thus can be for use in a method of neurorestoration. Valproic acid has also been shown to aid neurorestoration in a rat model of PD [62], although not in combination with a bacterial therapy. Valproic acid has been shown to increase MAP2 expression.

In some embodiments, R comprises an aryl group. In some embodiments, the aryl group is a phenyl group. In some embodiments, the phenyl group comprises a hydroxyl group. In some embodiments, the hydroxyl group is at ring position 2, 3, 4, 5 or 6. In some embodiments, the hydroxyl group is at ring position 4. In some embodiments, R consists of a 4-hydroxyphenylacetyl group. In some embodiments, the one or more organic acids comprise 4-hydroxyphenylacetic acid. The inventors have shown that this organic acid or bacterial strains described herein that produce this organic acid can be used to promote neurite outgrowth. 4-hydroxyphenylacetic acid is also an antioxidant. In some embodiments, the one or more organic acids comprising 4-hydroxyphenylacetic acid can be used in the treatment or prevention of neurodegenerative disorders to reduce oxidative stress. 4-hydroxyphenylacetic acid is an intermediate of dopamine and norepinephrine. Dopamine and norepinephrine (also known as noradrenaline) are neurotransmitters acting in the sympathetic nervous system. Levels of dopamine and norepinephrine are reduced in subjects suffering from neurodegenerative diseases, for example Parkinson's disease. The inventors have found that commensal bacterial strains described herein that produce 4-hydroxyphenylacetic acid increase the levels of noradrenaline, serotonin or 5-hydroxytryptamine (5-HT) in the brain. Therefore, 4- hydroxyphenylacetic acid may be useful in the treatment or prevention of neurodegenerative diseases characterised by lower levels of norepheniphrine, dopamine, serotonin or 5-hydroxytryptamine. In some embodiments, 4- hydroxyphenylacetic acid may be useful in the treatment or prevention of neurodegenerative diseases.

In some embodiments, R comprises an alkenyl group. In some embodiments, the alkenyl group is at least partially cyclical. As referred to herein, a "partially cyclical" group is a hydrocarbon chain comprising a linear chain portion and a cyclical chain portion. In some embodiments, the partially cyclical alkenyl group comprises 19 carbon atoms. In some embodiments, R comprises in the range of 1 to 8 methyl substituent groups. In some embodiments, R comprises in the range of 1 to 8 carbon- to- carbon double bonds. In some embodiments, the organic acid is retinoic acid or a derivative thereof. The inventors have found that these organic acids when administered in combination with the bacterial strains of the invention increase the activation of BDNF. As such, in some embodiments, these organic acids may be used to increase the activation of BDNF. In some embodiments, these organic acids can be used to increase the activation of BDNF in the treatment or prevention of neurodegenerative diseases.

The organic acids for use in the invention may be identified by using the culturing and administration protocols described in the Examples. For instance. organic acids for use in the invention can be identified by culturing with neuroblastoma cells and then assessing cytokine levels and levels of neuroprotection or neuroproliferation and neuritogenesis. A useful organic acid may enhance neurite outgrowth activity at least comparable to valproic acid, hexanoic acid or retinoic acid, as shown in the Examples. In particular, a useful organic acid may elicit comparable effects on the neurodegenerative disease models and comparable effects on cytokine and growth factor levels, to the effects shown in

the Examples, when the organic acid is administered in combination with a commensal bacterial strain of the invention. For example, suitable organic acids will increase the activation of BDNF comparable with retinoic acid when administered in combination with a bacterial strain of the invention. In the first aspect, the organic acid is produced by the commensal bacterial strain of the invention.

In some embodiments, suitable organic acids of the invention as those that act together with the commensal bacterial strain of the invention to enhance a therapeutic response. For instance, the Examples show that administration of valproic acid together with MRX0029 increases the secretion of BDNF. BDNF can help support the survival of existing neurons and helps the growth and development of new neurons and synapses. Therefore, certain organic acids of the invention may be for use in methods of neuropreservation, or in other words, to prevent neuron death.

The compositions of the invention may further comprise short chain fatty acids (SCFAs). SCFAs are organic acids comprising a carboxylic acid group bonded to a linear or branched hydrocarbon alkyl group consisting of 0 to 4 carbon atoms. SCFAs have been shown to regulate the permeability of the blood brain barrier. In particular, SCFAs have been shown to redress defective BBB permeability, thus restoring permeability to physiologically appropriate levels. In some embodiments, the SCFA is selected from the list consisting of formic acid, ethanoic acid, propanoic acid, butyric acid, 2-methylpropanoic acid isovaleric acid, or a salts or esters thereof. In some embodiments, the SCFA is part of the therapeutic combination. In some embodiments, the SCFA is produced by the commensal bacterial strain of the invention.

In some embodiments, the SCFA for use in the invention is butyric acid or a salt thereof. In some embodiments, the commensal bacterial strain produces butyric acid or a salt thereof. In some embodiments, the commensal bacterial strain that produces butyric acid or a salt thereof is the *M.massiliensis* strain referred to herein as strain MRX0029. Suitable biotypes of the bacterial strain that produce the SCFA can be identified using any of the other methods described in the previous section, for example, metabolite profiling, genome analysis, or amplified ribosomal DNA restriction analysis.

In some embodiments, the compositions of the invention may further comprise succinic acid or a salt thereof. In some embodiments, the commensal bacterial strain produce succinic acid or a salt thereof. In some embodiments, the commensal bacterial strain that produces succinic acid is the strain referred to herein as strain MRX0005. Succinic acid is a Krebs cycle metabolite involved in oxidative phosphorylation. Dysfunction of oxidative phosphorylation has been reported in neurodegenerative disorders including Alzheimer's disease, Parkinson's disease and Spinocerebellar ataxia type 1 [63,64]). Therefore increasing the availability of succinic acid may reverse defects in oxidative phosphorylation and increase mitochondrial activity to improve the health of neurons subject to neurodegenerative disease, such as PD [65].

Therapeutic uses

As demonstrated in the examples, the bacterial compositions of the invention are effective for treating neurodegenerative disorders. In particular, treatment with compositions of the invention increase neuroproliferation or neuritogenesis or act as a neuroprotectant against agents that destroy neurons, such as dopaminergic neurons. Therefore, the compositions of the invention may be useful for treating or preventing neurodegenerative diseases that are the result of neuron death.

Compositions of the invention can decrease the activation of the NFκB promoter, which activates cytokine production, for example IL-1β, IL-1α, IL-18, TNFα and IL-6. Treating cells with mutant α-synuclein is a model for familial Parkinson's. A point mutation at position 53 from adenine to threonine leads to α-synuclein mis-folding. The incorrectly folded α-synuclein subsequently aggregates into insoluble fibrils which form Lewy bodies. Therefore, the compositions of the invention may be useful for treating or preventing neurodegenerative disorders that are the result of neuroinflammation, protein misfolding and/or environmental exposure. Compositions of the invention can be used for treatment of familial Parkinson's. Activation of the NFκB promoter is mediated through the TLR4 ligand. TLR4 is known to mediate cell death in the mouse model MPTP, which simulates of Parkinson's disease. Compositions of the invention can be used to inhibit the ability of TLR4 to activate the NFκB promoter. Of particular relevance for PD, both TLR2 and TLR4 were found to be upregulated in brains of PD patients [66]. Moreover α-syn has been described as a ligand for TLR2 [67] and we have demonstrated that α-syn is also a ligand for TLR4 using HEK-TLR4 cells [68].

Compositions of the invention decrease the secretion of pro-inflammatory cytokines such as IL-6, which can be induced by lipopolysaccharide (LPS). Treatment of cells with LPS simulates Parkinson's caused by environmental factors. Compositions of the invention can be used to decrease IL-6 secretion. Compositions of the invention can be used for treatment of environmental Parkinson's.

Compositions of the invention can increase the secretion of IL-8. IL-8 has been shown to play a role in neuron myelination. In some embodiments, compositions of the invention can be used to increase IL-8 secretion.

The therapeutic compositions of the invention can increase the activation of BDNF. BDNF acts on certain neurons of the central nervous system to support the survival of existing neurons and help the growth and development of new neurons and synapses. BDNF is active in the hippocampus, cortex and basal forebrain, and is important for long-term memory. The compositions of the invention can therefore be used to increase the secretion of BDNF. The compositions may therefore be used in the treatment of neurodegenerative diseases associated with the impairment of long-term memory. The compositions of the invention may be used for improving long-term memory, in particular for improving long-term memory that is impaired by a neurodegenerative disease.

In certain embodiments, the compositions of the invention increase the mitochondria metabolic activity in neuronal cells.

Examples of neurodegenerative diseases to be treated by compositions of the invention include: Parkinson's disease, including progressive supranuclear palsy, progressive supranuclear palsy, Steele-Richardson-Olszewski syndrome, normal pressure hydrocephalus, vascular or arteriosclerotic parkinsonism and drug-induced parkinsonism; Alzheimer's disease, including Benson's syndrome; multiple sclerosis; Huntington's disease; amyotrophic lateral sclerosis; Lou Gehrig's disease; motor neurone disease; prion disease; spinocerebellar ataxia; spinal muscular atrophy; dementia, including Lewy body, vascular and frontotemporal dementia; primary progressive aphasia; mild cognitive impairment; HIV-related cognitive impairment, progressive inflammatory neuropathy, and corticobasal degeneration.

In certain embodiments, the compositions of the invention are for use in reducing neuron death, in particular, in the treatment of neurodegenerative disorders. In certain embodiments, the compositions of the invention are for use in protecting neurons, in particular in the treatment of neurodegenerative disorders.

In certain embodiments, the compositions of the invention are for use in reducing or preventing loss of dopaminergic cells in the substantia nigra. In certain embodiments, the compositions of the invention are for use in reducing or preventing the degeneration of dopaminergic neurons in the substantia nigra pars compacta. In certain embodiments, the compositions of the invention are for use in reducing or preventing the degeneration of dopaminergic neurons in the *substantia nigra pars* compacta and the consequent loss of their projecting nerve fibers in the striatum. In certain embodiments, the compositions of the invention are for use in reducing or preventing loss of nigrostriatal dopaminergic neurons.

In certain embodiments, the compositions of the invention are for use in increasing dopamine levels. In certain embodiments, the compositions of the invention are for use in increasing DOPAC (3,4-Dihydroxyphenylacetic acid) levels. In certain embodiments, the compositions of the invention are for use in increasing dopamine and DOPAC levels. In certain embodiments, the dopamine and/or DOPAC levels are increased in the striatum. Dopamine and DOPAC levels may be measured using any appropriate method known in the art, such as a radioenzymatic method, for example in plasma or CSF (for example as described in [69]), or a reverse-phase HPLC method, perhaps with electrochemical detection, for example in plasma or CSF (for example as described in [70]).

The neuroprotective properties of the compositions of the invention, as shown in the Examples, mean that the compositions may be particularly effective for preventing or delaying onset or progression of neurodegenerative disorders. In certain embodiments, the compositions of the invention are for use in delaying onset or progression of neurodegenerative disorders.

Modulation of the microbiota-gut-brain axis

Communication between the gut and the brain (the microbiota-gut-brain axis) occurs via a bidirectional neurohumoral communication system. Recent evidence shows that the microbiota that resides in the

gut can modulate brain development and produce behavioural phenotypes via the microbiota-gut-brain axis. Indeed, a number of reviews suggest a role of the microbiota-gut-brain axis in maintaining central nervous system functionality and implicate dysfunction of the microbiota-gut-brain axis in the development of central nervous system disorders and conditions [16],[19],[71].

The bidirectional communication between the brain and the gut (*i.e.* the-gut-brain axis) includes the central nervous system, neuroendocrine and neuroimmune systems, including the hypothalamus-pituitary-adrenal (HPA) axis, sympathetic and parasympathetic arms of the autonomic nervous system (ANS), including the enteric nervous system (ENS) and the vagus nerve, and the gut microbiota.

As demonstrated in the examples, the compositions of the present invention can modulate the microbiota-gut-brain axis and reduce cell death associated with neurodegenerative disorders. Accordingly, the compositions of the invention may be useful for treating or preventing neurodegenerative disorders, in particular those disorders and conditions associated with dysfunction of the microbiota-gut-brain axis.

In particular embodiments, the compositions of the invention may be useful for treating or preventing a disease or condition selected from the group consisting of: Parkinson's disease, including progressive supranuclear palsy, progressive supranuclear palsy, Steele-Richardson-Olszewski syndrome, normal pressure hydrocephalus, vascular or arteriosclerotic parkinsonism and drug-induced parkinsonism; Alzheimer's disease, including Benson's syndrome; multiple sclerosis; Huntington's disease; amyotrophic lateral sclerosis; Lou Gehrig's disease; motor neurone disease; prion disease; spinocerebellar ataxia; spinal muscular atrophy; dementia; including Lewy body; vascular and frontotemporal dementia; primary progressive aphasia; mild cognitive impairment; HIV-related cognitive impairment, progressive inflammatory neuropathy, and corticobasal degeneration.

The compositions of the invention may be particularly useful for treating or preventing chronic disease, treating or preventing disease in patients that have not responded to other therapies (such as treatment with Levodopa, dopamine agonists, MAO-B inhibitors, COMT inhibitors, Glutamate antagonists, and/or anticholinergics), and/or treating or preventing the tissue damage and symptoms associated with dysfunction of the microbiota-gut-brain axis.

In certain embodiments, the compositions of the invention modulate the CNS. In some embodiments, the compositions of the invention modulate the autonomic nervous system (ANS). In some embodiments, the compositions of the invention modulate the enteric nervous system (ENS). In some embodiments, the compositions of the invention modulate the hypothalamic, pituitary, adrenal (HPA) axis. In some embodiments, the compositions of the invention modulate the neuroendocrine pathway. In some embodiments, the compositions of the invention modulate the neuroimmune pathway. In some embodiments, the compositions of the invention modulate the CNS, the ANS, the ENS, the HPA axis and/or the neuroendocrine and neuroimmune pathways. In certain embodiments, the compositions of

the invention module the levels of commensal metabolites and/or the gastrointestinal permeability of a subject.

The signalling of the microbiota-gut-brain axis is modulated by neural systems. Accordingly, in some embodiments, the compositions of the invention modulate signalling in neural systems. In certain embodiments, the compositions of the invention modulate the signalling of the central nervous system. In some embodiments, the compositions of the invention modulate signalling in sensory neurons. In other embodiments, the compositions of the invention modulate signalling in motor neurons. In some embodiments, the compositions of the invention modulate the signalling in the ANS. In some embodiments, the ANS is the parasympathetic nervous system. In preferred embodiments, the compositions of the invention modulate the signalling of the vagus nerve. In other embodiments, the ANS is the sympathetic nervous system. In other embodiments, the compositions of the invention modulate the signalling in the enteric nervous system. In certain embodiments, the signalling of ANS and ENS neurons responds directly to luminal contents of the gastrointestinal tract. In other embodiments, the signalling of ANS and ENS neurons responds indirectly to neurochemicals produced by luminal bacteria. In other embodiments, the signalling of ANS and ENS neurons responds to neurochemicals produced by luminal bacteria or enteroendocrine cells. In certain preferred embodiments, the neurons of the ENS activate vagal afferents that influence the functions of the CNS. In some embodiments, the compositions of the invention regulate the activity of enterochromaffin cells.

Neurodegenerative diseases

Parkinson's disease

Parkinson's disease is a common neurodegenerative disease neuropathologically characterised by degeneration of heterogeneous populations of neural cells (dopamine-producing cells). The clinical diagnosis of Parkinson's disease requires bradykinesia and at least one of the following core symptoms: resting tremor; muscle rigidity and postural reflex impairment. Other signs and symptoms that may be present or develop during the progression of the disease are autonomic disturbances (sialorrhoea, seborrhoea, constipation, micturition disturbances, sexual functioning, orthostatic hypotension, hyperhydrosis), sleep disturbances and disturbances in the sense of smell or sense of temperature. Parkinson's disease is a neurodegenerative diseases that may develop or persist due to dysfunction of the microbiota-gut-brain axis. Therefore, in preferred embodiments, the compositions of the invention are for use in treating or preventing Parkinson's disease in a subject.

In further preferred embodiments, compositions of the invention are for use in a method of treating or preventing Parkinson's disease. Compositions of the invention may improve motor and cognitive functions in models of Parkinson's disease. Treatment with the compositions may modulate signalling in the central, autonomic and enteric nervous systems; may modulate the activity of the HPA axis pathway; may modulate neuroendocrine and/or neuroimmune pathways; and may modulate the levels

of commensal metabolites, inflammatory markers and/or gastrointestinal permeability of a subject, all of which are implicated in the neuropathology of Parkinson's disease. In preferred embodiments, the invention provides a composition comprising a bacterial strain of the species *Megasphaera massiliensis* for use in a method of treating or preventing Parkinson's disease. Compositions using *Megasphaera massiliensis* may be particularly effective for treating Parkinson's disease. The composition may further comprise an organic acid.

In preferred embodiments, the compositions of the invention prevent, reduce or alleviate one or more of the symptoms of Parkinson's disease in a subject. In preferred embodiments, the compositions of the invention prevent, reduce or alleviate one or more core symptoms of Parkinson's disease in a subject. In certain embodiments, the compositions of the invention prevent, reduce or alleviate bradykinesia in a subject. In certain embodiments, the compositions of the invention prevent, reduce or alleviate resting tremor; muscle rigidity and/or postural reflex impairment in a subject. In certain embodiments, the compositions of the invention prevent, reduce or alleviate one or more symptoms associated with Parkinson's disease progression selected from autonomic disturbances (sialorrhoea, seborrhoea, constipation, micturition disturbances, sexual functioning, orthostatic hypotension, hyperhydrosis), sleep disturbances and disturbances in the sense of smell or sense of temperature.

In preferred embodiments, the compositions of the invention prevent, reduce or alleviate depressive symptoms comorbid with Parkinson's disease. In certain embodiments, the compositions of the invention improve verbal memory and/or executive functions. In certain embodiments, the compositions of the invention improve attention, working memory, verbal fluency and/or anxiety.

In other preferred embodiments, the compositions of the invention prevent, reduce or alleviate cognitive dysfunctions comorbid with Parkinson's disease.

In certain embodiments, the compositions of the invention prevent, reduce or alleviate Parkinson's disease progression. In certain embodiments, the compositions of the invention prevent, reduce or alleviate later motor complications. In certain embodiments, the compositions of the invention prevent, reduce or alleviate late motor fluctuations. In certain embodiments, the compositions of the invention prevent, reduce or alleviate neuronal loss. In certain embodiments, the compositions of the invention improve symptoms of Parkinson's disease dementia (PDD). In certain embodiments, the compositions of the invention prevent, reduce or alleviate impairment of executive function, attention and/or working memory. In certain embodiments, the compositions of the invention improve dopaminergic neurotransmission. In certain embodiments, the compositions of the invention prevent, reduce or alleviate impaired dopaminergic neurotransmission.

In some embodiments, the compositions of the invention improve the symptoms of Parkinson's disease according to a symptomatic or diagnostic scale. In certain embodiments, the tests for assessing symptomatic improvement of motor function in Parkinson's disease is the Unified Parkinson's Disease

Rating Scale. In particular, UPDRS II considers the activity of daily life and UPDRS III considers motor-examination.

In some embodiments, the compositions of the invention improve the symptoms associated with PDD according to a symptomatic or diagnostic test and/or scale. In certain embodiments, the test or scale is selected from the Hopkins Verbal Learning Test – Revised (HVLT-R); the Delis-Kaplan Executive Function System (D-KEFS) Color-Word Interference Test; the Hamilton Depression Rating Scale (HAM-D 17; depression); the Hamilton Anxiety Rating Scale (HAM-A; anxiety) and the Unified Parkinson's Disease Rating Scale (UPDRS; PD symptom severity).

In some embodiments, the compositions of the invention improve the Clinical Global Impression – Global Improvement (CGI-I) scale for assessing psychiatric and neurological disorders. In some embodiments, the compositions of the invention display a positive effect on global social and occupational impairment of the subject with Parkinson's disease.

In certain embodiments, the compositions of the invention are for use in treating or preventing neurological disorders such as Parkinson's disease in a subject wherein said use involves reducing or preventing loss of dopaminergic cells in the substantia nigra. In certain embodiments, the compositions of the invention are for use in treating or preventing neurological disorders such as Parkinson's disease in a subject wherein said use involves reducing or preventing the degeneration of dopaminergic neurons in the substantia nigra pars compacta. In certain embodiments, the compositions of the invention are for use in treating or preventing neurological disorders such as Parkinson's disease in a subject wherein said use involves reducing or preventing the degeneration of dopaminergic neurons in the substantia nigra pars compacta and the consequent loss of their projecting nerve fibers in the striatum. In certain embodiments, the compositions of the invention are for use in treating or preventing neurological disorders such as Parkinson's disease in a subject wherein said use involves reducing or preventing loss of nigrostriatal dopaminergic neurons.

In certain embodiments, the compositions of the invention are for use in treating or preventing neurological disorders such as Parkinson's disease in a subject wherein said use involves increasing dopamine levels. In certain embodiments, the compositions of the invention are for use in treating or preventing neurological disorders such as Parkinson's disease in a subject wherein said use involves increasing DOPAC levels. In certain embodiments, the compositions of the invention are for use in treating or preventing neurological disorders such as Parkinson's disease in a subject wherein said use involves increasing dopamine and DOPAC levels. In certain embodiments, the dopamine and/or DOPAC levels are increased in the striatum.

Alzheimer's disease and dementia

In DSM-5, the term dementia was replaced with the terms major neurocognitive disorder and mild neurocognitive disorder. Neurocognitive disorder is a heterogeneous class of psychiatric diseases. The most common neurocognitive disorder is Alzheimer's disease, followed by vascular dementias or

mixed forms of the two. Other forms of neurodegenerative disorders (*e.g.* Lewy body disease, frontotemporal dementia, Parkinson's dementia, Creutzfeldt-Jakob disease, Huntington's disease, and Wernicke-Korsakoff syndrome) are accompanied by dementia.

Alzheimer's disease and dementia are also characterised by neuronal loss, so the neuroprotective and neuroproliferative effects shown in the examples for the compositions of the invention indicate that they may be useful for treating or preventing these conditions.

The symptomatic criteria for dementia under DSM-5 are evidence of significant cognitive decline from a previous level of performance in one or more cognitive domains selected from: learning and memory; language; executive function; complex attention; perceptual-motor and social cognition. The cognitive deficits must interfere with independence in everyday activities. In addition, the cognitive deficits do not occur exclusively in the context of a delirium and are not better explained by another mental disorder (for example MDD or schizophrenia).

In addition to the primary symptom, subjects with neurodegenerative disorders display behavioural and psychiatric symptoms including agitation, aggression, depression, anxiety, apathy, psychosis and sleep-wake cycle disturbances.

Neurodegenerative disorders may develop or persist due to dysfunction of the microbiota-gut-brain axis. Therefore, in preferred embodiments, the compositions of the invention are for use in treating or preventing neurodegenerative disorders in a subject. In preferred embodiments, the neurodegenerative disorder is Alzheimer's disease. In other embodiments, the neurodegenerative disorder is selected from vascular dementias; mixed form Alzheimer's disease and vascular dementia; Lewy body disease; frontotemporal dementia; Parkinson's dementia; Creutzfeldt-Jakob disease; Huntington's disease; and Wernicke-Korsakoff syndrome.

In preferred embodiments, the compositions of the invention prevent, reduce or alleviate one or more of the symptoms of neurodegenerative disorders in a subject. In certain embodiments, the compositions of the invention prevent, reduce or alleviate the occurrence of cognitive decline in a subject. In certain embodiments, the compositions of the invention improve the level of performance of a subject with neurodegenerative disorders in one or more cognitive domains selected from: learning and memory; language; executive function; complex attention; perceptual-motor and social cognition. In some embodiments, the compositions of the invention prevent, reduce or alleviate the occurrence of one or more behavioural and psychiatric symptoms associated with neurodegenerative disorders selected from agitation, aggression, depression, anxiety, apathy, psychosis and sleep-wake cycle disturbances.

In certain embodiments, the compositions of the invention prevent, reduce or alleviate symptomatic disease by intervention in suspected pathogenic mechanisms at a preclinical stage. In certain embodiments, the compositions of the invention improve disease modification, with slowing or arrest of symptom progression. In some embodiments, the slowing or arrest of symptom progression correlates with evidence in delaying the underlying neuropathological process. In preferred

embodiments, the compositions of the invention improve symptoms of neurodegenerative disorders comprising enhanced cognitive and functional improvement. In preferred embodiments, the compositions of the invention improve the behavioural and psychiatric symptoms of dementia (BPSD). In preferred embodiments, the compositions of the invention improve the ability of a subject with neurodegenerative disorder to undertake everyday activities.

In preferred embodiments, the compositions of the invention improve both cognition and functioning in a subject with Alzheimer's disease. In some embodiments, the composition of the invention improves the cognitive endpoint in a subject with Alzheimer's disease. In some embodiments, the compositions of the invention improve the functional endpoint in a subject with Alzheimer's disease. In preferred embodiments, the compositions of the invention improve the cognitive and functional endpoint in a subject with Alzheimer's disease. In yet further preferred embodiments, the compositions of the invention improve the overall clinical response (the global endpoint) in a subject with Alzheimer's disease.

In some embodiments, the compositions of the invention improve the symptoms of neurodegenerative disorders according to a symptomatic or diagnostic test. In certain embodiments, the tests for assessing symptomatic improvement of Alzheimer's disease (and other neurodegenerative disorders) are selected from objective cognitive, activities of daily living, global assessment of change, health related quality of life tests and tests assessing behavioural and psychiatric symptoms of neurodegenerative disorders.

In certain embodiments, the objective cognitive tests for assessment of symptomatic improvement use the Alzheimer's disease Assessment Scale cognitive subscale (ADAS-cog) and the classic ADAS scale. In certain embodiments, symptomatic improvement of cognition is assessed using the Neurophysiological Test Battery for Use in Alzheimer's Disease (NTB).

In some embodiments, the global assessment of change test uses the Clinical Global Impression – Global Improvement (CGI-I) scale for assessing psychiatric and neurological disorders. In some embodiments, the global scale is the Clinician's Interview Based Impression of Change plus (CIBIC-plus). In some embodiments, the global scale is the Alzheimer's Disease Cooperative Study Unit Clinician's Global Impression of Change (ADCS-CGIC).

In certain embodiments, the health related quality of life measures are the Alzheimer's Disease-Related QOL (ADRQL) and the QOL-Alzheimer's Disease (QOL-AD).

In certain embodiments, the tests assessing behavioural and psychiatric symptoms of neurodegenerative disorders are selected from the Behavioural pathology in Alzheimer's Disease Rating Scale (BEHAVE-AD); the Behavioural Rating Scale for Dementia (BRSD); the Neuropsychiatric Inventory (NPI); and the Cohen-Mansfield Agitation Inventory (CMAI).

In some embodiments, the compositions of the invention are particularly effective at preventing, reducing or alleviating neurodegenerative disorders when used in combination with another therapy for treating neurodegenerative disorders. In certain embodiments, such therapies include acetylcholinesterase inhibitors including donepezil (Aricept®), galantamine (Razadyne®) and rivastigmine (Exelon ®), and memantine.

Multiple Sclerosis

Multiple sclerosis (MS) is a demyelinating disease in which the myelin sheath surrounding neurons in the brain and spinal cord are damaged. The exact underlying causes of MS are unknown, but are thought to vary between individuals. Certain forms of MS are hereditary. Environmental factors are also thought to contribute to MS. In some individuals, a combination of both genetic and environmental factors may trigger the onset of MS.

There are a wide variety of symptoms associated with MS. Subjects may exhibit almost any neurological symptom associated with the impairment of autonomic, visual, motor or sensory control. The exact symptoms will vary depending on the site of neuronal damage/demyelination.

IL-8 has been implicated in the formation of myelin sheaths. The compositions of the invention may therefore be for use in the remyelination of neurons in subjects with MS. The compositions of the invention may also be used to protect neurons from demyelination. In other words, the compositions of the invention may be for use in a method of treating or preventing multiple sclerosis by restoring or preventing loss of neuron myelin sheaths.

In some embodiments, the compositions of the invention prevent, reduce or alleviate one or more symptoms of MS in a subject. In some embodiments, the compositions of the invention prevent, reduce or alleviate fatigue in a subject. In certain embodiments, the compositions of the invention prevent, reduce or alleviate resting tremor, muscle weakness, muscle spasms, muscle stiffness, paraesthesia and/or ataxia in a subject. In certain embodiments, the compositions of the invention prevent, reduce or alleviate one or more symptoms associated with MS progression selected from the list consisting of autonomic disturbances: constipation, micturition disturbances, sexual functioning, dysphagia, dysarthria, syncope, vertigo and/or dizziness; sleep disturbances; and disturbances in the sense of smell or sense of temperature. In some embodiments, the compositions of the invention prevent, reduce or alleviate one or more ocular symptoms associated with MS. In some embodiments, the ocular symptom is selected from the list consisting of loss of vision, eye pain, colour blindness, double vision and/or involuntary eye movements in a subject.

In some embodiments, the compositions of the invention prevent, reduce or alleviate dizziness, vertigo, neuropathic pain, musculoskeletal pain, cognitive dysfunction, bowel incontinence, dysphagia, dysarthria, or any combination thereof.

In some embodiments, the compositions of the invention prevent, reduce or alleviate depressive symptoms or anxiety comorbid with MS.

In some embodiments, the compositions of the invention the improvement of symptoms are determined using the 2017 McDonald criteria for diagnosing MS.

In certain embodiments, treatment with the compositions of the invention results in a reduction in MS incidence or MS severity. In certain embodiments, the compositions of the invention are for use in reducing relapse incidence or relapse severity. In certain embodiments, treatment with the compositions of the invention prevents a decline in motor function or results in improved motor function associated with MS. In certain embodiments, the compositions of the invention are for use in preventing a decline in motor function or for use in improving motor function in the treatment of MS. In certain embodiments, treatment with the compositions of the invention prevents the development of paralysis in MS. In certain embodiments, the compositions of the invention are for use in preventing paralysis in the treatment of MS.

In certain embodiments the compositions of the invention are for use in preventing multiple sclerosis in a patient that has been identified as at risk of multiple sclerosis, or that has been diagnosed with early-stage multiple sclerosis or “relapsing-remitting” multiple sclerosis. The compositions of the invention may be useful for preventing the development of MS. The compositions of the invention may be useful for preventing the progression of MS. In certain embodiments, the compositions of the invention are for use in a patient identified as having a genetic predisposition to MS, such as major histocompatibility complex (MHC) class II phenotype, human leukocyte antigen (HLA)-DR2 or HLA-DR4.

The compositions of the invention may be useful for managing or alleviating multiple sclerosis. The compositions of the invention may be particularly useful for reducing symptoms associated with multiple sclerosis. Treatment or prevention of multiple sclerosis may refer to, for example, an alleviation of the severity of symptoms or a reduction in the frequency of exacerbations or the range of triggers that are a problem for the patient. In certain embodiments, the compositions of the invention slow or stop progression of the disease.

In certain embodiments, the compositions of the invention are for use in treating relapsing-remitting MS. In alternative embodiments, the compositions of the invention are for use in treating progressive MS, such as secondary progressive MS (SPMS), which develops over time following diagnosis of RRMS, primary progressive MS (PPMS) which exhibits gradual continuous neurologic deterioration and progressive relapsing MS (PRMS), which is similar to PPMS but with overlapping relapses.

In certain embodiments, the compositions of the invention are for use in treating one or more of symptoms of MS selected from the group consisting of: fatigue, vision problems, numbness, tingling, muscle spasms, muscle stiffness, muscle weakness, mobility problems, pain, problems with thinking,

learning and planning, depression and anxiety, sexual problems, bladder problems, bowel problems, speech and swallowing difficulties.

Neurochemical factors, neuropeptides and neurotransmitters and the microbiota-gut-brain axis

As outlined above, the microbiota-gut-brain axis is modulated by a number of different physiological systems. The microbiota-gut-brain axis is modulated by a number of signalling molecules. Alterations in the levels of these signalling molecules results in neurodegenerative diseases. The experiments performed by the inventors indicate that administration of *Megasphaera* commensal bacterial strains, and in particular *Megasphaera massiliensis,* can modulate levels of indole and kynurenine. Dysregulation of these metabolites can lead to neurodegenerative diseases, such as Parkinson's disease.

In certain embodiments, the compositions of the invention modulate the levels of brain monoamines and metabolites thereof. In preferred embodiments the metabolite is kynurenine. In certain embodiments, the compositions of the invention modulate kynurenine, which is the main route of tryptophan metabolism, which serves as a route to nicotinamide adenine dinucleotide (NAD+) production. Kynurenine can be metabolized to neuroactive compounds such as kynurenic acid (KYNA) and 3-hydroxy-l-kynurenine (3-OH-l-KYN), and in further steps to quinolinic acid (QUIN). Dysregulation of the kynurenine pathway can lead to activation of the immune system and the accumulation of potentially neurotoxic compounds. Alterations in the kynurenine metabolism may be involved in the development of Parkinson's diseases. Kynurenine levels have been demonstrated to be decreased in the frontal cortex, putamen and substantia nigra pars compacta of patients with PD (Parkinson's disease) [72]. Therefore, in certain embodiments the compositions of the invention are for use in increasing the levels of kynurenine in the treatment of Parkinson's disease.

In certain embodiments of the invention the compositions of the invention can increase the levels kynurenin. Increased levels of kynurenine have been shown to attenuate MPP+-induced neuronal cell death *in vitro* in a human dopaminergic neuroblastoma cell line [73]. In certain embodiments kynurenine and kynurenic acid, can activate GI aryl hydrocarbon receptor (Ahr) and GPR35 receptors. Activation of Ahr receptor induces IL-22 production, which can inhibit local inflammation. Activation of GPR35 inducing the production of inositol triphosphate and Ca2+ mobilization.

In certain embodiments, the compositions of the invention modulate the levels of indole. In preferred embodiments the metabolite is kynurenine. In certain embodiments, the compositions of the invention modulate kynurenine, which it the main route of tryptophan metabolism.

The signalling of the microbiota-gut-brain axis is modulated by levels of neurochemical factors, neuropeptides and neurotransmitters. Accordingly, in certain embodiments, the compositions of the invention modulates levels of neurochemical factors, neuropeptides and neurotransmitters. Accordingly, in certain preferred embodiments, the compositions of the invention directly alter CNS biochemistry.

The signalling of the microbiota-gut-brain axis is modulated by levels of γ-aminobutyric acid (GABA). Accordingly, in preferred embodiments, the compositions of the invention modulate the levels of GABA. GABA is an inhibitory neurotransmitter that reduces neuronal excitability. In certain embodiments, the compositions of the invention increase the levels of GABA. In certain embodiments, the compositions of the invention decrease the levels of GABA. In certain embodiments, the compositions of the invention alter GABAergic neurotransmission. In certain embodiments, the compositions of the invention modulate the level of GABA transcription in different regions of the central nervous system. In certain embodiments, the commensal derived GABA crosses the blood-brain barrier and affects neurotransmission directly. In certain embodiments, the compositions of the invention lead to a reduction of GABA in the hippocampus, amygdala and/or locus coeruleus. In certain embodiments, the compositions of the invention lead to an increase of GABA in cortical regions.

Immune response

The signalling of the microbiota-gut-brain axis is modulated by alterations in the immune response and inflammatory factors and markers. Accordingly, in certain embodiments, the compositions of the invention may modulate the immune response. In certain embodiments, the compositions of the invention modulate the systemic levels of circulating neuroimmune signalling molecules. In certain preferred embodiments, the compositions of the invention modulate pro-inflammatory cytokine production and inflammation. In certain embodiments, the compositions of the invention modulate the inflammatory state. In certain embodiments, the compositions of the invention decrease IL-6 production and secretion. In certain embodiments, the compositions of the invention decrease the activation of the NFκB promoter. In certain embodiments, the compositions of the invention are able to modulate the activation of IL-6 production by the potent pro-inflammatory endotoxin lipopolysaccharide (LPS). In certain embodiments, the compositions of the invention are able to modulate the activation of the NFκB promoter by LPS and α-synuclein mutant proteins such as A53T. Increased circulating levels of cytokines are closely associated with various neurodegenerative disorders, including Parkinson's, dementia and Alzheimer's. In certain embodiments, the compositions of the invention are for use in reducing IL-6 levels and/or NFκB levels in the treatment of a neurodegenerative disorder. In some embodiments, the compositions of the invention increase the secretion of IL-8. IL-8 has been shown to induce myelin sheath formation and restore or preserve effective neuronal communication. Thus, in some embodiments, the compositions of the invention are for use in inducing myelin sheath formation in the treatment of neurodegenerative diseases. In some embodiments, the compositions of the invention are for use in restoring neuronal communication. In some embodiments, the compositions of the invention are for use in preserving neuronal communication.

The signalling of the microbiota-gut-brain axis is modulated by levels of commensal metabolites. Accordingly, in certain embodiments, the compositions of the invention modulate the systemic levels

of microbiota metabolites. In certain preferred embodiments, the compositions of the invention modulate the level of short chain fatty acids (SCFAs). In certain embodiments the level of SCFAs is increased or decreased. In some embodiments, the level of SCFAs is increased. In some embodiments, the SCFA is butyric acid (BA) (or butyrate). In some embodiments, the SCFA is propionic acid (PPA). In some embodiments, the SCFA is acetic acid. In certain embodiments, the compositions of the invention modulate the ability of SCFAs to cross the blood-brain barrier.

Histone acetylation and deacetylation are important epigenetic regulators of gene expression. An imbalance in histone acetylation and deacetylation can result in apoptosis. Dysregulation of such histone acetyltransferases has been implicated in the pathogenesis associated with age-associated neurodegenerative diseases, such as Parkinson's disease, Huntington's disease, Alzheimer's disease, amyotrophic lateral sclerosis and cognitive decline [74]. Accordingly, in certain embodiments, the compositions of the invention can modulate histone deacetylase activity. In certain embodiments, the compositions of the invention can reduce histone deacetylase activity. In certain embodiments, the compositions of the invention can reduce histone acetylase activity. In certain embodiments, the compositions of the invention can reduce class 1 histone deacetylase activity.

Patients with neurodegenerative diseases, including Parkinson's disease, Huntington's disease, Alzheimer's disease and amyotrophic lateral sclerosis, exhibit high levels of lipid peroxidation. Lipid are vulnerable to oxidation by reactive oxygen species, and the brain is rich in polyunsaturated fatty acids. Accordingly, in certain embodiments, the compositions of the invention can modulate lipid peroxidation. In certain embodiments, the compositions of the invention can reduce lipid peroxidation. Reducing the oxidative damage caused by reactive oxygen species can be used to target early the stages neurodegenerative diseases. Accordingly, in certain embodiments, the compositions of the invention are for use in treating early stage neurodegeneration. Also accordingly, in certain embodiments, the compositions of the invention are for use in preventing the development of a neurodegenerative disorder. In such embodiments, the compositions of the invention may be for use in a patient that has been identified as at risk of developing a neurodegenerative disorder.

The signalling of the microbiota-gut-brain axis is modulated by levels of gastrointestinal permeability. Accordingly, in some embodiments, the compositions of the invention alter the integrity of the gastrointestinal tract epithelium. In certain embodiments, the compositions of the invention modulate the permeability of the gastrointestinal tract. In certain embodiments, the compositions of the invention modulate the barrier function and integrity of the gastrointestinal tract. In certain embodiments, the compositions of the invention modulate gastrointestinal tract motility. In certain embodiments, the compositions of the invention modulate the translocation of commensal metabolites and inflammatory signalling molecules into the bloodstream from the gastrointestinal tract lumen.

The signalling of the microbiota-gut-brain axis is modulated by microbiome composition in the gastrointestinal tract. Accordingly, in certain embodiments, the compositions of the invention

modulates the microbiome composition of the gastrointestinal tract. In certain embodiments, the compositions of the invention prevents microbiome dysbiosis and associated increases in toxic metabolites (e.g. LPS). In certain embodiments, the compositions of the invention modulate the levels of Clostridium in the gastrointestinal tract. In preferred embodiments, the compositions of the invention reduce the level of Clostridium in the gastrointestinal tract. In certain embodiments, the compositions of the invention reduce the levels of Campylobacter jejuni. In certain embodiments, the compositions of the invention modulate the proliferation of harmful anaerobic bacteria and the production of neurotoxins produced by these bacteria. In certain embodiments, the compositions of the invention modulate the microbiome levels of Lactobacillus and/or Bifidobacterium. In certain embodiments, the compositions of the invention modulate the microbiome levels of Sutterella, Prevotella, Rumincoccus genera and/or the Alcaligenaceae family. In certain embodiments, the compositions of the invention increase the level of *Lactobacillus plantarum* and/or *Saccharomyces boulardii*.

Brain injury

The examples demonstrate that the compositions of the invention are neuroprotective and have HDAC inhibitory activity. HDAC2 is a crucial target for functional recovery from stroke [75] and HDAC inhibition can prevent white matter injury [76], so the compositions of the invention may be useful in the treatment of brain injury.

In certain embodiments, the compositions of the invention are for use in treating brain injury. In some embodiments, the brain injury is a traumatic brain injury. In some embodiments, the brain injury is an acquired brain injury. In some embodiments, the compositions of the invention are for use in treating brain injury resulting from trauma. In some embodiments, the compositions of the invention are for use in treating brain injury resulting from a tumour. In some embodiments, the compositions of the invention are for use in treating brain injury resulting from a stroke. In some embodiments, the compositions of the invention are for use in treating brain injury resulting from a brain haemorrhage. In some embodiments, the compositions of the invention are for use in treating brain injury resulting from encephalitis. In some embodiments, the compositions of the invention are for use in treating brain injury resulting from cerebral hypoxia. In some embodiments, the compositions of the invention are for use in treating brain injury resulting from cerebral anoxia.

In preferred embodiments, the compositions of the invention are for use in treating stroke. The effects shown in the examples are particularly relevant to the treatment of stroke. Stroke occurs when blood flow to at least a part of the brain is interrupted. Without an adequate supply of blood to provide oxygen and nutrients to the brain tissue and to remove waste products from the brain tissue, brain cells rapidly begin to die. The symptoms of stroke are dependent on the region of the brain which is affected by the inadequate blood flow. Symptoms include paralysis, numbness or weakness of the muscles, loss of balance, dizziness, sudden severe headaches, speech impairment, loss of memory, loss of reasoning ability, sudden confusion, vision impairment, coma or even death. A stroke is also referred

to as a brain attack or a cerebrovascular accident (CVA). The symptoms of stroke may be brief if adequate blood flow is restored within a short period of time. However, if inadequate blood flow continues for a significant period of time, the symptoms can be permanent.

In some embodiments, the stroke is cerebral ischemia. Cerebral ischemia results when there is insufficient blood flow to the tissues of the brain to meet metabolic demand. In some embodiments, the cerebral ischemia is focal cerebral ischemia, i.e. confined to a specific region of the brain. In some embodiments the cerebral ischemia is global cerebral ischemia, i.e. encompassing a wide area of the brain tissue. Focal cerebral ischemia commonly occurs when a cerebral vessel has become blocked, either partially or completely, reducing the flow of blood to a specific region of the brain. In some embodiments the focal cerebral ischemia is ischemic stroke. In some embodiments, the ischemic stroke is thrombotic, i.e. caused by a thrombus or blood clot, which develops in a cerebral vessel and restricts or blocks blood flow. In some embodiments the ischemic stroke is a thrombotic stroke. In some embodiments, the ischemic stroke is embolic, i.e. caused by an embolus, or an unattached mass that travels through the bloodstream and restricts or blocks blood flow at a site distant from its point of origin. In some embodiments the ischemic stroke is an embolic stroke. Global cerebral ischemia commonly occurs when blood flow to the brain as a whole is blocked or reduced. In some embodiments the global cerebral ischemia is caused by hypoperfusion, i.e. due to shock. In some embodiments the global cerebral ischemia is a result of a cardiac arrest.

In some embodiments the subject diagnosed with brain injury has suffered cerebral ischemia. In some embodiments, the subject diagnosed with brain injury has suffered focal cerebral ischemia. In some embodiments, the subject diagnosed with brain injury has suffered an ischemic stroke. In some embodiments, the subject diagnosed with brain injury has suffered a thrombotic stroke. In some embodiments, the subject diagnosed with brain injury has suffered an embolic stroke. In some embodiments, the subject diagnosed with brain injury has suffered global cerebral ischemia. In some embodiments, the subject diagnosed with brain injury has suffered hypoperfusion. In some embodiments, the subject diagnosed with brain injury has suffered a cardiac arrest.

In some embodiments, the compositions of the invention are for use in treating cerebral ischemia. In some embodiments, the compositions of the invention are for use in treating focal cerebral ischemia. In some embodiments, the compositions of the invention are for use treating ischemic stroke. In some embodiments, the compositions of the invention are for use in treating thrombotic stroke. In some embodiments, the compositions of the invention are for use in treating embolic stroke. In some embodiments, the compositions of the invention are for use in treating global cerebral ischemia. In some embodiments, the compositions of the invention are for use in treating hypoperfusion.

In some embodiments, the stroke is hemorrhagic stroke. Hemorrhagic stroke is caused by bleeding into or around the brain resulting in swelling, pressure and damage to the cells and tissues of the brain. Hemorrhagic stroke is commonly a result of a weakened blood vessel that ruptures and bleeds into the

surrounding brain. In some embodiments, the hemorrhagic stroke is an intracerebral hemorrhage, i.e. caused by bleeding within the brain tissue itself. In some embodiments the intracerebral hemorrhage is caused by an intraparenchymal hemorrhage. In some embodiments the intracerebral hemorrhage is caused by an intraventricular hemorrhage. In some embodiments the hemorrhagic stroke is a subarachnoid hemorrhage i.e. bleeding that occurs outside of the brain tissue but still within the skull. In some embodiments, the hemorrhagic stroke is a result of cerebral amyloid angiopathy. In some embodiments, the hemorrhagic stroke is a result of a brain aneurysm. In some embodiments, the hemorrhagic stroke is a result of cerebral arteriovenous malformation (AVM).

In some embodiments the subject diagnosed with brain injury has suffered hemorrhagic stroke. In some embodiments, the subject diagnosed with brain injury has suffered an intracerebral hemorrhage. In some embodiments, the subject diagnosed with brain injury has suffered an intraparenchymal hemorrhage. In some embodiments, the subject diagnosed with brain injury has suffered an intraventricular hemorrhage. In some embodiments, the subject diagnosed with brain injury has suffered a subarachnoid hemorrhage. In some embodiments, the subject diagnosed with brain injury has suffered cerebral amyloid angiopathy. In some embodiments, the subject diagnosed with brain injury has suffered a brain aneurysm. In some embodiments, the subject diagnosed with brain injury has suffered cerebral AVM.

In some embodiments, the compositions of the invention are for use in treating hemorrhagic stroke. In some embodiments, the compositions of the invention are for use in treating an intracerebral hemorrhage. In some embodiments, the compositions of the invention are for use in treating an intraparenchymal hemorrhage. In some embodiments, the compositions of the invention are for use in treating an intraventricular hemorrhage. In some embodiments, the compositions of the invention are for use in treating a subarachnoid hemorrhage. In some embodiments, the compositions of the invention are for use in treating a cerebral amyloid angiopathy. In some embodiments, the compositions of the invention are for use in treating a brain aneurysm. In some embodiments, the compositions of the invention are for use in treating cerebral AVM.

Restoration of adequate blood flow to the brain after a period of interruption, though effective in alleviating the symptoms associated with stroke, can paradoxically result in further damage to the brain tissue. During the period of interruption, the affected tissue suffers from a lack of oxygen and nutrients, and the sudden restoration of blood flow can result in inflammation and oxidative damage through the induction of oxidative stress. This is known as reperfusion injury, and is well documented not only following stroke, but also following a heart attack or other tissue damage when blood supply returns to the tissue after a period of ischemia or lack of oxygen. In some embodiments the subject diagnosed with brain injury has suffered from reperfusion injury as a result of stroke. In some embodiments, the compositions of the invention are for use in treating reperfusion injury as a result of stroke.

A transient ischemic attack (TIA), often referred to as a mini-stroke, is a recognised warning sign for a more serious stroke. Subjects who have suffered one or more TIAs are therefore at greater risk of stroke. In some embodiments the subject diagnosed with brain injury has suffered a TIA. In some embodiments, the compositions of the invention are for use in treating a TIA. In some embodiments, the compositions of the invention are for use in treating brain injury in a subject who has suffered a TIA.

High blood pressure, high blood cholesterol, a familial history of stroke, heart disease, diabetes, brain aneurysms, arteriovenous malformations, sickle cell disease, vasculitis, bleeding disorders, use of nonsteroidal anti-inflammatory drugs (NSAIDs), smoking tobacco, drinking large amounts of alcohol, illegal drug use, obesity, lack of physical activity and an unhealthy diet are all considered to be risk factors for stroke. In particular, lowering blood pressure has been conclusively shown to prevent both ischemic and hemorrhagic strokes [77], [78]. In some embodiments, the compositions of the invention are for use in treating brain injury in a subject who has at least one risk factor for stroke. In some embodiments the subject has two risk factors for stroke. In some embodiments the subject has three risk factors for stroke. In some embodiments the subject has four risk factors for stroke. In some embodiments the subject has more than four risk factors for stroke. In some embodiments the subject has high blood pressure. In some embodiments the subject has high blood cholesterol. In some embodiments the subject has a familial history of stroke. In some embodiments the subject has heart disease. In some embodiments the subject has diabetes. In some embodiments the subject has a brain aneurysm. In some embodiments the subject has arteriovenous malformations. In some embodiments the subject has vasculitis. In some embodiments the subject has sickle cell disease. In some embodiments the subject has a bleeding disorder. In some embodiments the subject has a history of use of nonsteroidal anti-inflammatory drugs (NSAIDs). In some embodiments the subject smokes tobacco. In some embodiments the subject drinks large amounts of alcohol. In some embodiments the subject uses illegal drugs. In some embodiments the subject is obese. In some embodiments the subject is overweight. In some embodiments the subject has a lack of physical activity. In some embodiments the subject has an unhealthy diet.

The examples indicate that the compositions of the invention may be useful for treating brain injury and aiding recovery when administered before the injury event occurs. Therefore, the compositions of the invention may be particularly useful for treating brain injury when administered to subjects at risk of brain injury, such as stroke.

In certain embodiments, the compositions of the invention are for use in reducing the damage caused by a potential brain injury, preferably a stroke. The compositions may reduce the damage caused when they are administered before the potential brain injury occurs, in particular when administered to a patient identified as at risk of a brain injury.

The examples indicate that the compositions of the invention may be useful for treating brain injury and aiding recovery when administered after the injury event occurs. Therefore, the compositions of the invention may be particularly useful for treating brain injury when administered to subjects following a brain injury, such as stroke.

In some embodiments, the compositions of the invention treat brain injury by reducing motoric damage. In some embodiments, the compositions of the invention treat brain injury by improving motor function. In some embodiments, the compositions of the invention treat brain injury by improving muscle strength. In some embodiments, the compositions of the invention treat brain injury by improving memory. In some embodiments, the compositions of the invention treat brain injury by improving social recognition. In some embodiments, the compositions of the invention treat brain injury by improving neurological function.

Treatment of brain injury may refer to, for example, an alleviation of the severity of symptoms. Treatment of brain injury may also refer to reducing the neurological impairments following stroke. Compositions of the invention for use in treating stroke may be provided to the subject in advance of the onset of stroke, for example in a patient identified as being at risk of stroke. Compositions of the invention for use in treating stroke may be provided after a stroke has occurred, for example, during recovery. Compositions of the invention for use in treating stroke may be provided during the acute phase of recovery (i.e. up to one week after stroke). Compositions of the invention for use in treating stroke may be provided during the subacute phase of recovery (i.e. from one week up to three months after stroke). Compositions of the invention for use in treating stroke may be provided during the chronic phase of recovery (from three months after stroke).

In certain embodiments, the compositions of the invention are for use in combination with a secondary active agent. In certain embodiments, the compositions of the invention are for use in combination with aspirin or tissue plasminogen activator (tPA). Other secondary agents include other antiplatelets (such as clopidogrel), anticoagulants (such as heparins, warfarin, apixaban, dabigatran, edoxaban or rivaroxaban), antihypertensives (such as diuretics, ACE inhibitors, calcium channel blockers, beta-blockers or alpha-blockers) or statins. The compositions of the invention may improve the patient's response to the secondary active agent.

In certain embodiments, the compositions of the invention reduce the effect of ischemia on tissues. In certain embodiments, the compositions of the invention reduce the amount of damage to tissues caused by ischemia. In certain embodiments, the tissues damaged by ischemia are the cerebral tissues. In certain embodiments, the compositions of the invention reduce necrosis or the number of necrotic cells. In certain embodiments, the compositions of the invention reduce apoptosis or the number of apoptotic cells. In certain embodiments, the compositions of the invention reduce the number of necrotic and apoptotic cells. In certain embodiments, the compositions of the invention prevent cell death by necrosis and/or apoptosis. In certain embodiments, the compositions of the invention prevent cell death

by necrosis and/or apoptosis caused by ischemia. In certain embodiments, the compositions of the invention improve the recovery of the tissue damaged by ischemia. In certain embodiments, the compositions of the invention improve the speed of clearance of necrotic cells and/or apoptotic cells. In certain embodiments, the compositions of the invention improve the efficacy of the clearance of necrotic cells and/or apoptotic cells. In certain embodiments, the compositions of the invention improve the replacement and/or regeneration of cells within tissues. In certain embodiments, the compositions of the invention improve the replacement and/or regeneration of cells within tissues damaged by ischemia. In certain embodiments, the compositions of the invention improve the overall histology of the tissue (for example upon a biopsy).

Modes of administration

Preferably, the compositions of the invention are to be administered to the gastrointestinal tract in order to enable delivery to and / or partial or total colonisation of the intestine with the commensal bacterial strain of the invention. Generally, the compositions of the invention are administered orally, but they may be administered rectally, intranasally, or via buccal or sublingual routes. In some embodiments, a composition comprises the strain and the organic acid of the invention. In some embodiments, separate compositions of the organic acid and the commensal bacterial strain are provided.

In certain embodiments, the compositions comprising the commensal bacterial strain of the invention may be administered as a foam, as a spray or a gel.

In certain embodiments, the compositions of the invention may be administered as a suppository, such as a rectal suppository, for example in the form of a theobroma oil (cocoa butter), synthetic hard fat (e.g. suppocire, witepsol), glycero-gelatin, polyethylene glycol, or soap glycerin composition.

In certain embodiments, the composition of the invention is administered to the gastrointestinal tract via a tube, such as a nasogastric tube, orogastric tube, gastric tube, jejunostomy tube (J tube), percutaneous endoscopic gastrostomy (PEG), or a port, such as a chest wall port that provides access to the stomach, jejunum and other suitable access ports.

The compositions of the invention may be administered once, or they may be administered sequentially as part of a treatment regimen. In certain embodiments, the compositions of the invention are to be administered daily.

In certain embodiments of the invention, treatment according to the invention is accompanied by assessment of the patient's gut microbiota. Treatment may be repeated if delivery of and / or partial or total colonisation with the strain of the invention is not achieved such that efficacy is not observed, or treatment may be ceased if delivery and / or partial or total colonisation is successful and efficacy is observed.

In certain embodiments, the composition of the invention may be administered to a pregnant animal, for example a mammal such as a human in order to prevent an inflammatory or autoimmune disease developing in her child *in utero* and / or after it is born.

The compositions of the invention may be administered to a patient that has been diagnosed with a neurodegenerative disease, or that has been identified as being at risk of a neurodegenerative disease. The compositions may also be administered as a prophylactic measure to prevent the development of neurodegenerative disease in a healthy patient.

The compositions of the invention may be administered to a patient that has been identified as having an abnormal gut microbiota. For example, the patient may have reduced or absent colonisation by *Megasphaera* , and in particular *Megasphaera massiliensis.*

The compositions comprising the bacteria of the invention may be administered as a food product, such as a nutritional supplement.

In some embodiments, a composition comprising a pharmaceutically acceptable salt or ester of the organic acid may be administered intravenously. In some embodiments, the organic acid is lyophilised and administered orally.

In some embodiments, the composition comprising the commensal bacterial strain and the composition comprising the organic acid are to be administered simultaneously, separately or sequentially. Each of the different compositions may be administered by any combination of the modes of administration described herein. Generally, the compositions of the invention are for the treatment of humans, although they may be used to treat animals including monogastric mammals such as poultry, pigs, cats, dogs, horses or rabbits. The compositions of the invention may be useful for enhancing the growth and performance of animals. If administered to animals, oral gavage may be used.

Compositions

Generally, the composition of the invention comprises bacteria. In some embodiments, the composition further comprises an organic acid or a pharmaceutically acceptable salt or ester thereof. In preferred embodiments of the invention, the composition is formulated in freeze-dried form. For example, the composition of the invention may comprise granules or gelatin capsules, for example hard gelatin capsules, comprising a bacterial strain of the invention and/or an organic acid of the invention. In some embodiments, the organic acid of the invention and the bacteria of the invention and formulated as separate compositions. In some embodiments, each of the separate compositions are formulated in a freeze-dried form. General guidance on the formulation of the compositions of the invention can be found for example, in *Aulton's Pharmaceutics: The Design and Manufacture of Medicines*.

Preferably, the composition of the invention comprises lyophilised bacteria. Lyophilisation of bacteria is a well-established procedure and relevant guidance is available in, for example, references [79], [], [81].

Alternatively, the composition of the invention may comprise a live, active bacterial culture.

In some embodiments, the bacterial strain in the composition of the invention has not been inactivated, for example, has not been heat-inactivated. In some embodiments, the bacterial strain in the composition of the invention has not been killed, for example, has not been heat-killed. In some embodiments, the bacterial strain in the composition of the invention has not been attenuated, for example, has not been heat-attenuated. For example, in some embodiments, the bacterial strain in the composition of the invention has not been killed, inactivated and/or attenuated. For example, in some embodiments, the bacterial strain in the composition of the invention is live. For example, in some embodiments, the bacterial strain in the composition of the invention is viable. For example, in some embodiments, the bacterial strain in the composition of the invention is capable of partially or totally colonising the intestine. For example, in some embodiments, the bacterial strain in the composition of the invention is viable and capable of partially or totally colonising the intestine.

In some embodiments, the composition comprises a mixture of live bacterial strains and bacterial strains that have been killed.

In preferred embodiments, the composition of the invention is encapsulated to enable delivery of the bacterial strain and/or the organic acid or a pharmaceutically acceptable salt or ester thereof to the intestine. Encapsulation protects the composition from degradation until delivery at the target location through, for example, rupturing with chemical or physical stimuli such as pressure, enzymatic activity, or physical disintegration, which may be triggered by changes in pH. Any appropriate encapsulation method may be used. Exemplary encapsulation techniques include entrapment within a porous matrix, attachment or adsorption on solid carrier surfaces, self-aggregation by flocculation or with cross-linking agents, and mechanical containment behind a microporous membrane or a microcapsule. Guidance on encapsulation that may be useful for preparing compositions of the invention is available in, for example, references [82] and [83].

The composition may be administered orally and may be in the form of a tablet, capsule or powder. Encapsulated products are preferred because *Megasphaera* are anaerobes. Other ingredients (such as vitamin C, for example), may be included as oxygen scavengers and prebiotic substrates to improve the delivery and / or partial or total colonisation and survival *in vivo*. Alternatively, the probiotic composition of the invention may be administered orally as a food or nutritional product, such as milk or whey based fermented dairy product, or as a pharmaceutical product.

The composition may be formulated as a probiotic.

A composition of the invention includes a therapeutically effective amount of a bacterial strain of the invention and/or a therapeutically effective amount an organic acid or a pharmaceutically acceptable salt or ester thereof of the invention. A therapeutically effective amount of a bacterial strain and/or an organic acid of the invention is sufficient to exert a beneficial effect upon a patient. A therapeutically

effective amount of a bacterial strain may be sufficient to result in delivery to and / or partial or total colonisation of the patient's intestine.

A suitable daily dose of the bacteria, for example for an adult human, may be from about 1 x 10^3 to about 1 x 10^{11} colony forming units (CFU); for example, from about 1 x 10^7 to about 1 x 10^{10} CFU; in another example from about 1 x 10^6 to about 1 x 10^{10} CFU.

In certain embodiments, the composition contains the bacterial strain in an amount of from about 1 x 10^6 to about 1 x 10^{11} CFU/g, respect to the weight of the composition; for example, from about 1 x 10^8 to about 1 x 10^{10} CFU/g. The dose may be, for example, 1 g, 3g, 5g, and 10g.Typically, a probiotic, such as the composition of the invention, is optionally combined with at least one suitable prebiotic compound. A prebiotic compound is usually a non-digestible carbohydrate such as an oligo- or polysaccharide, or a sugar alcohol, which is not degraded or absorbed in the upper digestive tract. Known prebiotics include commercial products such as inulin and transgalacto-oligosaccharides.

In certain embodiments, the probiotic composition of the present invention includes a prebiotic compound in an amount of from about 1 to about 30% by weight, respect to the total weight composition, (e.g. from 5 to 20% by weight). Carbohydrates may be selected from the group consisting of: fructo- oligosaccharides (or FOS), short-chain fructo-oligosaccharides, inulin, isomalt-oligosaccharides, pectins, xylo-oligosaccharides (or XOS), chitosan-oligosaccharides (or COS), beta-glucans, arable gum modified and resistant starches, polydextrose, D-tagatose, acacia fibers, carob, oats, and citrus fibers. In one aspect, the prebiotics are the short-chain fructo-oligosaccharides (for simplicity shown herein below as FOSs-c.c); said FOSs-c.c. are not digestible carbohydrates, generally obtained by the conversion of the beet sugar and including a saccharose molecule to which three glucose molecules are bonded.

In some embodiments, the organic acid is provided as a lyophilised salt or ester thereof. The lyophilised organic acid product may be formulated in a single dosage form. The lyophilised organic acid may be formulated in a repeat dosage form. The lyophilised organic acid product may be formulated with the lyophilised bacteria in a single dosage form. Alternatively, the organic acid product may be formulated with the lyophilised bacteria in a repeat dosage form.

In some embodiments, the organic acid product may be formulated as a "slow release" or "fast release" composition. "Slow release" compositions result in lower initial increases in serum plasma concentrations of the organic acid product but have a more sustained effect, with elevated plasma levels of the organic acid remaining longer. By contrast, "fast release" compositions are formulated to provide a high initial dose of the organic acid product, resulting in higher initial plasma concentration but with a shorter duration effect.

In some embodiments, the organic acid is administered intravenously. For example, the organic acid may be sodium valproate and may be administered to a subject in a 60 min infusion at a rate of no more than 20 mg/min. A typical daily dose of the organic acid or a pharmaceutically acceptable salt or

ester thereof will vary depending on the physical characteristics of the subject, the route of administration and/or the desired duration of the effect of the composition. In certain embodiments, the compositions of the invention are used in combination with another therapeutic compound for treating or preventing the neurodegenerative disorder.

In some embodiments, the compositions of the invention are administered with nutritional supplements that modulate neuroprotection or neuroproliferation. In preferred embodiments, the nutritional supplements comprise or consist of nutritional vitamins. In certain embodiments, the vitamins are vitamin B6, magnesium, dimethylglycine (vitamin B16) and vitamin C. In certain embodiments, the compositions of the invention are administered in combination with another probiotic.

In certain embodiments, the compositions of the invention are for use in enhancing the effect of a second agent on a neurodegenerative disease. The immune modulatory effects of the compositions of the invention may make the brain more susceptible to conventional therapies such as Levodopa, dopamine agonists, MAO-B inhibitors, COMT inhibitors, Glutamate antagonists, or anticholinergics, which are exemplary secondary agents to be administered in combination (sequentially or contemporaneously) with the compositions of the invention.

The compositions of the invention may comprise pharmaceutically acceptable excipients or carriers. Examples of such suitable excipients may be found in the reference [84]. Acceptable carriers or diluents for therapeutic use are well known in the pharmaceutical art and are described, for example, in reference [85]. Examples of suitable carriers include lactose, starch, glucose, methyl cellulose, magnesium stearate, mannitol, sorbitol and the like. Examples of suitable diluents include ethanol, glycerol and water. The choice of pharmaceutical carrier, excipient or diluent can be selected with regard to the intended route of administration and standard pharmaceutical practice. The pharmaceutical compositions may comprise as, or in addition to, the carrier, excipient or diluent any suitable binder(s), lubricant(s), suspending agent(s), coating agent(s), solubilising agent(s). Examples of suitable binders include starch, gelatin, natural sugars such as glucose, anhydrous lactose, free-flow lactose, beta-lactose, corn sweeteners, natural and synthetic gums, such as acacia, tragacanth or sodium alginate, carboxymethyl cellulose and polyethylene glycol. Examples of suitable lubricants include sodium oleate, sodium stearate, magnesium stearate, sodium benzoate, sodium acetate, sodium chloride and the like. Preservatives, stabilizers, dyes and even flavouring agents may be provided in the pharmaceutical composition. Examples of preservatives include sodium benzoate, sorbic acid and esters of p-hydroxybenzoic acid. Antioxidants and suspending agents may be also used.

The compositions of the invention may be formulated as a food product. For example, a food product may provide nutritional benefit in addition to the therapeutic effect of the invention, such as in a nutritional supplement. Similarly, a food product may be formulated to enhance the taste of the composition of the invention or to make the composition more attractive to consume by being more similar to a common food item, rather than to a pharmaceutical composition. In certain embodiments,

the composition of the invention is formulated as a milk-based product. The term "milk-based product" means any liquid or semi-solid milk- or whey- based product having a varying fat content. The milk-based product can be, e.g., cow's milk, goat's milk, sheep's milk, skimmed milk, whole milk, milk recombined from powdered milk and whey without any processing, or a processed product, such as yoghurt, curdled milk, curd, sour milk, sour whole milk, butter milk and other sour milk products. Another important group includes milk beverages, such as whey beverages, fermented milks, condensed milks, infant or baby milks; flavoured milks, ice cream; milk-containing food such as sweets.

In some embodiments, the compositions of the invention comprise one or more bacterial strains of the genus *Megasphaera* and do not contain bacteria from any other genera, or which comprise only *de minimis* or biologically irrelevant amounts of bacteria from another genera. Thus, in some embodiments, the invention provides a composition comprising one or more bacterial strains of the genus *Megasphaera*, which does not contain bacteria from any other genera or which comprises only *de minimis* or biologically irrelevant amounts of bacteria from another genera, for use in therapy.

In some embodiments, the compositions of the invention comprise one or more bacterial strains of the species *Megasphaera massiliensis* and do not contain bacteria from any other species, or which comprise only *de minimis* or biologically irrelevant amounts of bacteria from another species. Thus, in some embodiments, the invention provides a composition comprising one or more bacterial strains of the species *Megasphaera massiliensis*, which does not contain bacteria from any other species or which comprises only *de minimis* or biologically irrelevant amounts of bacteria from another species, for use in therapy.

In some embodiments, the compositions of the invention comprise one or more bacterial strains of the species *Megasphaera massiliensis* and do not contain bacteria from any other *Megasphaera* species, or which comprise only *de minimis* or biologically irrelevant amounts of bacteria from another *Megasphaera* species. Thus, in some embodiments, the invention provides a composition comprising one or more bacterial strains of the species *Megasphaera massiliensis*, which does not contain bacteria from any other *Megasphaera* species or which comprises only *de minimis* or biologically irrelevant amounts of bacteria from another *Megasphaera* species, for use in therapy.

In certain embodiments, the compositions of the invention contain a single bacterial strain or species and do not contain any other bacterial strains or species. Such compositions may comprise only *de minimis* or biologically irrelevant amounts of other bacterial strains or species. Such compositions may be a culture that is substantially free from other species of organism.

In some embodiments, the invention provides a composition comprising a single bacterial strain of the genus *Megasphaera,* which does not contain bacteria from any other strains or which comprises only *de minimis* or biologically irrelevant amounts of bacteria from another strain for use in therapy.

In some embodiments, the invention provides a composition comprising a single bacterial strain of the species *Megasphaera massiliensis,* which does not contain bacteria from any other strains or which comprises only *de minimis* or biologically irrelevant amounts of bacteria from another strain for use in therapy.

In some embodiments, the compositions of the invention comprise more than one bacterial strain. For example, in some embodiments, the compositions of the invention comprise more than one strain from within the same species (e.g. more than 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 35, 40 or 45 strains), and, optionally, do not contain bacteria from any other species. In some embodiments, the compositions of the invention comprise less than 50 strains from within the same species (e.g. less than 45, 40, 35, 30, 25, 20, 15, 12, 10, 9, 8, 7, 6, 5, 4 or 3 strains), and, optionally, do not contain bacteria from any other species. In some embodiments, the compositions of the invention comprise 1-40, 1-30, 1-20, 1-19, 1-18, 1-15, 1-10, 1-9, 1-8, 1-7, 1-6, 1-5, 1-4, 1-3, 1-2, 2-50, 2-40, 2-30, 2-20, 2-15, 2-10, 2-5, 6-30, 6-15, 16-25, or 31-50 strains from within the same species and, optionally, do not contain bacteria from any other species. The invention comprises any combination of the foregoing.

In some embodiments, the composition comprises a microbial consortium. For example, in some embodiments, the composition comprises the *Megasphaera* commensal bacterial strain as part of a microbial consortium. For example, in some embodiments, the Megasphaera commensal bacterial strain is present in combination with one or more (e.g. at least 2, 3, 4, 5, 10, 15 or 20) other bacterial strains from other genera with which it can live symbiotically *in vivo* in the intestine. For example, in some embodiments, the composition comprises a commensal bacterial strain of Megasphaera the invention in combination with a bacterial strain from a different genus. In some embodiments, the microbial consortium comprises two or more bacterial strains obtained from a faeces sample of a single organism, e.g. a human. In some embodiments, the microbial consortium is not found together in nature. For example, in some embodiments, the microbial consortium comprises bacterial strains obtained from faeces samples of at least two different organisms. In some embodiments, the two different organisms are from the same species, e.g. two different humans. In some embodiments, the two different organisms are an infant human and an adult human. In some embodiments, the two different organisms are a human and a non-human mammal.

In some embodiments, the composition of the invention additionally comprises a bacterial strain that has the same safety and therapeutic efficacy characteristics as strain MRX0029, but which is not MRX0029, or which is not a *Megasphaera massiliensis*.

In some embodiments in which the composition of the invention comprises more than one bacterial strain, species or genus, the individual bacterial strains, species or genera may be for separate, simultaneous or sequential administration. For example, the composition may comprise all of the more than one bacterial strain, species or genera, or the bacterial strains, species or genera may be stored separately and be administered separately, simultaneously or sequentially. In some embodiments, the

more than one bacterial strains, species or genera are stored separately but are mixed together prior to use.

In some embodiments, the bacterial strain for use in the invention is obtained from human adult faeces. In some embodiments in which the composition of the invention comprises more than one bacterial strain, all of the bacterial strains are obtained from human adult faeces or if other bacterial strains are present they are present only in *de minimis* amounts. The bacteria may have been cultured subsequent to being obtained from the human adult faeces and being used in a composition of the invention.

As mentioned above, in some embodiments, the one or more *Megasphaera* commensal bacterial strains is/are the only therapeutically active agent(s) in a composition of the invention. In some embodiments, the bacterial strain(s) in the composition is/are the only therapeutically active agent(s) in a composition of the invention.

The compositions for use in accordance with the invention may or may not require marketing approval.

In certain embodiments, the invention provides the above pharmaceutical composition, wherein said bacterial strain is lyophilised. In certain embodiments, the invention provides the above pharmaceutical composition, wherein said bacterial strain is spray dried. In certain embodiments, the invention provides the above pharmaceutical composition, wherein the bacterial strain is lyophilised or spray dried and wherein it is live. In certain embodiments, the invention provides the above pharmaceutical composition, wherein the bacterial strain is lyophilised or spray dried and wherein it is viable. In certain embodiments, the invention provides the above pharmaceutical composition, wherein the bacterial strain is lyophilised or spray dried and wherein it is capable of partially or totally colonising the intestine. In certain embodiments, the invention provides the above pharmaceutical composition, wherein the bacterial strain is lyophilised or spray dried and wherein it is viable and capable of partially or totally colonising the intestine.

In some cases, the lyophilised bacterial strain is reconstituted prior to administration. In some cases, the reconstitution is by use of a diluent described herein.

The compositions of the invention can comprise pharmaceutically acceptable excipients, diluents or carriers.

In certain embodiments, the invention provides a pharmaceutical composition comprising: a bacterial strain of the invention; and a pharmaceutically acceptable excipient, carrier or diluent; wherein the bacterial strain is in an amount sufficient to treat a neurodegenerative disorder when administered to a subject in need thereof.

In certain embodiments, the invention provides pharmaceutical composition comprising: a bacterial strain of the invention; and a pharmaceutically acceptable excipient, carrier or diluent; wherein the bacterial strain is in an amount sufficient to treat or prevent a neurodegenerative disorder.

In certain embodiments, the invention provides the above pharmaceutical composition, wherein the amount of the bacterial strain is from about 1×10^3 to about 1×10^{11} colony forming units per gram with respect to a weight of the composition.

In certain embodiments, the invention provides the above pharmaceutical composition, wherein the composition is administered at a dose of 1 g, 3 g, 5 g or 10 g.

In certain embodiments, the invention provides the above pharmaceutical composition, wherein the composition is administered by a method selected from the group consisting of oral, rectal, subcutaneous, nasal, buccal, and sublingual.

In certain embodiments, the invention provides the above pharmaceutical composition, comprising a carrier selected from the group consisting of lactose, starch, glucose, methyl cellulose, magnesium stearate, mannitol and sorbitol.

In certain embodiments, the invention provides the above pharmaceutical composition, comprising a diluent selected from the group consisting of ethanol, glycerol and water.

In certain embodiments, the invention provides the above pharmaceutical composition, comprising an excipient selected from the group consisting of starch, gelatin, glucose, anhydrous lactose, free-flow lactose, beta-lactose, corn sweetener, acacia, tragacanth, sodium alginate, carboxymethyl cellulose, polyethylene glycol, sodium oleate, sodium stearate, magnesium stearate, sodium benzoate, sodium acetate and sodium chloride.

In certain embodiments, the invention provides the above pharmaceutical composition, further comprising at least one of a preservative, an antioxidant and a stabilizer.

In certain embodiments, the invention provides the above pharmaceutical composition, comprising a preservative selected from the group consisting of sodium benzoate, sorbic acid and esters of p-hydroxybenzoic acid.

In certain embodiments, the invention provides the above pharmaceutical composition, wherein said bacterial strain is lyophilised.

In certain embodiments, the invention provides the above pharmaceutical composition, wherein when the composition is stored in a sealed container at about 4◦C or about 25◦C and the container is placed in an atmosphere having 50% relative humidity, at least 80% of the bacterial strain as measured in colony forming units, remains after a period of at least about: 1 month, 3 months, 6 months, 1 year, 1.5 years, 2 years, 2.5 years or 3 years.

In some embodiments, the composition of the invention is provided in a sealed container comprising a composition as described herein. In some embodiments, the sealed container is a sachet or bottle. In some embodiments, the composition of the invention is provided in a syringe comprising a composition as described herein.

The composition of the present invention may, in some embodiments, be provided as a pharmaceutical formulation. For example, the composition may be provided as a tablet or capsule. In some embodiments, the capsule is a gelatine capsule ("gel-cap").

In some embodiments, the compositions of the invention are administered orally. Oral administration may involve swallowing, so that the compound enters the gastrointestinal tract, and/or buccal, lingual, or sublingual administration by which the compound enters the blood stream directly from the mouth.

Pharmaceutical formulations suitable for oral administration include solid plugs, solid microparticulates, semi-solid and liquid (including multiple phases or dispersed systems) such as tablets; soft or hard capsules containing multi- or nano-particulates, liquids (e.g. aqueous solutions), emulsions or powders; lozenges (including liquid-filled); chews; gels; fast dispersing dosage forms; films; ovules; sprays; and buccal/mucoadhesive patches.

In some embodiments the pharmaceutical formulation is an enteric formulation, i.e. a gastro-resistant formulation (for example, resistant to gastric pH) that is suitable for delivery of the composition of the invention to the intestine by oral administration. Enteric formulations may be particularly useful when the bacteria or another component of the composition is acid-sensitive, e.g. prone to degradation under gastric conditions.

In some embodiments, the enteric formulation comprises an enteric coating. In some embodiments, the formulation is an enteric-coated dosage form. For example, the formulation may be an enteric-coated tablet or an enteric-coated capsule, or the like. The enteric coating may be a conventional enteric coating, for example, a conventional coating for a tablet, capsule, or the like for oral delivery. The formulation may comprise a film coating, for example, a thin film layer of an enteric polymer, e.g. an acid-insoluble polymer.

In some embodiments, the enteric formulation is intrinsically enteric, for example, gastro-resistant without the need for an enteric coating. Thus, in some embodiments, the formulation is an enteric formulation that does not comprise an enteric coating. In some embodiments, the formulation is a capsule made from a thermogelling material. In some embodiments, the thermogelling material is a cellulosic material, such as methylcellulose, hydroxymethylcellulose or hydroxypropylmethylcellulose (HPMC). In some embodiments, the capsule comprises a shell that does not contain any film forming polymer. In some embodiments, the capsule comprises a shell and the shell comprises hydroxypropylmethylcellulose and does not comprise any film forming polymer (e.g. see [86]). In some embodiments, the formulation is an intrinsically enteric capsule (for example, Vcaps® from Capsugel).

In some embodiments, the formulation is a soft capsule. Soft capsules are capsules which may, owing to additions of softeners, such as, for example, glycerol, sorbitol, maltitol and polyethylene glycols, present in the capsule shell, have a certain elasticity and softness. Soft capsules can be produced, for example, on the basis of gelatine or starch. Gelatine-based soft capsules are commercially available

from various suppliers. Depending on the method of administration, such as, for example, orally or rectally, soft capsules can have various shapes, they can be, for example, round, oval, oblong or torpedo-shaped. Soft capsules can be produced by conventional processes, such as, for example, by the Scherer process, the Accogel process or the droplet or blowing process.

Culturing methods

The bacterial strains for use in the present invention can be cultured using standard microbiology techniques as detailed in, for example, references [87], [] and [89].

The solid or liquid medium used for culture may be YCFA agar or YCFA medium. YCFA medium may include (per 100ml, approximate values): Casitone (1.0 g), yeast extract (0.25 g), $NaHCO_3$ (0.4 g), cysteine (0.1 g), K_2HPO_4 (0.045 g), KH_2PO_4 (0.045 g), NaCl (0.09 g), $(NH_4)_2SO_4$ (0.09 g), $MgSO_4 \cdot 7H_2O$ (0.009 g), $CaCl_2$ (0.009 g), resazurin (0.1 mg), hemin (1 mg), biotin (1 μg), cobalamin (1 μg), *p*-aminobenzoic acid (3 μg), folic acid (5 μg), and pyridoxamine (15 μg).

Bacterial strains for use in vaccine compositions

The inventors have identified that the bacterial strains of the invention are useful for treating or preventing neurodegenerative disorders. This is likely to be a result of the effect that the bacterial strains of the invention have on the host immune system. Therefore, the compositions of the invention may also be useful for preventing neurodegenerative disorders, when administered as vaccine compositions. In certain such embodiments, the bacterial strains of the invention may be killed, inactivated or attenuated. In certain such embodiments, the compositions may comprise a vaccine adjuvant. In certain embodiments, the compositions are for administration via injection, such as via subcutaneous injection.

General

The practice of the present invention will employ, unless otherwise indicated, conventional methods of chemistry, biochemistry, molecular biology, immunology and pharmacology, within the skill of the art. Such techniques are explained fully in the literature. See, *e.g.*, references [90] and [91, 97], *etc.*

The term "comprising" encompasses "including" as well as "consisting" *e.g.* a composition "comprising" X may consist exclusively of X or may include something additional *e.g.* X + Y.

The term "about" in relation to a numerical value *x* is optional and means, for example, $x \pm 10\%$.

The word "substantially" does not exclude "completely" *e.g.* a composition which is "substantially free" from Y may be completely free from Y. Where necessary, the word "substantially" may be omitted from the definition of the invention.

References to a percentage sequence identity between two nucleotide sequences means that, when aligned, that percentage of nucleotides are the same in comparing the two sequences. This alignment and the percent homology or sequence identity can be determined using software programs known in

the art, for example those described in section 7.7.18 of ref. [98]. A preferred alignment is determined by the Smith-Waterman homology search algorithm using an affine gap search with a gap open penalty of 12 and a gap extension penalty of 2, BLOSUM matrix of 62. The Smith-Waterman homology search algorithm is disclosed in ref. [99].

Unless specifically stated, a process or method comprising numerous steps may comprise additional steps at the beginning or end of the method, or may comprise additional intervening steps. Also, steps may be combined, omitted or performed in an alternative order, if appropriate.

Various embodiments of the invention are described herein. It will be appreciated that the features specified in each embodiment may be combined with other specified features, to provide further embodiments. In particular, embodiments highlighted herein as being suitable, typical or preferred may be combined with each other (except when they are mutually exclusive).

MODES FOR CARRYING OUT THE INVENTION

Example 1 – Efficacy of bacterial inocula to act as a neuroprotectant

Summary

Neuroblastoma cells were treated with compositions comprising bacterial strains according to the invention. The SH-SY5Y neuroblastoma cells used are dopamine producing and well-established as an *in vitro* model for studying neurodegenerative diseases. The ability of the bacterial strains to increase neuroproliferation was observed. The neuroblastoma cells were treated with dopaminergic neurotoxin 1-methyl-4-phenylpyridinium (MPP), which induces permanent symptoms of Parkinson's disease in neuroblastoma cells. The ability of the bacterial strains to act as a neuroprotectant against MPP was investigated.

Material and Methods

Bacterial strains

Megasphaera massiliensis MRX0029; *Parabacteroides distasonis* MRX0005

Cell line

SH-SY5Y neuroblastoma cells were purchased from ECCACC (Cat. no: 94030304) and were grown in MEM (Sigma Aldrich, cat n. M2279) supplemented with Nutrient Mixture F-12 Ham (Sigma Aldrich, cat n. N4888).

Method

Once grown the SH-SY5Y neuroblastoma cells were plated on 96-well plate at 11,000 cells/well and incubated for 2 days. The cells were then transferred to differentiation medium (which contains FBS at 1%) and 10 uM retinoic acid (Sigma Aldrich, cat. n. R2625-100MG). Differentiation medium was replaced every other day and cells were harvested at 7 day of differentiation. Cells were pre-treated

with or without MPP (Sigma Aldrich, cat. n. D048-1G) for 8 hours. Subsequently, cells were treated with 10% bacterial supernatant and incubated overnight. Cell viability was measured by using CCK-8 reagent (Sigma Aldrich, Cell Counting Kit – 8, cat. n. 96992-3000TESTS-F) and read at 450nm wavelength.

Results

The results of these experiments are shown in Figure 1. Treatment of neuroblastoma cells with MRX0029 or MRX0005 led to an increase in the proliferation of neurons. Neuroblastoma cells that were treated with MPP together with the bacterial strain had increased cell viability compared to the cells treated with MPP alone (which had decreased viability). The protective effect was greater for MRX0029-treated cells, which rescued viability more than the positive control cells treated with Quercetin. These data show that the bacterial strains can act as a neuroprotectant.

Example 2a – Efficacy of bacterial inocula to reduce IL-6 secretion.

Summary

Activation of proinflammatory cytokines has been associated with neuron damage in neurodegenerative disease. Lipopolysaccharide (LPS) is a known stimulator of the proinflammatory cytokine IL-6. Human glioblastoma astrocytoma cells were treated with compositions comprising bacterial strains according to the invention in combination with LPS to observe their ability to modulate the levels of IL-6.

Material and Methods

Bacterial strains

Megasphaera massiliensis MRX0029; *Parabacteroides distasonis* MRX0005

Cell line

MG U373 is a human glioblastoma astrocytoma derived from a malignant tumour and were purchased from Sigma-Aldrich (cat n. 08061901-1VL). MG U373 human glioblastoma astrocytoma cells were grown in MEM (Sigma Aldrich, cat n. M-2279) supplemented with 10% FBS, 1% Pen Strep, 4mM L-Glut, 1X MEM Non essential Amino Acid solution and 1X Sodium Piruvate.

Method

Once grown the MG U373 cells were plated on 24-well plate at 100,000 cells/well. The cells were treated with LPS (1ug/mL) alone or with 10% of bacteria supernatant from MRX0029 or MRX0005 for 24h. A control was also performed where the cells were incubated in untreated media.. Afterwards the cell free supernatants were collected, centrifuged at 10,000g for 3min at 4°C. IL-6 was measured using the Human IL-6 ELISA Kit from Peprotech (cat n.#900-K16) according to manufacturer instructions.

Results

The results of these experiments are shown in Figure 2. Treatment of neuroblastoma cells with LPS and the bacteria strains led to a decrease in the level of IL-6 secreted.

Example 2b – Efficacy of bacterial inocula to modulate IL-8 secretion.

Summary

As neuro-inflammation plays a pivotal role in neurodegenerative diseases and IL-8 has been shown to have neuro-positive effects, the effect of compositions comprising bacterial strains of the invention and LPS on the activation of IL-8 were assessed. Human glioblastoma astrocytoma cells were treated with compositions comprising bacterial strains according to the invention in combination with LPS to observe their ability to modulate the levels of IL-8.

Material and Methods

Bacterial strains

Megasphaera massiliensis MRX0029; *Parabacteroides distasonis* MRX0005

Cell line

MG U373 is a human glioblastoma astrocytoma derived from a malignant tumour and were purchased from Sigma-Aldrich (cat n. 08061901-1VL). MG U373 human glioblastoma astrocytoma cells were grown in MEM (Sigma Aldrich, cat n. M-2279) supplemented with 10% FBS, 1% Pen Strep, 4mM L-Glut, 1X MEM Non essential Amino Acid solution and 1X Sodium Piruvate.

Method

Once grown the MG U373 cells were plated on 24-well plate at 100,000 cells/well. The cells were treated with LPS (1ug/mL) alone or with 10% of bacteria supernatant from MRX0029 for 24h. Afterwards the cell free supernatants were collected, centrifuged at 10,000g for 3min at 4°C. IL-8 was measured using Human IL-8 ELISA Kit from Peprotech (cat n.#900-K18) according to manufacturer instruction.

Results

The results of these experiments are shown in Figure 3. Treatment of neuroblastoma cells with the bacteria strains lead to an increase in IL-8 secretion independently of the presence of LPS.

Example 2C – Efficacy of bacterial inocula to reduce α-synuclein-induced inflammation.

Summary

Neuroinflammation plays a pivotal role in Parkinson's disease and α-synuclein has been shown to induce neuroinflammation *in vivo*. Therefore, the ability of the bacteria strains of the invention to inhibit α-synuclein-induced neuroinflammation was assessed. A co-culture of human glioblastoma

astrocytoma cells and neuroblastoma cells were exposed to wild-type α-synuclein and the mutant isoforms E46K and A53T and treated with compositions comprising bacterial strains according to the invention. The ability of the bacteria strains to inhibit α-synuclein-induced secretion of IL-6 was then tested.

Material and Methods

Bacterial strains

Megasphaera massiliensis MRX0029*; Parabacteroides distasonis* MRX0005

Cell line

MG U373 is a human glioblastoma astrocytoma derived from a malignant tumour and were purchased from Sigma-Aldrich (cat n. 08061901-1VL). MG U373 human glioblastoma astrocytoma cells were grown in MEM (Sigma Aldrich, cat n. M-2279) supplemented with 10% FBS, 1% Pen Strep, 4mM L-Glut, 1X MEM Non essential Amino Acid solution and 1X Sodium Piruvate.

SH-SY5Y is a human neurobastoma cell line derived from a malignant neuroblastoma and can be purchased from Sigma-Aldrich (cat n. 94030304-1VL). The cells were grown in 50 % MEM and 50% Nutrient Mixture F-12 Ham media supplemented with 2mM L-Glutamine, 10% heat inactivated FBS, 100 U/ml penicillin, 100 µg/ml streptomycin. Cells on growth medium were plated on 96-well plate at 11,000 cells/well and placed in the incubator. After 2 days, media were replaced with differentiation medium (growth medium containing 1% FBS) and 10 µM retinoic acid. Differentiation medium was replaced every other day and cells were used after 7 days of differentiation.

Method

SHSY5Y cells were plated on 12 well plates at a density of 50,000 cells/well. The cells were grown in 50 % MEM and 50% Nutrient Mixture F-12 Ham media supplemented with 2mM L-Glutamine, 10% heat inactivated FBS, 100 U/ml penicillin, 100 µg/ml streptomycin. Cells on growth medium were plated on 96-well plate at 11,000 cells/well and placed in the incubator. After 2 days, media were replaced with differentiation medium (growth medium containing 1% FBS) and 10 µM retinoic acid. Differentiation medium was replaced every other day and cells were used after 7 days of differentiation. U373 were plated on 12 transwell plates (0.4µm polyester membrane, Costar) at a density of 50,000cells/well for 72 hrs. Cells were co-cultured together for 24hrs before treatment in differentiation medium (growth medium containing 1% FBS without retinoic acid).

Thereafter cells were treated with 25µg/ml α-synuclein (Wt, A53T, E46K) in the presence or absence of 10% bacteria supernatant for 48 hrs. Cell free Supernatants were collected, spun-dwon at 10000g for 3 min at 4°C, aliquoted and stored at -80 0C. Human IL-6 and IL-8 were measured as described above.

Results

The results of these experiments are shown in Figure 4. Treatment of cells with wild-type α-synuclein and the mutant isoforms E46K and A53T induced moderate secretion of IL-6 (Figure 4A). The α-syn-induced secretion of IL-6 was inhibited in cells treated with the bacteria strains (Figure 4A). The reduction in IL-6 secretion was greatest on administration of MRX0029.

Example 3 – Efficacy of bacterial inocula to reduce NFκB activation

Summary

Activation of the NFκB promoter leads to the production of proinflammatory cytokines including IL-1β, IL-1α, IL-18, TNFα and IL-6. The NFκB promoter can be activated by α-synuclein and LPS by stimulating the TLR4 ligand. Mutations in α-synuclein, such as α-synuclein A53T, are implicated in familial Parkinson's. Treatment of neuronal cells with LPS simulates Parkinson's caused by environmental factors. The ability of compositions comprising bacterial strains according to the invention to inhibit the activation of the NFκB promoter was investigated.

Material and Methods

Bacterial strain

Megasphaera massiliensis MRX0029

Cell line

Human Hek blue TLR4 were purchased from InvivoGen (cat n. hkb-htlr4). Human Hek blue TLR4 were grown in DMEM high glucose (Sigma Aldrich, cat n. D-6171) supplemented with 10% FBS, 1% Pen Strep, 4mM L-Glut, Normocin and 1X HEK Blue selection solution.

Method

Once grown the Human Hek blue cells were plated in 96 well plates at 25,000 cells/well in 4 replicates. One set of cells were treated with α-synuclein A53T (1ug/mL) alone or with 10% of bacteria supernatant from MRX0029 for 22h. The second set of cells were treated with LPS (10 ng/mL, from Salmonella enterica serotype Typhimurium, Sigma Aldrich, cat n. L6143) alone or with 10% of bacteria supernatant from MR029 for 22h. The cells were subsequently spun down and 20ul of the supernatant was mixed with 200ul of Quanti Blue reagent (InvivoGen, cat n. rep-qb2), incubated for 2 h and absorbance read at 655nm.

Results

The results of these experiments are shown in Figure 5 and 6. Figure 5 shows that the activation of the NFκB promoter by α-synuclein is not inhibited by MRX0029. Figure 6 shows that the activation of the NFκB promoter by LPS is inhibited by MRX0029.

Example 4 – Efficacy of bacteria to alter neurite outgrowth

Summary

Neurite outgrowth is an important process for the development of connections between neurons. The ability of bacterial strains and organic acids to induce neurite outgrowth was therefore tested by measuring transcriptional levels of microtubule associated protein MAP2, a specific neuronal differentiation marker.

Bacterial strain

Megasphaera massiliensis MRX0029.

Method

SHSY5Y were plated in 10cm petri dishes a density of $2x10^6$ cells. After 24h cells were treated in differentiation medium (growth medium containing 1% FBS without RA) with 10% bacteria supernatants or YCFA+, 10uM RA, 200uM hexanoic acid or 200uM valproic acid, for 17 hrs. There after representative images were taken using phase contrast EVOS XL core microscope at 40X/0.65 magnification. Cells were collected, and total RNA was isolated according to RNeasy mini kit protocol (Qiagen). cDNAs were made using the high capacity cDNA reverse transcription kit (Applied Biosystems). Gene expression was measured using qPCR. GAPDH was used as internal control. Fold change was calculated according to the $2^{(-\Delta\Delta ct)}$ method.

Immunofluorescence and Confocal microscopy

Cells were seeded onto 8 well chamber slides (Marienfeld Laboratory Glassware) at $5x10^4$ cells/well overnight and were treated with 10% bacterial supernatant for 24 hrs. For differentiation, cells were treated with 10nM Retinoic acid for 5 days before treating with bacterial supernatant. Cells were then fixed with 4% paraformaldehyde in PBS for 20 minutes at room temperature (RT). Fixed cells were washed with PBS, and permeabilized with 1% Triton X-100 in PBS for 10 minutes. After washing with PBS, the slides were incubated with blocking buffer (4% BSA/PBS) for 1hr at RT before adding anti-MAP2 antibody (sc-74421, Santa Cruz Biotechnology Inc) diluted in 1% BSA/PBS for 12hr at 4°C. They were then washed twice with PBS, followed by incubation with Alexa Flour 488 conjugated anti-mouse (Molecular Probes Inc) and Alexa Flour 594 conjugated Phalloidin (ab176757, Abcam) for 1hr at RT. After washing 3X with PBS, the slides were mounted with Vectorshield containing DAPI (Sigma, Aldrich). Slides were viewed using a Zeiss Axioscope microscope equipped with a 63x/1.2 W Korr objective and filter sets suitable for detection of the fluorochromes used. Manual exposure times for the digital acquisition of images immuno-labelled with MAP-2 were kept constant allowing comparison between different wells and treatments. Phalloidin (F-actin) and DAPI exposure times varied to suit the field of view. Randomised fields of view were acquired using a QImaging camera controlled by Image Pro Plus software. Images were saved as TIFs and opened in Adobe Photoshop CC 2015.1.2 and overlays of the MAP-2, DAPI and Phalloidion images overlaid and merged.

Representative images were selected to illustrate the differences in abundance and location of the proteins examined

Results

The results are shown in Figure 7. Figure 7A shows representative microscopy images of undifferentiated SHSY-5Y cells incubated with each of the acids and bacteria supernatants. Treatment of cells with MRX0029 induced a neuron-like phenotype, showing similar features to cells treated with retinoic acid (which is used for terminal differentiation of neuroblastoma cells), where cell bodies are bigger and pyramidal-shaped, with neurites and processed branching out to network with neighbour cells. Figure 7B shows that MRx0029 significantly upregulates MAP2 in undifferentiated neuroblastoma cells. Phalloidin (an actin cytoskeleton-binding agent) staining further proved a different arrangement of cytoskeletal structure in cells treated with MRx0029, further supporting the neuronal differentiation hypothesis for MRx0029 (Fig. 7B)

Example 5 – Efficacy of bacterial inocula to alter antioxidant capacity

Summary

The ability of compositions comprising bacterial strains according to the invention to alter the antioxidant capacity. The antioxidant capacity of the bacterial strain was established using the well-known ABTS (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid)) assay.

Bacterial strain

Megasphaera massiliensis MRX0029

Method

Bacterial cells (10^6 or greater) were collected and centrifuged. They were resuspended in assay buffer (using three times the pellet volume). The suspension was sonicated on ice for 5 minutes and then spun down at 12,000 x g for 10 minutes. The supernatant was removed and measured using the ABTS assay kit produced by Sigma Aldrich (code CS0790), in accordance with manufacturer's instructions.

Results

The results of these experiments are shown in Figure 8. Figure 8 shows that the MRX0029 has an antioxidant capacity of approximately 2mM compared to Trolox.

Example 6 – Efficacy of bacterial inocula to alter lipid peroxidation levels

Summary

The ability of compositions comprising bacterial strains according to the invention to alter lipid peroxidation levels was investigated. The thiobarbituric reactive substances assay (TBARs) was used to measure the by-products of lipid peroxidation.

Material and Methods

Bacterial strain

Megasphaera massiliensis MRX0029

Method

Bacterial cells (10^6 or greater) were collected and centrifuged, a wash step was performed with isotonic saline before the pellet was re-suspended in potassium chloride assay buffer. The suspension was sonicated on ice for 10 minutes and then spun down at 10,000 x g for 10 minutes. The supernatant was removed and the level of lipid peroxidation evaluated using the thiobarbituric reactive substances assay.

Results

The results of the experiments are shown in Figure 9. Figure 9 shows that MRx0029 is able to inhibit lipid peroxidation by approximately 20 %, which is a higher antioxidant capacity than the positive control, butylated hydroxytoluene (1% w/v).

Example 7a – Efficacy of bacterial inocula to reduce oxidative levels in cells

Background

The generation of reactive oxygen species contributes to the pathology of neurodegenerative diseases. The ability of bacterial strains to protect differentiated SHSY-5Y and U373 cells from reactive oxygen species (ROS) generated by treatment with Tert-Butyl Hydrogen Peroxide (TBHP) was investigated.

Material and Methods

Bacterial strain

Megasphaera massiliensis MRX0029

Method

SHSY-5Y cells were plated in black flat bottom 96 well plate at density of 5000 cells/well and placed in the CO2 incubator. After 24 h, media were replaced with differentiation medium (growth medium containing 1% FBS) and 10 μM retinoic acid. Differentiation medium was replaced every other day. On Day 10 the differentiation medium was removed and cells were washed with pre-warmed PBS and stained with 10uM DCFDA molecular probe for 20 mins in growth medium containing 1% FBS. Then cells were washed with pre-warmed PBS again and treated with 100uM TBHP in the presence or absence of 10% bacteria supernatant for 2h. Fluorescence intensity was measured using TECAN plate reader at Ex/Em 485/530 nm.

Results

The results of the experiments are shown in Figure 10. Figure 10b shows that MRX0029 is able to inhibit ROS production in differentiated SHSY-5Y neuroblastoma cells. MRX0029 did not have an

effect on the generation of ROS in U373 astroglioblastoma cells (Figure 10a). This shows that this aspect of the antioxidant effect is neuron-specific.

Example 7b – neuroprotection

RA-differentiated SHSY-5Y cells were treated with MPP+, the active metabolite of MPTP, a chemical widely used to mimic *in vitro* and *in vivo* some of the features of PD pathology. Cell viability was measured as the rate of mitochondria respiration (Figure 11). Both MRx0005 and MRx0029 showed significant effects and promote *per se* an increase of the mitochondria metabolic activity in SHSY-5Y cells. MRX0029 showed complete protection from MPP+, restoring cell viability nearly to the same level of untreated cells and higher than quercetin positive control. MRx0005 protection was about 20% compared to YCFA-MPP+ treated sample, about the same observed for the quercetin positive control (Fig. 11).

Example 8 – Efficacy of bacterial inocula on histone deacetylase activity

Summary

The ability of compositions comprising bacterial strains according to the invention to alter histone deacetylase activity was investigated. Dysregulation of histone deacetylase has been implicated in the pathogenesis associated with age-associated neurodegenerative diseases.

Material and Methods

Bacterial strain

Megasphaera massiliensis MRX0029

Cell line

The cell line HT-29 was used because histone deacetylase is present.

Method

Cell free supernatants of stationary phase bacterial cultures were isolated by centrifugation and filtering in a 0.22 uM filter. HT-29 cells were used 3 days' post confluence and stepped down in 1 mL DTS 24 hours prior to commencement of the experiment. The HT-29 cells were challenged with 10 % cell free supernatant diluted in DTS and this was left to incubate for 48 hours. Nuclease proteins were then extracted using the Sigma Aldrich Nuclease extraction kit and samples were snap frozen prior to HDAC activity measurement. HDAC activity kit was assessed fluorometrically using the Sigma Aldrich (UK) kit.

Results

The results of the experiments are shown in Figure 12. Figure 12 shows that MRX0029 is able reduce the levels of histone deacetylase activity.

Example 8a – Further analysis of the mechanism of histone deacetylation inhibition

Introduction

The gut microbiota, with its immense diversity and metabolic capacity, represents a huge metabolic reservoir for production of a vast variety of molecules with potential to influence HDAC activity. Few studies have assessed the HDAC inhibitory activity of microbially-derived metabolites other than butyrate, which has been shown to inhibit HDAC and is associated with improvement of motor function in Huntington's disease [100]. The inventors therefore sought to determine which metabolites are responsible for HDAC inhibition and further elucidate the mechanisms by which inhibition is achieved.

Material and Methods

Bacterial culture and cell-free supernatant collection

Pure cultures of bacteria were grown anaerobically in YCFA broth until they reached their stationary growth phase. Cultures were centrifuged at 5,000 x g for 5 minutes and the cell-free supernatant (CFS) was filtered using a 0.2 μM filter (Millipore, UK). 1 mL aliquots of the CFS were stored at -80 °C until use. Sodium butyrate, hexanoic and valeric acid were obtained from Sigma Aldrich (UK) and suspensions were prepared in YCFA broth.

SCFA and MCFA quantification of bacterial supernatants

Short chain fatty acids (SCFAs) and medium chain fatty acids (MCFAs) from bacterial supernatants were analysed and quantified by MS Omics APS as follows. Samples were acidified using hydrochloride acid, and deuterium labelled internal standards where added. All samples were analyzed in a randomized order. Analysis was performed using a high polarity column (Zebron™ ZB-FFAP, GC Cap. Column 30 m x 0.25 mm x 0.25 μm) installed in a GC (7890B, Agilent) coupled with a quadropole detector (59977B, Agilent). The system was controlled by ChemStation (Agilent). Raw data was converted to netCDF format using Chemstation (Agilent), before the data was imported and processed in Matlab R2014b (Mathworks, Inc.) using the PARADISe software described in [101].

Specific HDAC activity analysis

Specific HDAC inhibition activity was analysed for HDAC1, 2, 3, 4, 5, 6, 9 using fluorogenic assay kits for each type of HDAC (BPS Bioscience, CA). Assays were conducted according to manufacturer's instructions and each sample were performed in replicates. Cell free supernatants were diluted 1 in 10 and exposed to specific HDAC proteins provided in the kit to maintain consistency between methods.

Results

Histone deacetylase-inhibiting gut commensal microbial metabolites are butyrate and valeric acid

MRx0029, whose supernatant showed strong HDAC inhibition in assays with either HT29 whole cell or HT29 cell lysate, produced valeric acid and hexanoic acid at mean concentrations of 5.08 mM and 1.60 mM, respectively (Figure 13A and C).

To investigate which metabolites were responsible for the strain-induced HDAC inhibition, different concentrations of hexanoic acid, valeric acid and sodium butyrate were measured for their HDAC inhibition on whole HT-29 cells and on HT-29 cell lysate. The results in Fig. 13B show significant ($P<0.05$) inhibition of HDAC activity by sodium butyrate on whole cells as well as on the cell lysate, while hexanoic acid did not show significant inhibitory activity. Valeric acid inhibited total HDAC activity (* ($p<0.05$), ** ($p<0.005$), *** ($P<0.001$), **** ($p<0.0001$)).

Potent total HDAC inhibitors investigated target class I HDACs.

The specific HDAC inhibition profile of the test bacteria strain was investigated. Specific HDAC inhibition assays (BPS Bioscience, CA) were carried out for Class I and Class II HDACs. The ability of the bacterial strain to inhibit HDAC enzymes was compared to butyrate, hexanoic and valeric acid (Figures 14 and 15). Our results demonstrate that MRX0029, is a very potent inhibitor of Class 1 HDAC enzymes (HDAC1, 2 and 3). Inhibition of class II HDACs was not as significant (data not shown).

Discussion

The strain with HDAC inhibitory activity produced significant amounts of valeric acid and hexanoic acid as well as significant amounts of sodium butyrate (Figure 13C). When tested as pure substances, valeric acid and sodium butyrate resulted in significant HDAC inhibition ($p<0.0001$).

Interestingly, the results for specific HDAC activity show that the tested strain is a potent inhibitor of Class I HDACs, and particularly HDAC2. Class I HDACs (HDAC1, 2, 3 and 8) reside in the nucleus and are ubiquitously expressed in several human cell types. HDACs 1–3 share more than 50% homology, but have distinct structures and cellular functions [102]. They are primarily involved in cell survival, proliferation and differentiation, and thus there inhibition may be useful is wide array of diseases [103]; [104]; [105]; [106]; [107].

Example 9 – Level of indole production in bacteria

Summary

The ability of the bacteria of the invention to produce indole was investigated. Indole has been implicated in attenuating inflammation and oxidative stress.

Material and Methods

Bacterial strain

Megasphaera massiliensis MRX0029
ATCC 11775 is a bacterial reference strain that is known to produce indole.

Method

Intact bacterial cells in stationary phase were incubated with 6mM Tryptophan for 48 hours. Bacterial species which possess the enzyme tryptophanase will utilise tryptophan as a substrate to produce indole. Following the 48 hour incubation period, the supernatant was removed and added to Kovac's reagent for quantification of indole. Standards, stock solutions and reagents were prepared using standardised methods validated in-house.

Results

The results of the experiments are shown in Figure 16. Figure 16 shows that MRX0029 has the capacity to produce indole from tryptophan, at concentrations of approximately 0.2mM.

Example 10 – Level of kynurenine production in bacteria

Summary

The ability of the bacteria of the invention to produce kynurenine was investigated. Dysregulation of the kynurenine pathway can lead to activation of the immune system and the accumulation of potentially neurotoxic compounds. Alterations in the kynurenine metabolism may be involved in the development of Parkinson's diseases.

Bacterial strain

Megasphaera massiliensis MRX0029
DSM 17136 is a strain of *Bacteroides copricola* that is known to produce kynurenine.

Method

Cell free supernatants of stationary phase bacterial cultures were isolated by centrifugation and filtering in a 0.22 uM filter and frozen until use. Kynurenine standards, stock solutions and reagents were prepared using standardised methods validated in-house. Sample were treated with trichloroacetic acid and centrifuged at 10,000xg for 10 minutes at 4°C. The supernatant was collected and dispensed into a 96 well plate. Ehrlich's reagent was used for kynurenine detection and added at a ratio of 1:1.

Results

The results of the experiments are shown in Figure 17. Figure 17 shows that MRX0029 has the capacity to produce kynurenine at a concentration of approximately 40 μM.

Example 11 – Levels of Dopamine, DOPAC and HVA in striatum in bacteria-treated MPTP mice

Parkinson's disease is a common neurodegenerative disorder whose cardinal clinical features include tremor, slowness of movement, stiffness, and postural instability. These symptoms are primarily attributable to the degeneration of dopaminergic neurons in the substantia nigra pars compacta and the consequent loss of their projecting nerve fibers in the striatum [108]. Mice treated with MPTP (1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine) selectively lose significant numbers of nigrostriatal

dopaminergic neurons [109]. MPTP induced loss of dopaminergic cells in substantia nigra mimics the clinical condition in Parkinson's disease and is therefore a useful model to test anti-parkinsonian drugs.

The aim of this study was to evaluate the effects of MRX0029 anaerobic bacteria using MPTP lesioned mice.

48 male mice were allocated to 4 different treatment groups (groups A, B, E and I, with n=12 animals in each group). The treatment groups are shown in Table 1 below and the project time course is outlined below.

Table 1: Treatment groups

Group	n	Treatment					Lesion			
		Substance	Safety level	Dose	Route	Schedule	Substance	Dose	Route	Schedule
A	12	Vehicle (PBS)	-	-	p.o.	18 days: day(-14) - day3	Vehicle (0.9% saline)		i.p.	day0
B	12	Vehicle (PBS)	-	-	p.o.	18 days: day(-14) - day3	MPTP	4x 20 mg/kg	i.p.	day0
E	12	MRx0029 *Megasphaera sp.* (gly)	S1/S2	2 x 10^8 bacteria	p.o.	18 days: day(-14) - day3	MPTP	4x 20 mg/kg	i.p.	day0
I	12	Vehicle (PBS)	-	-	p.o.	18 days: day(-14) - day3	MPTP	4x 20 mg/kg	i.p.	day0
		7-nitroindazole	-	50 mg/kg	i.p.	day0 (2x i.p.)				

Groups A, B, E and I were treated daily for 18 days via oral gavage with either bacteria (MRx0029 – group E), or vehicle (PBS). Oral treatment started 14 days before MPTP lesion. Group I animals received a daily vehicle (PBS) p.o. (per oral) treatment and were injected i.p. (intraperitoneal) with the reference drug 30 min before and 90 min after first MPTP on day 0. The application volume for p.o. and vehicle treatment was 200 µl per mouse. Bacteria strain of group E was from glycerol stocks (gly). For oral treatment, gavages for applications were stored in vial containing 70% Ethanol and were flushed before and after each use with distilled water. Every treatment group had its own gavage and ethanol vial and distilled water vial. The tubes and gavages were not changed between the groups. Directly before treatment each syringe was flushed with N2.

On day 0 MPTP (20 mg/kg bodyweight (b.w.) 4 times, 2h inter-treatment interval) was injected i.p. in animals of groups B, E and I. One group of animals (A) was sham lesioned by i.p. administration of the MPTP vehicle (0.9% saline). The application volume was 10 µl per g body weight. Weighing of the animals was performed before the MPTP treatment to dose the animals according to their actual body weight. Afterwards animals received the daily p.o. treatment.

Formulation of preparations for dosing and preparation of glycerol stocks for dosing

Name of the Bacteria strain:	MRx0029 *Megasphaera sp.*
Storage condition/stability:	-80 °C
Vehicle:	1x PBS
Treatment dosages:	2 x 10^8 bacteria
Administration:	200µl
Lot Number:	n/a

For treatment group E (MRx0029)

1.) 1 glycerol stock was taken from the -80 °C freezer and placed under anaerobic conditions (anaerobic jar with sachet) at 37 °C in order to thaw (this took 30-40 mins).

2.) The completely thawed glycerol stock was centrifuged at 6000 x g for 10 min at room temperature.

3.) The supernatant was discarded without disturbing the pellet (e.g. using a pipette).

4.) 4.22 mL of sterile pre-warmed (37 °C) 1 x PBS was added and gently mixed using a pipette.

5.) The mice were dosed with 200 µL of the bacterial solution. The animals were dosed within 15 mins after resuspension of the pellet with PBS.

Reference drug group formulation

Storage condition/stability:	−20°C
Vehicle:	Peanut oil
Treatment dosages:	50 mg/kg
Administration:	i.p. (30 min before and 90 min after 1st MPTP treatment)
Batch Number:	MKBS6671V

The appropriate amount of 7-Nitroindazole was dissolved in peanut oil to reach the final concentration of 50 mg/kg.

Materials and Methods

Animals

Mouse line:	C57BL/6J (JAX™ Mice Strain) JAX™ Mice Stock Number 000664
Provider:	Charles River Laboratories
Age at start:	~10 weeks
Sex:	Male
Number of animals:	48

Specific handling of Animals and Randomization

Gloves were changed between each treatment group and sprayed with 70% ethanol solution between each cage of the same group to minimize the risk of contamination whenever animals were handled (e.g.: treatment, behavioural testing, cleaning and tissue sampling).

The treatment was at random and alternated daily so as to prevent the same groups being treated at the same time each day. Animals were randomized per cage at the tissue sampling.

Tissue sampling and processing

On day 4 animals of all groups were sacrificed and brains were collected. Therefore, mice were deeply anesthetized by Pentobarbital injection (600mg/kg).

Blood (approximately 500 µl) was collected by heart puncture. Mice were then transcardially perfused with 0.9% saline and brains were removed and hemisected. The left hemisphere was subdivided into striatal tissue (for HPLC), substantia nigra tissue as well as residual brain, weighed and immediately frozen and stored at -80°C. Instruments and surfaces which were in contact with the animals had to be cleaned with 70% ethanol before the next animal was dissected.

Biochemical Analysis of Dopamine, DOPAC and HVA levels with HPLC in striatum

The striatal samples (n=6 from each treatment group; total 24 samples) were mixed at a ratio of 1:10 (w/v) with 0.2 M perchloric acid including 100 µM EDTA-2Na and homogenized at 0 °C in a glass-pestlemicro-homogenizer. Following standing for 30 min on ice, the homogenates were centrifuged at 10,000 RPM for 10 minutes in a refrigerated centrifuge Biofuge Fresco (Heraeus Instruments, Germany). The supernatants were carefully aspirated and mixed with 0.4 M Na-acetate buffer, pH 3 at a ratio 1:2 (v/v) and filtered through a 0.22 µm centrifugal filter (Merck Millipore, Germany) for 4 min at 14 000 g at 4 °C. The filtrates were stored at -80 °C before HPLC analysis.

HPLC analysis

Concentrations of DA, DOPAC and HVA in the striatal samples were determined by column liquid chromatography with electrochemical detection [110;111]. The HPLC system (HTEC-500, Eicom Corp., Kyoto, Japan) including a pulse-free microflow pump, a degasser and an amperometric detector equipped with a glassy-carbon electrode operating at +0.45 V vs. an Ag/AgCl ref. electrode was used. Samples were injected by use of a CMA/200 Refrigerated Microsampler (CMA/Microdialysis, Stockholm, Sweden). The chromatograms were recorded and integrated by use of a computerized data acquisition system (DataApex, Prague, Czech Republic). DA, DOPAC and HVA were separated on a 150 x 2.1 i.d. mm column (CA5-ODS, Eicom Corp., Kyoto, Japan). The mobile phase consisted of 0.1 M phosphate buffer at pH 6.0, 0.13 mM EDTA, 2.3 mM sodium-1-octanesulfonate and 20 % (v/v) methanol. The detection limit (signal-to-noise ratio = 3) for DA was estimated to 0.5 fmol in 15 µl (0.03 nM) injected onto the column.

Results

Administration of bacteria strains was well tolerated by the animals. On the MPTP lesion day and if necessary on the day afterwards a red light was used to warm the animals. If animals were in bad conditions (felt cold, dehydrated, abnormal behaviour), they were supplied with wet food and subcutaneous saline treatment if necessary.

For analysis of Dopamine, DOPAC and HVA levels, striatal tissue of 6 animals per treatment group were used. Data were analyzed by using Kruskal-Wallis test followed by Dunn's multiple comparison post hoc test or One-way analysis of variance followed by Bonferroni post hoc test (A vs. all(*), B vs. all, I vs. all (#)). */# = $p<0.05$; ** = $p<0.01$; *** = $p<0.001$.

The healthy animals in group A had high levels of Dopamine, DOPAC and HVA whereas MPTP treatment in group B reduced this and the positive control (group I) recovered the production to some degree (Figure 21). Animals of group I tended to have higher Dopamine levels than the bacteria treated group and group B (Figure 21A). DOPAC (a Dopamine metabolite) levels in general were significantly lower in animals of group B compared to DOPAC levels of unlesioned animals of group A (Figure 21B).

Significantly, treatment with MRx0029 (group E) was found to recover production of Dopamine and DOPAC (Figures 21A and 21B, respectively). Treatment with MRx0029 may therefore be useful for treating or preventing neurodegenerative disorders.

Example 12 – Stability testing

A composition described herein containing at least one bacterial strain described herein is stored in a sealed container at 25°C or 4°C and the container is placed in an atmosphere having 30%, 40%, 50%, 60%, 70%, 75%, 80%, 90% or 95% relative humidity. After 1 month, 2 months, 3 months, 6 months, 1 year, 1.5 years, 2 years, 2.5 years or 3 years, at least 50%, 60%, 70%, 80% or 90% of the bacterial

strain shall remain as measured in colony forming units determined by standard protocols.

Example 13 – Level of BDNF secretion in SHSY-5Y cells

Background

Brain-derived neurotrophic factor (BDNF) is a ubiquitous molecule in the brain associated with neural development, neuro-protection and neuro-regeneration. BDNF not only protects against neurodegeneration but also mental disorders like depression and anxiety, which are quite common amongst patients diagnosed with PD or AD.

Methods

SH-SY5-SY were plated in 24 wells plate at density of 60,000 cells/well and placed in the incubator. After 24 h, media were replaced with differentiation medium (growth medium containing 1% FBS) and 10 µM retinoic acid. Differentiation medium was replaced every other day and cells were used on day 10 of differentiation. For the treatment differentiation medium was removed and replaced with 450ul of full growth media and 50 µl of bacteria SN was added to the treated wells or YCFA+ was added as negative Control.

Results

The results are shown in Figure 18, which shows that administration of MRX0029 in combination with retinoic acid increases the secretion of BDNF from differentiated neuroblasoma cells. Compositions comprising commensal bacteria and organic acids may therefore be useful in therapy.

Example 14 – Metabolite production – metabolites in the brain

Background

Metabolites present in bacteria supernatants can directly influence the host response to oxidative stress, cell-to-cell communication and neuroprotection. Metabolites that play a key role in neurological processes were measured during the *ex vivo* screening in brain tissue of mice fed with MRx0005 and MRx0029.

Methods

Animals

BALBc (Envigo, UK) adult male mice were group housed under a 12 h light-dark cycle; standard rodent chow and water were available ad libitum. All experiments were performed in accordance with European guidelines following approval by University College Cork Animal Ethics Experimentation Committee. Animals were 8 weeks old at the start of the experiment.

Study Design

Animals were allowed to habituate to their holding room for one week after arrival into the animal unit. They receive oral gavage (200µL dose) of live biotherapeutics at a dose of 1 X 10^9 CFU for 6 consecutive days between 15:00 and 17:00. On day 7, the animals are decapitated, and tissues are harvested for experimentation.

Tissue Collection

Animals were sacrificed in a random fashion regarding treatment and testing condition; sampling occurred between 9.00 a.m. and 1:00 p.m. Trunk blood was collected in potassium EDTA (Ethylene Diamine Tetra Acetic Acid) tubes and spun for 15 min at 4000 g. Plasma was isolated and stored at −80 °C for further analysis. The brain was quickly excised, dissected and each brain region was snap-frozen on dry ice and stored at −80 °C for further analysis. Spleen was removed and processed immediately after culls for *ex-vivo* immune stimulation. Intestinal tissue (2 cm segments of ileum and colon closest to the caecum were excised, and the furthest 1cm of tissue from the caecum were used) were mounted into the Ussing chambers for intestinal permeability assay. The caecum was removed, weighted and stored at −80 °C for SCFAs analysis.

Monoamine Analysis

Neurotransmitter concentration was analysed by HPLC on samples from the brainstem. Briefly, brainstem tissue was sonicated in 500 µl of chilled mobile phase spiked with 4 ng/40 µl of N-Methyl 5-HT (Sigma Chemical Co., UK) as internal standard. The mobile phase contained 0.1 M citric acid, 5.6 mM octane-1-sulphonic acid (Sigma), 0.1 M sodium dihydrogen phosphate, 0.01 mM EDTA (Alkem/Reagecon, Cork) and 9% (v/v) methanol (Alkem/Reagecon) and was adjusted to pH 2.8 using 4 N sodium hydroxide (Alkem/Reagecon). Homogenates were then centrifuged for 15 min at 22,000 × g at 4 °C and 40 µl of the supernatant injected onto the HPLC system which consisted of a SCL 10-Avp system controller, LECD 6A electrochemical detector (Shimadzu), a LC-10AS pump, a CTO-10A oven, a SIL-10A autoinjector (with sample cooler maintained at 40 C) and an online Gastorr Degasser (ISS, UK). A reverse-phase column (Kinetex 2.6 u C18 100 × 4.6 mm, Phenomenex) maintained at 30 °C was employed in the separation (Flow rate 0.9 ml/min). The glassy carbon working electrode combined with an Ag/AgCl reference electrode (Shimdazu) operated a +0.8 V and the chromatograms generated were analyzed using Class-VP 5 software (Shimadzu). The neurotransmitters were identified by their characteristic retention times as determined by standard injections, which run at regular intervals during the sample analysis. The ratios of peak heights of analyte versus internal standard were measured and compared with standard injection. Results were expressed as ng of neurotransmitter per g fresh weight of tissue.

Metabolite analysis

For GC-metabolite analysis, samples of bacterial supernatants were derivatized with methyl chloroformate using a slightly modified version of the protocol described in [112]. All samples were analyzed in a randomized order. Analysis was performed using GC (7890B, Agilent) coupled with a

quadropole detector (59977B, Agilent). The system was controlled by ChemStation (Agilent). Raw data was converted to netCDF format using Chemstation (Agilent), before the data was imported and processed in Matlab R2014b (Mathworks, Inc.) using the PARADISe software described in [101].

For fatty acid analysis samples were acidified using hydrochloride acid, and deuterium labelled internal standards where added. All samples were analyzed in a randomized order. Analysis was performed using a high polarity column (Zebron™ ZB-FFAP, GC Cap. Column 30 m x 0.25 mm x 0.25 µm) installed in a GC (7890B, Agilent) coupled with a quadropole detector (59977B, Agilent). The system was controlled by ChemStation (Agilent). Raw data was converted to netCDF format using Chemstation (Agilent), before the data was imported and processed in Matlab R2014b (Mathworks, Inc.) using the PARADISe software described by [101].

Results – neurotransmitter production

The results are shown in Figure 19, which shows that in brains of mice fed with MRx0029, noradrenaline levels are increased (p=0.0507), accompanied with a slight increase of serotonin and 5-HIAA. These data support the metabolite analysis set out below, suggesting that MRx00029 is a major producer of 4-hydroxyphenylacetic acid, a known antioxidant [113]. More importanly, 4-hydroxyphenylacetic acid is a synthetic intermediate of dopamine and norepinephrine and an important bio-active molecule [114]. In fact, in PD, degenerative changes extend beyond the dopaminergic system, affecting equally the serotonergic and noradrenergic systems, which in turn leads to decreased levels of serotonin (5-hydroxytryptamine, 5-HT) and noradrenaline (norepinephrine) in both striatal and extra-striatal structures [115]. L-DOPA targets mainly the dopamine-related features of PD, however it does not address the decreases in both 5-HT and noradrenaline. Adding to this is that the longer is the duration of L-DOPA treatment, the more visible are a range of motor and nonmotor complications (e.g. dyskinesia, psychiatric symptoms) [116]. Therefore, these data demonstrate that bacteria that produce organic acids, such as 4-hydroxyphenylacetic acid, may be useful in therapy, in particular in the treatment of neurodegenerative diseases.

Results – metabolite production

Metabolites present in bacteria supernatants can directly influence the host response to oxidative stress, cell-to-cell communication and neuroprotection in the specific. Metabolites in the supernatant of cultures of MRX0029 and MRX0005 were analysed and the results are shown in Figure 20.

A few metabolites showed a striking difference between the two strains analysed. The concentration of succinic acid was particularly elevated in MRx0005. Interestingly, the ratio sample/media for 4-hydroxyphenylacetic acid was significantly higher in MRx0029 (Fig. 20A).

Fatty acid analysis in the supernatants revealed an interesting dichotomy in the two strains: MRx0005 produced mainly acetic and propanoic acid, while MRx0029 produced butanoic, pentanoic and hexanoic acid, both in the linear and branched forms (Fig. 20B). The two strains looked very different

and in particular, the production of succinic acid and 4-hydroxyphenylacetic acid by MRx0005 and MRx0029 respectively was notable (Figure 20A). Furthermore, MRx0005 seems to produce more C2 and C3 short chain fatty acids, while MRx00029 produced more C4 (butyrate) and both linear and branched medium chain fatty acids, including hexanoic acid.

Succinic acid is a Krebs cycle metabolite involved in oxidative phosphorylation. Oxidative phosphorylation complex is a key step for synaptic trafficking of proteins and vesicles to proximal and distal regions [117]. Its dysfunction has been reported in neurodegenerative disorders including Alzheimer's disease, Parkinson's disease and Spinocerebellar ataxia type 1 [63]. These findings are particularly interesting as succinic acid can augment mitochondrial activity and support vulnerable neurons in neurodegenerative disease related to misfolded proteins including PD [65]. BDNF and succinic acid have both a similar protective activity not only in neuro-degeneration but also in mental disorders like depression and anxiety, which are quite common amongst patients diagnosed with PD or AD.

Figure 20B also demonstrates that MRX0029 is a butyrate (butanoic acid) producer. This may be significant because butyrate has a known role is reducing impermeability of the blood brain barrier, which has a neuroprotective effect [118]. This property of MRx0029 (and other neuroprotective bacteria) may contribute to its effacy.

Example 15 - Modulation of the mRNA expression of tight junction proteins by MRx0029

Since recent evidence suggests that intestinal dysfunction and inflammation is a non-motor symptom associated with PD, the ability of the bacterial strains of the invention to cause any intestinal barrier dysfunction was investigated. HT29-mtx epithelial, mucin-producing cell monolayers [119] were used as an *in vitro* model to evaluate gut barrier disruption and immune stimulation following treatment with MRx0005 and MRx0029. Differentiated HT29-mtx cells exposed to phorbol 12-myristate-13-acetate (PMA) secreted a significant amount of IL-8; in contrast treatment for 24h with MRx005 and MRx0029 bacterial supernatants, induced an even lower secretion of IL-8 compared than both untreated and YCFA-treated cells (Fig. 22A).

The ability of MRx0005 and MRx0029 to regulate epithelial permeability by modifying intracellular signal transduction involved in the expression and localization of proteins involved in the gut barrier formation was then investigated.

RNA was isolated and Quantitative RT-PCR (qRT-PCR) analysis was performed to characterize the changes in gene expression of tight junction proteins during incubation with MRx0005 and MRx0029. The administration of MRx0029 enhanced Occludin, Vlillin, Tight Junction Protein 1 and 2 (respectively TJP1 and TJP2) mRNA expression after 2h incubation (Fig. 22B). In contrast, exposure

to MRx0005 did not alter the gene expression of tight junction proteins indicating that the two strains act differentially on the intestinal barrier.

The *in vitro* results were compared with data from the *ex vivo* parallel analysis on the gut of mice fed with MRx0005 and MRx0029. Gene expression of TJP2 and occludin was quantified in the colon and ileum. The *ex vivo* data perfectly mirror the *in vitro* data as MRx0029 was able to significantly up-regulate TJP1 and Occludin (p=0.073) in the colon region of the murine intestine (Fig. 22C+22D). MRx0029 was also able to decrease the permeability function in the colon of the same mice (Fig. 22E+22F).

Materials and methods - RNA extraction and qPCR analysis

Total RNA was extracted using the RNeasy mini kit (Qiagen, Manchester, JUK) according to the manufacturer's instructions, and the RNA concentration determined by absorbance at 260/280nm using a spectrophotometer (nano-Drop ND-1000; Thermo Scientific, Wilmington, DE). For mRNA expression analysis, cDNA was prepared from total RNA using the High-Capacity cDNA reverse transcription kit (Applied Biosystems, UK) according to the manufacturer's instructions. The reverse transcription reactions were performed in a Thermo cycler (Biometra, Germany) at 25°C for 10min, 37°C for 120min, and 85°C for 5 min, hold on at 4°C. Resulting cDNA was amplified in duplicates by the SYBR-Green PCR assay, and products were detected on QuantStudio 6 flex real-time PCR machine (Applied Biosystems, UK) using a standardised profile (initial denaturation of 95°C for 10 minutes, followed by 40 cycles of 15 seconds of denaturation at 95°C and 60 seconds of annealing/extension at 60/65°C, depending on the primers. A dissociation stage was added after the 40 cycles to generate a melting curve. Analysis was performed using the Applied Biosystems QuantStudio Real-Time PCR Software v1.2. The primer sequences for Actin, Villin, Occludin TJP1 and TJP2 are provided in the sequence listing.

Example 16

Methods

Animals

The animals and study design used were the same as for Example 14.

Bacterial strains

- 755: *Parabacteroides distasonis (MRX005)*
- *Megasphaera massiliensis (MRX0029)*

Tissue Collection

Animals were sacrificed in a random fashion regarding treatment and testing condition; sampling occurred between 9.00 a.m. and 2:30 p.m. Trunk blood was collected in potassium EDTA (Ethylene Diamine Tetra Acetic Acid) tubes and spun for 15 min at 4000 g. Plasma was isolated and stored at −80 °C for further analysis. The brain was quickly excised, dissected and each brain region was snap-frozen on dry ice and stored at −80 °C for further analysis. Spleen was removed, collected in 5 mL RPMI media (with L-glutamine and sodium bicarbonate, R8758 Sigma + 10 % FBS (F7524, Sigma) + 1% Pen/Strep (P4333, Sigma)) and processed immediately after culls for ex-vivo immune stimulation. Intestinal tissue (2 3cm segments of ileum and colon closest to the caecum were excised, and the furthest 1cm 2cm of tissue from the caecum were used) were mounted into the Ussing chambers for intestinal permeability assay. The caecum was removed, weighted and stored at −80 °C for SCFAs analysis.

Monoamine Analysis

The neurotransmitter concentration was analysed as described in Example 10

Spleen Cytokine Assay

Spleens were collected immediately in 5mL RPMI media following sacrifice and cultured immediately. Spleen cells were first homogenised in this RPMI media, followed by 5 mins incubation with 1ml of RBC lysis buffer (11814389001 ROCHE, Sigma). A further 10 ml of RPMI media was added, followed by 200G centrifugation for 5 mins. The supernatant was then filtered through 40um strainer. Cells were counted and seeded (4,000,000/mL media). After 2.5 h of adaptation, cells were stimulated with lipopolysaccharide (LPS-2 μg/ml) or concanavalin A (ConA-2.5 μg/ml) for 24 h. Following stimulation, the supernatants were harvested to assess the cytokine release using Proinflammatory Panel 1 (mouse) V-PLEX Kit (Meso Scale Discovery, Maryland, USA) for TNFα, IL-10, IL-1β, Interferon γ, CXCL2 and IL6. The analyses were performed using MESO QuickPlex SQ 120, SECTOR Imager 2400, SECTOR Imager 6000, SECTOR S 600.

Gene Expression Analysis

Total RNA was extracted using the mirVana™ miRNA Isolation kit (Ambion/Llife technologies, Paisley, UK) and DNase treated (Turbo DNA-free, Ambion/life technologies) according to the manufacturers recommendations. RNA was quantified using NanoDrop™ spectrophotometer (Thermo Fisher Scientific Inc., Wilmington, Delaware, USA) according to the manufacturer's instructions. RNA quality was assessed using the Agilent Bioanalyzer (Agilent, Stockport, UK) according to the manufacturer's procedure and an RNA integrity number (RIN) was calculated. RNA with RIN value >7 was used for subsequent experiments. RNA was reverse transcribed to cDNA using the Applied Biosystems High Capacity cDNA kit (Applied Biosystems, Warrington, UK) according to manufacturer's instructions. Briefly, Multiscribe Reverse Transcriptase (50 U/μL) (1)(2)(1)(10) was added as part of RT master mix, incubated for 25°C for 10 min, 37°C for 2 h, 85°C for 5 min and stored at 4°C. Quantitative PCR was carried out using probes (6 carboxy fluorescein - FAM) designed

by Applied Biosystems to mouse specific targeted genes, while using β-actin as an endogenous control. Amplification reactions contained 1 µl cDNA, 5 µl of the 2X PCR Master mix (Roche), 900 nM of each primer and were brought to a total of 10 µl by the addition of RNase-free water. All reactions were performed in triplicate using 96-well plates on the LightCycler®480 System. Thermal cycling conditions were as recommended by the manufacturer (Roche) for 55 cycles. To check for amplicon contamination, each run contained no template controls in triplicate for each probe used. Cycle threshold (Ct) values were recorded. Data was normalized using β-actin and transformed using the $2^{-\Delta\Delta CT}$ method and presented as a fold change vs. control group.

Short Chain Fatty Acids Analysis in the Caecal Content

Caecum content was mixed and vortexed with MilliQ water and incubated at room temperature for 10 min. Supernatants were obtained by centrifugation (10000 g, 5 min, 4 °C) to pellet bacteria and other solids and filtration by 0.2µm. It was transferred to a clear GC vial and 2-Ethylbutyric acid (Sigma) was used as the internal standard. The concentration of SCFA was analyzed using a Varian 3500 GC flame-ionization system, fitted with a with a ZB-FFAP column (30 m x 0.32 mm x 0.25 mm; Phenomenex). A standard curve was built with different concentrations of a standard mix containing acetate, propionate, iso-butyrate, n-butyrate, isovalerate and valerate (Sigma). Peaks were integrated by using the Varian Star Chromatography Workstation version 6.0 software. All SCFA data are expressed as µmol/g.

Statistical Analysis

Normally distributed data are presented as mean ± SEM; Non-parametric datasets are presented as median with inter-quartile range. Unpaired two-tailed t-test were applied to analyse parametric data and Mann-Whitney test was used for non-parametric. Spearman's rank correlation coefficient was employed for the correlation analysis in the pooled datasets. A p value < 0.05 was deemed significant in all cases.

Results – Neurotransmitter production

The results in Figure 23 show the effect of MRx005 treatment on the concentration of neurotransmitters in the brain of mice. Most notably, treatment with MRx005 leads to a decrease in dopamine.

Results – Gene expression

Expression of genes for neurotransmitter receptors [serotonin receptor 1a(5-HTR1a), dopamine D1 receptor, GABA receptor subunit B1, GABAA receptor, NMDA2A (Grin2A) and NMDA2B (Grin2b) receptor], inflammatory markers [IL-1β, IL6, CD11b, TNFα and TLR4], and endocrine markers [corticosterone releasing factor (CRF), corticosterone releasing factor receptors 1 and 2 (CRFR1, CRFR2), brain-derived neurotrophin factor (BDNF), vasopressin receptor, oxytocin receptor, glucocorticoid receptor and mineralocorticoid receptor] were analysed in brain tissue from the hippocampus, amygdala and prefrontal cortex.

Figures 24-38 show the changes in gene expression after MRX005 or MRX0029 treatment in the hippocampal, amygdala and prefrontal cortex. Treatment with MRx0029 led to an increase in glucocorticoid receptor expression in the amygdala (Figure 31C). Figure 32A shows that MRx005 significantly increased the expression of BDNF in the amygdala, while treatment with MRx0029 significantly increased the expression of TLR4 in the amygdala (Figure 32).

Both MRx005 and MRx0029 can increase expression of CD11b in the amygdala (Figure 33A), while the expression of IL-6, Grin2a and Grin2b is reduced after MRx005 treatment (Figures 33B-D). In addition, MRx005 and MRx0029 significantly increased the expression of GABRA2 and increased the expression of GABBR1 in the amygdala.

Treatment with MRx005 led to a significant increase in the expression of BDNF in the prefrontal cortex (Figure 35B).

Discussion

MRx005 and MRx0029 administration caused changes in gene expression, especially in the amygdala.

Results – Effect on Tph1 and IDO-1 expression

Figure 39 shows that MRx0029 can significantly increase the expression tryptophan hydroxylase- 1 (Tph1) in the colon and that MRX005 treatment can increase IDO-1 expression in the colon. Treatment with MRX005 increased the expression of Tph1 and IDO1 in the ileum (Figure 40).

Indoleamine-pyrrole 2,3-dioxygenase-1 (IDO-1) the first and rate-limiting enzyme in the tryptophan/kynurenine pathway while tryptophan hydroxylase 1 (Tph1), an isoform of the enzyme tryptophan hydroxylase, responsible for the synthesis of serotonin. These data suggest that MRx0029 and MRx005 may affect serotonin levels and the tryptophan/kynurenine pathway.

Results – Effect on tryptophan metabolite levels

Figure 41 shows the effect of treatment with MRx005 on the levels of circulating kynurenine and tryptophan.

Results – Effect on cytokine expression from splenocytes

The ex-vivo splenocyte assay involves challenging the splenocytes (cells isolated from the spleen - a main organ involved in immune defence), with a bacterio- or viral-mimetic challenge.

MRX005 significantly reduced the levels of interferon-γ in splenocytes following a challenge with LPS (Figure 42). In addition, MRX005 reduced the levels of interleukin-6 and tumour necrosis factor after a challenge with LPS (Figures 44 and 45, respectively). Treatment with MRx0029 led to a reduction in interferon-γ, interleukin-1β and interleukin-6 following a challenge with LPS (Figures 42, 43 and 44, respectively).

Treatment with MRx005 and MRx0029 led to an increase in the levels of the chemoattractant CXCL1 (Figure 47).

Results – Effect on Caecal Short Chain Fatty Acid Levels

Short chain fatty acids (SCFAs) are produced when non-digestible fibres from the diet are fermented by bacteria in the gut. The effects of MRX005 administration are shown in Figure 48.

Example 17 – Further analysis of MRX029 and MRX005-induced changes in gene expression levels

Methods

Cell line

SH-SY5Y cells

Bacterial strains

- 755: *Parabacteroides distasonis (MRX005)*
- *Megasphaera massiliensis (MRX0029)*

qPCR

SHSY5Y were plated in 10cm petri dishes a density of $2x10^6$ cells. After 24h cells were treated in differentiation medium (growth medium containing 1% FBS without RA) with 10% bacteria supernatants or YCFA+, 10uM RA, 200uM hexanoic acid or 200uM valproic acid, for 17 hrs. There after representative images were taken using phase contrast EVOS XL core microscope at 40X/0.65 magnification. Cells were collected, and total RNA was isolated according to RNeasy mini kit protocol (Qiagen). cDNAs were made using the high capacity cDNA reverse transcription kit (Applied Biosystems). Gene expression was measured using qPCR. GAPDH was used as internal control. Fold change was calculated according to the $2^{(-\Delta\Delta ct)}$ method. The primer sequences for MAP2, DRD2, GABRB3, SYP, PINK1, PARK7 and NSE are provided in the sequence listing.

Immuno-labelling and cell imaging

Cells were seeded onto 8-well chamber slides (Marienfeld Laboratory Glassware) at $5x10^4$ cells/well overnight and were treated with 10% bacterial supernatant for 24 h. For differentiation, cells were treated with 10 nM RA for 5 days before treating with cell-free bacterial supernatant for 24 h. Afterwards, the cells were fixed with 4% paraformaldehyde in PBS for 20 minutes at room temperature (RT). Fixed cells were washed with PBS, and permeabilized with 1% Triton X-100 in PBS for 10 minutes. After washing with PBS, the slides were incubated with blocking buffer (4% BSA/PBS) for 1 h at RT before adding anti-MAP2 antibody or β3-tubulin (sc-74421 and sc-80005 respectively, Santa Cruz Biotechnology Inc) diluted in 1% BSA/PBS for 12 h at 4°C. They were then washed twice with PBS, followed by incubation with Alexa Flour 488 conjugated anti-mouse (Molecular Probes Inc) and Alexa Flour 594 conjugated Phalloidin (ab176757, Abcam) for 1 h at RT. After washing 3X with PBS,

the slides were staining with DAPI and mounted with Vectashield® (Vector Laboratories). Slides were viewed using a Axioskop 50 microscope (Zeiss) equipped with a 63x/1.2 W Korr objective and filter sets suitable for detection of the fluorochromes used. Manual exposure times for the digital acquisition of images immuno-labelled with MAP-2 were kept constant allowing comparison between different wells and treatments. Phalloidin (F-actin) and DAPI exposure times varied to suit the field of view. Randomised fields of view were acquired using a QImaging camera controlled by Image Pro Plus software. Images were saved as TIFF files and opened in Adobe Photoshop CC 2015.1.2. Images of the MAP-2, DAPI and Phalloidin images were then overlaid and merged. Representative images were selected to illustrate the differences in abundance and location of the proteins examined.

Immunoblotting

SH-SY5Y cells cultured under the indicated conditions described above, treated with MRx0005 and MRx0029 for 24h and then lysed in RIPA buffer containing cocktail of protease inhibitors (Roche Diagnostics, UK). Protein concentration was estimated using the BCA protein assay kit (Pierce Biotechnology, Rockford, IL), separated by SDS-PAGE and transferred to a PVDF membrane. Membranes were then blocked with 5% non-fat dry milk or 5% BSA and incubated overnight at 4°C with the primary antibodies (respectively MAP2 and β3-tubulin). The blots were then incubated with the appropriate horseradish peroxidase (HRP)-conjugated secondary antibody, and proteins were detected by chemiluminescence detection kit (Pierce Biotechnology, Rockford, IL). For both MAP2 and β3-tubulin, β-actin served as a control to monitor protein loading variability amongst samples.

Results and Discussion

Gene expression

Figures 7a (graph insert) and 49 show the MRx0029 and MRX005-induced changes in expression levels of Actin, Villin, Occludin TJP1, TJP2, MAP2, DRD2, GABRB3, SYP, PINK1, PARK7 and NSE.

Microscopy and Immunoblotting

Figure 50 shows the change in the level of expression of MAP2 in SHSY5Y cells as determined by confocal microscopy. The expression levels of MAP2 and B3-tubulin were also quantified by immunoblot analysis. The results shown in Figure 50M and 50N indicate that MRX029 induces an increase in the level expression of MAP2.

Sequences

SEQ ID NO:1 (*Megasphaera massiliensis* gene for 16S ribosomal RNA, partial sequence, strain: NP3 - JX424772.1)

```
   1 agagtttgat cctggctcag gacgaacgct ggcggcgtgc ttaacacatg caagtcgaac
  61 gagaagagat gagaagcttg cttcttatca attcgagtgg caaacgggtg agtaacgcgt
```

```
 121 aagcaacctg cccttcagat ggggacaaca gctggaaacg gctgctaata ccgaatacgt
 181 tctttccgcc gcatgacggg aagaagaaag ggaggccttc gggctttcgc tggaggaggg
 241 gcttgcgtct gattagctag ttggaggggt aacggcccac caaggcgacg atcagtagcc
 301 ggtctgagag gatgaacggc cacattggga ctgagacacg gcccagactc ctacgggagg
 361 cagcagtggg gaatcttccg caatggacga aagtctgacg gagcaacgcc gcgtgaacga
 421 tgacggcctt cgggttgtaa agttctgtta tatgggacga acagggcatc ggttaatacc
 481 cggtgtcttt gacggtaccg taagagaaag ccacggctaa ctacgtgcca gcagccgcgg
 541 taatacgtag gtggcaagcg ttgtccggaa ttattgggcg taaagggcgc gcaggcggca
 601 tcgcaagtcg gtcttaaaag tgcggggctt aaccccgtga ggggaccgaa actgtgaagc
 661 tcgagtgtcg gagaggaaag cggaattcct agtgtagcgg tgaaatgcgt agatattagg
 721 aggaacacca gtggcgaaag cggctttctg gacgacaact gacgctgagg cgcgaaagcc
 781 aggggagcaa acgggattag ataccccggt agtcctggcc gtaaacgatg gatactaggt
 841 gtaggaggta tcgactcctt ctgtgccgga gttaacgcaa taagtatccc gcctggggag
 901 tacggccgca aggctgaaac tcaaaggaat tgacgggggc ccgcacaagc ggtggagtat
 961 gtggtttaat tcgacgcaac gcgaagaacc ttaccaagcc ttgacattga ttgctacgga
1021 aagagatttc cggttcttct tcggaagaca agaaaacagg tggtgcacgg ctgtcgtcag
1081 ctcgtgtcgt gagatgttgg gttaagtccc gcaacgagcg caacccctat cttctgttgc
1141 cagcacctcg ggtggggact cagaagagac tgccgcagac aatgcggagg aaggcgggga
1201 tgacgtcaag tcatcatgcc ccttatggct tgggctacac acgtactaca atggctctta
1261 atagagggac gcgaaggagc gatccggagc aaaccccaaa aacagagtcc cagttcggat
1321 tgcaggctgc aactcgcctg catgaagcag gaatcgctag taatcgcagg tcagcatact
1381 gcggtgaata cgttcccggg ccttgtacac accgcccgtc acaccacgaa agtcattcac
1441 acccgaagcc ggtgaggcaa ccgcaaggaa ccagccgtcg aaggtggggg cgatgattgg
1501 ggtgaagtcg taacaaggt
```

SEQ ID NO:2 (consensus 16S rRNA sequence for *Megasphaera massiliensis* strain MRX0029)

```
TGAGAAGCTTGCTTCTTATCGATTCTAGTGGCAAACGGGTGAGTAACGCGTAAGCAACCTGCCCTTCAGATGGGGAC
AACAGCTGGAAACGGCTGCTAATACCGAATACGTTCTTTCCGCCGCATGACGGGAAGAAGAAAGGGAGGCCTTCGGG
CTTTCGCTGGAGGAGGGGCTTGCGTCTGATTAGCTAGTTGGAGGGGTAACGGCCCACCAAGGCGACGATCAGTAGCC
GGTCTGAGAGGATGAACGGCCACATTGGGACTGAGACACGGCCCAGACTCCTACGGGAGGCAGCAGTGGGGAATCTT
CCGCAATGGACGAAAGTCTGACGGAGCAACGCCGCGTGAACGATGACGGCCTTCGGGTTGTAAAGTTCTGTTATATG
GGACGAACAGGACATCGGTTAATACCCGGTGTCTTTGACGGTACCGTAAGAGAAAGCCACGGCTAACTACGTGCCAG
CAGCCGCGGTAATACGTAGGTGGCAAGCGTTGTCCGGAATTATTGGGCGTAAAGGGCGCGCAGGCGGCATCGCAAGT
CGGTCTTAAAAGTGCGGGGCTTAACCCCGTGAGGGGACCGAAACTGTGAAGCTCGAGTGTCGGAGAGGAAAGCGGAA
TTCCTAGTGTAGCGGTGAAATGCGTAGATATTAGGAGGAACACCAGTGGCGAAAGCGGCTTTCTGGACGACAACTGA
CGCTGAGGCGCGAAAGCCAGGGGAGCAAACGGGATTAGATACCCCGGTAGTCCTGGCCGTAAACGATGGATACTAGG
TGTAGGAGGTATCGACTCCTTCTGTGCCGGAGTTAACGCAATAAGTATCCCGCCTGGGGAGTACGGCCGCAAGGCTG
AAACTCAAAGGAATTGACGGGGGCCCGCACAAGCGGTGGAGTATGTGGTTTAATTCGACGCAACGCGAAGAACCTTA
CCAAGCCTTGACATTGATTGCTACGGAAAGAGATTTCCGGTTCTTCTTCGGAAGACAAGAAAACAGGTGGTGCACGG
CTGTCGTCAGCTCGTGTCGTGAGATGTTGGGTTAAGTCCCGCAACGAGCGCAACCCCTATCTTCTGTTGCCAGCACC
TCGGGTGGGGACTCAGAAGAGACTGCCGCAGACAATGCGGAGGAAGGCGGGGATGACGTCAAGTCATCATGCCCCTT
ATGGCTTGGGCTACACACGTACTACAATGGCTCTTAATAGAGGGAAGCGAAGGAGCGATCCGGAGCAAACCCCAAAA
ACAGAGTCCCAGTTCGGATTGCAGGCTGCAACTCGCCTGCATGAAGCAGGAATCGCTAGTAATCGCAGGTCAGCATA
CTGCGGTGAATACGTTCCCGGGCCTTGTACACACCGCCCGTCACACCACGAAAGTCATTCACACCCGAAGCCGGTGA
GGCAACCGCAAG
```

Primers used for qPCR (with SEQ ID NO in brackets)

Name	Forward sequence	Reverse sequence

ACTB	GATCAAGATCATTGCTCCTC (3)	TTGTCAAGAAAGGGTGTAAC (4)
GAPDH	GGTATCGTGGAAGGACTCATG (5)	ATGCCAGTGAGCTTCCCGTTC (6)
MAP2	CTCAGCACCGCTAACAGAGG (7)	CATTGGCGCTTCTCTCCTC (8)
Occludin	AAGAGGAATTTTGACACTGG (9)	GCCATGTACTCTTCACTTTC (10)
TJ1	AAGTCACACTGGTGAAATCC (11)	CTCTTGCTGCCAAACTATCT (12)
TJP2	CCCTCCCCTGGATCAGGAT (13)	GCCATCAAACTCGTCCATCA (14)
Villin	CATTACCTGCTCTACGTTTG (15)	AGATGGACATAAGATGAGGTG (16)

SEQ ID NO:17 (consensus 16S rRNA sequence for *Parabacteroides distasonis* strain MRX0005)

AMCCGGGTGGCGACCGGCGCACGGGTGAGTAACGCGTATGCAACTTGCCTATCAGAGGGGGATAACCCGGCGAAAGT
CGGACTAATACCGCATGAAGCAGGGATCCCGCATGGGAATATTTGCTAAAGATTCATCGCTGATAGATAGGCATGCG
TTCCATTAGGCAGTTGGCGGGGTAACGGCCCACCAAACCGACGATGGATAGGGGTTCTGAGAGGAAGGTCCCCCACA
TTGGTACTGAGACACGGACCAAACTCCTACGGGAGGCAGCAGTGAGGAATATTGGTCAATGGGCGTGAGCCTGAACC
AGCCAAGTCGCGTGAGGGATGAAGGTTCTATGGATCGTAAACCTCTTTTATAAGGGAATAAAGTGCGGGACGTGTCC
CGTTTTGTATGTACCTTATGAATAAGGATCGGCTAACTCCGTGCCAGCAGCCGCGGTAATACGGAGGATCCGAGCGT
TATCCGGATTTATTGGGTTTAAAGGGTGCGTAGGCGGCCTTTTAAGTCAGCGGTGAAAGTCTGTGGCTCAACCATAG
AATTGCCGTTGAAACTGGGAGGCTTGAGTATGTTTGAGGCAGGCGGAATGCGTGGTGTAGCGGTGAAATGCATAGAT
ATCACGCAGAACCCCGATTGCGAAGGCAGCCTGCCAAGCCATTACTGACGCTGATGCACGAAAGCGTGGGGATCAAA
CAGGATTAGATACCCTGGTAGTCCACGCAGTAAACGATGATCACTAGCTGTTTGCGATACACTGTAAGCGGCACAGC
GAAAGCGTTAAGTGATCCACCTGGGGAGTACGCCGGCAACGGTGAAACTCAAAGGAATTGACGGGGGCCCGCACAAG
CGGAGGAACATGTGGTTTAATTCGATGATACGCGAGGAACCTTACCCGGGTTTGAACGCATTCGGACMGAKGTGGAA
ACACATTTTCTAGCAATAGCCATTTGCGAGGTGCTGCATGGTTGTCGTCAGCTCGTGCCGTGAGGTGTCGGCTTAAG
TGCCATAACGAGCGCAACCCTTGCCACTAGTTACTAACAGGTAAAGCTGAGGACTCTGGTGGGACTGCCAGCGTAAG
CTGCGAGGAAGGCGGGGATGACGTCAAATCAGCACGGCCCTTACATCCGGGGCGACACACGTGTTACAATGGCGTGG
ACAAAGGGAAGCCACCTGGCGACAGGGAGCGAATCCCCAAACCACGTCTCAGTTCGGATCGGAGTCTGCAACCCGAC
TCCGTGAAGCTGGATTCGCTAGTAATCGCGCATCAGCCATGGCGCGGTGAATACGTTCCCGGGCCTTGTACACACCG
CCCGTCAAGCCATGGGAGCCGGGGGTACCTGAAGTCCGTAACCGCGAGGATCGGCCTAGGGTAAAACTGGTGACTGG
GGCTAAGTCGTACGGGG

Primers and probes used for *ex vivo* qPCR (with SEQ ID NO in brackets)

***Ex vivo*:**

Name	Forward sequence	Reverse sequence	Probe
ACTB	GAT TAC TGC TCT GGC TCC TAG (18)	GAC TCA TCG TAC TCC TGC TTG (19)	/56-FAM/CTG GCC TCA /ZEN/CTG TCC ACC TTC C/3IABkFQ/ (20)
GAPDH	AAT GGT GAA GGT CGG TGT G (21)	GTG GAG TCA TAC TGG AAC ATG TAG (22)	/56-FAM/TGC AAA TGG /ZEN/CAG CCC TGG TG/3IABkFQ/ (23)
BDNF	GCT GCC TTG ATG TTT ACT TTG AC (24)	GCA ACC GAA GTA TGA AAT AAC CA (25)	/56-FAM/ACC AGG TGA /ZEN/GAA GAG TGA TGA CCA TCC /3IABkFQ/ (26)
IL6	AGC CAG AGT CCT TCA GAG A (27)	TCC TTA GCC ACT CCT TCT GT (28)	/56-FAM/CCT ACC CCA /ZEN/ATT TCC AAT GCT CTC CT/3IABkFQ/ (29)

Additional primers used in qPCR (with SEQ ID NO in brackets)

Gene ID	Forward sequence	Reverse sequence

NSE	CCCTGTATCGTAAGAACGGT (30)	GCCACCATTGATCACGTTGA (31)
PINK1	CCCAAGCAACTAGCCCCTC (32)	GGCAGCACATCAGGGTAGTC (33)
PARK7	GTAGCCGTGATGTGGTCATTT (34)	CTGTGCGCCCAGATTACCT (35)
SYP	CTCGGCTTTGTGAAGGTGCT (36)	GGCTTCATGGCATCAACTTCA (37)

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0-1-1	Prepared Using	PCT Online Filing Version 3.5.000.256e MT/FOP 20141031/0.20.5.20
0-2	**International Application No.**	PCT/EP2018/065903
0-3	**Applicant's or agent's file reference**	P072872WO

1	**The indications made below relate to the deposited microorganism(s) or other biological material referred to in the description on:**	
1-1	**page**	16
1-2	**line**	1-5
1-3	**Identification of deposit**	
1-3-1	Name of depositary institution	NCIMB National Collections of Industrial, Food and Marine Bacteria (NCIMB)
1-3-2	Address of depositary institution	NCIMB Ltd, Ferguson Building, Craibstone Estate, Bucksburn, Aberdeen AB21 9YA, United Kingdom
1-3-3	Date of deposit	12 March 2015 (12.03.2015)
1-3-4	Accession Number	NCIMB 42382
1-5	**Designated States for Which Indications are Made**	All designations

2	**The indications made below relate to the deposited microorganism(s) or other biological material referred to in the description on:**	
2-1	**page**	11
2-2	**line**	31-34
2-3	**Identification of deposit**	
2-3-1	Name of depositary institution	NCIMB National Collections of Industrial, Food and Marine Bacteria (NCIMB)
2-3-2	Address of depositary institution	NCIMB Ltd, Ferguson Building, Craibstone Estate, Bucksburn, Aberdeen AB21 9YA, United Kingdom
2-3-3	Date of deposit	13 July 2017 (13.07.2017)
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CLAIMS

1. A composition comprising:
   (i) a commensal bacterial strain, and
   (ii) one or more organic acids with the following formula:
   R^n-COOH; or pharmaceutically acceptable salts or esters thereof.
2. The composition of claim 1, wherein R^n comprises an alkyl, alkenyl, alkynyl or aryl group.
3. The composition of any preceding claim, wherein R^n is a linear, branched, cyclic, partially cyclic or aromatic hydrocarbon.
4. The composition of any preceding claim, wherein R^n comprises at least 5 carbon atoms.
5. The compostion of any preceding claim, wherein R^n comprises in the range of 5 to 20 carbons.
6. The composition of any preceding claim, wherein R^n is R^1 and R^1 is an alkyl group comprising 5 carbons.
7. The composition of any preceding claim, wherein R^n is R^1 and R^1 is an alkyl and consists of 5 carbon atoms.
8. The composition of any preceding claim, wherein the one or more organic acids comprise hexanoic acid or a pharmaceutically acceptable salt or ester thereof.
9. The compostion of any preceding claim, wherein R^n is R^2 and R^2 comprises an aryl group comprising a phenyl group.
10. The composition of claim 9, wherein the phenyl group comprises a hydroxyl substituent, wherein optionally the hydroxyl group is at postion 4.
11. The composition of any preceding claim, wherein the one or more organic acids comprise 4-hydroxyphenylacetic acid.
12. The composition of any preceding claim, wherein R^n is R^3 and R^3 comprises a branched alkyl group.
13. The composition of claim 12, whererin R^n is R^3 and R^3 comprises at least 5 carbon atoms, wherein optionally R^3 comprises in the range of 5 to 9 carbon atoms.
14. The composition according to any of claims 12 to 13, wherein R^3 comprises a butyl group.
15. The composition according to any of claims 12 to 14, wherein R^3 further comprises a propyl group.
16. The composition of any preceding claim, wherein the one or more organic acids comprise valproic acid or a pharmaceutically acceptable salt or ester thereof.
17. The composition of any preceding claim, wherein R^n is R^4 and R^4 comprises a partially cyclical alkenyl group.
18. The composition according to claim 17, wherein R^4 comprises in the range of 14 to 21 carbons.
19. The composition according to any of claims 17 to 18, wherien R^4 comprises in the range of 1 to 8 substituent methyl groups.

20. The composition according to any of claims 17 to 19, wherein R^4 comprises in the range of 1 to 8 carbon- to- carbon double bonds.
21. The composition of any preceding claim, wherein the one or more organic acids comprise retinoic acid or a derivative thereof, or a pharmaceutically acceptable salt or ester thereof.
22. The composition of any preceding claim, wherein R^n is $R^5$and R^5 is an alkyl group comprising 4 carbon atoms.
23. The composition of any preceding claim, wherein R^n is R^5 and R^5 is an alkyl group consisting of 4 carbon atoms.
24. The composition of any preceding claim, wherein the one or more organic acids comprise valeric acid, or a pharmaceutically acceptable salt or ester thereof.
25. The composition of any preceding claim, wherein the composition induces one or more physiological functions selected from the list consisting of: promoting neurite outgrowth, neurorestoration, neuroprotection, inhibiting histone deacetylation, increasing BDNF activation, increasing indole production, reducing IL-6 activation and increasing IL-8 activation.
26. The composition of any preceding claim, wherein the commensal bacterial strain produces a short chain fatty acid.
27. The composition of claim 26, wherein the short chain fatty acid is butyric acid.
28. The composition of any preceding claim, wherein the commensal bacterial strain produces succinic acid.
29. The composition of any preceding claim, wherein the commensal bacterial strain is from a genus selected from the list consisting of *Bacteroides, Enterococcus, Escherichia, Klebsiella, Bifidobacterium, Staphylococcus, Lactobacillus, Megasphaera, Clostridium, Proteus, Pseudomonas, Salmonella, Faecalibacterium, Peptostreptococcus or Peptococcus*.
30. The composition of any preceding claim, wherein the strain is of the genus *Megasphaera* or is of the species *Megasphaera massiliensis*.
31. The composition of any preceding claim, wherein the bacterial strain has a 16s rRNA sequence that is at least 95%, 96%, 97%, 98%, 99%, 99.5% or 99.9% identical to SEQ ID NO:2.
32. The composition of any preceding claim, wherein the commensal bacteria is the strain deposited at NCIMB under accession number NCIMB 42787.
33. The composition of any preceding claim, wherein the commensal bacteria is capable of increasing the activation of IL-8 when administered to the gastrointestinal tract.
34. The composition of any preceding claim, for use in medicine.
35. A composition comprising a commensal bacterial strain for use in a method of treating or preventing a disease in a subject, wherein the composition is to be administered in combination with an organic acid, or a pharmaceutically acceptable salt or ester thereof.

36. A composition comprising one or more organic acids or pharmaceutically acceptable salts or esters thereof for use in a method of treating or preventing a disease in a subject, wherein the composition is to be administered in combination with a commensal bacterial strain.
37. The composition according to any preceding claim, for use in a method of treating or preventing a neurodegenerative disease.
38. The composition for use according to any of claims 35 to 36 or 37 when dependent on any of claims 35 to 36, wherein the organic acid has the following formula: R-COOH, wherein R comprises an alkyl, alkenyl, alkynyl or aryl group and comprises in the range of 4 to 20 carbon atoms.
39. A composition comprising a strain of a commensal bacteria for use in the treatment or prevention of a neurodegenerative disorder in a subject, wherein the strain produces one or more organic acids having the following formula: R^x-COOH,

    wherein R^x comprises an alkyl group comprising in the range of 4 to 11 carbons,

    or wherein R^x comprises a phenyl group with a substituent hydroxyl group, optionally wherein the hydroxyl group is at position 4.
40. A composition comprising a strain of a commensal bacteria for use in the treatment of brain injury in a subject, wherein the strain produces one or more organic acids having the following formula: R^x-COOH,

    wherein R^x comprises an alkyl group comprising in the range of 4 to 11 carbons,

    or wherein R^x comprises a phenyl group with a substituent hydroxyl group, optionally wherein the hydroxyl group is at position 4.
41. The composition of claim 39 or claim 40, wherein the strain produces hexanoic acid.
42. The composition of any of claims 39 to 41, wherein the strain produces 4-hydroxyphenylacetic acid.
43. The composition of any of claims 39 to 42, wherein the strain produces valeric acid.
44. The composition of any of claims 39-43, wherein the strain produces hexanoic acid, valeric acid and 4-hydroxyphenylacetic acid.
45. The composition for use according to any of claims claim 39-44, wherein the strain also produces a short chain fatty acid.
46. The composition for use according to claim 45, wherein the short chain fatty acid is butyric acid.
47. The composition for use according to any of claims 36-46, wherein the strain also produces succinic acid.
48. The composition of any of claims 39-47, wherein the strain is of the genus *Megasphaera,* or is of the species *Megasphaera massiliensis*.

49. The composition of any claims 39-48, wherein the bacterial strain has a 16s rRNA sequence that is at least 95%, 96%, 97%, 98%, 99%, 99.5% or 99.9% identical to SEQ ID NO:2.
50. The composition of any of claims 39-49, wherein the commensal bacteria is capable of increasing the activation of IL-8 when administered to the gastrointestinal tract.
51. The composition of any of claims 39-50, wherein the commensal bacteria is the strain deposited at NCIMB under accession number NCIMB 42787.
52. The composition of any of claims 39-51, wherein the composition comprises two or more strains of commensal bacteria.
53. The composition of claim 52, wherein the composition comprises a strain of the species *Parabacteroides distasonis* and a strain of the species *Megasphaera massiliensis*.
54. The composition of claim 53 wherein the strain of the species *Parabacteroides distasonis* has a 16s rRNA sequence that is at least 95%, 96%, 97%, 98%, 99%, 99.5% or 99.9% identical to SEQ ID NO:17, or wherein the strain of the species *Parabacteroides distasonis* has the 16s rRNA sequence represented by SEQ ID NO:17, and wherein the strain of the species *Megasphaera massiliensis* has a 16s rRNA sequence that is at least 95%, 96%, 97%, 98%, 99%, 99.5% or 99.9% identical to SEQ ID NO:2, or wherein the strain of the species *Megasphaera massiliensis* has the 16s rRNA sequence represented by SEQ ID NO:2.
55. The composition of claim 54, comprising the strain deposited at NCIMB under accession number NCIMB 42787 and the strain deposited at NCIMB under accession number NCIMB 42382.
56. The composition according to any preceding claim, wherein composition is for use in treating a neurodegenerative disorder and the neurodegenerative disorder is selected from the group consisting of Parkinson's disease, including progressive supranuclear palsy, progressive supranuclear palsy, Steele-Richardson-Olszewski syndrome, normal pressure hydrocephalus, vascular or arteriosclerotic parkinsonism and drug-induced parkinsonism; Alzheimer's disease, including Benson's syndrome; multiple sclerosis; Huntington's disease; amyotrophic lateral sclerosis; Lou Gehrig's disease; motor neurone disease; prion disease; spinocerebellar ataxia; spinal muscular atrophy; dementia, including Lewy body, vascular and frontotemporal dementia; primary progressive aphasia; mild cognitive impairment; HIV-related cognitive impairment, progressive inflammatory neuropathy and corticobasal degeneration.
57. The composition for use according to claim 56, wherein the composition is for use in a method of treating or preventing Parkinson's disease.
58. The composition of any preceding claim, wherein the composition is for use in a method of treating or preventing early-onset neurodegenerative disease.
59. The composition of any preceding claim, wherein the composition is for use in a method of preventing or delaying onset or progression of a neurodegenerative disorder.

60. The composition according to any preceding claim, wherein the composition is for use in a method of reducing inflammation in the treatement or prevention of a neurodegenerative disease.
61. The composition of any preceding claim, wherein the composition is for use in reducing neuron death or protecting neurons.
62. The composition of any preceding claim, wherein the composition is for use in a method of preventing or delaying onset or progression of a neurodegenerative disorder.
63. The composition according to any preceding claim, wherein the composition is for use in a method of reducing IL-6-mediated inflammation in the treatement or prevention of a neurodegenerative disease.
64. The composition of any preceding claim, wherein the composition is for use in a method of reducing IL-6 levels and/or NFκB levels in the treatment or prevention of a neurodegenerative disorder.
65. The composition according to any preceding claim, wherein the composition is for use in a method of increasing neuritogenesis in the subject in the treatement or prevention of a neurodegenerative disease.
66. The composition according to any preceding claim, wherein the composition is for use in a method of increasing neuritogenesis by inducing MAP2 activity.
67. The composition according to any preceding claim, wherein the composition is for use in reducing neuronal death in the subject.
68. The composition according to any of claims 1-39, wherein the composition is for use in the treatment of brain injury in a subject.
69. The composition according to claim 40 or claim 68, wherein in the composition is for use in the treatment of brain injury and the brain injury is stroke, such as cerebral ischemia, focal cerebral ischemia, ischemic stroke or hemorrhagic stroke.
70. The composition according to any of claims 39-69, wherein the commensal bacterial strain is engineered to produce the organic acid.
71. A food product comprising the composition of any preceding claim, for the use of any preceding claim.
72. A vaccine composition comprising the composition of any preceding claim, for the use of any preceding claim.
73. A method of treating or preventing a neurodegenerative disorder, comprising administering a composition of any preceding claim to a patient in need thereof.
74. A method of treating brain injury, comprising administering a composition of any preceding claim to a patient in need thereof.

FIG. 1 Protection against neurotoxicity

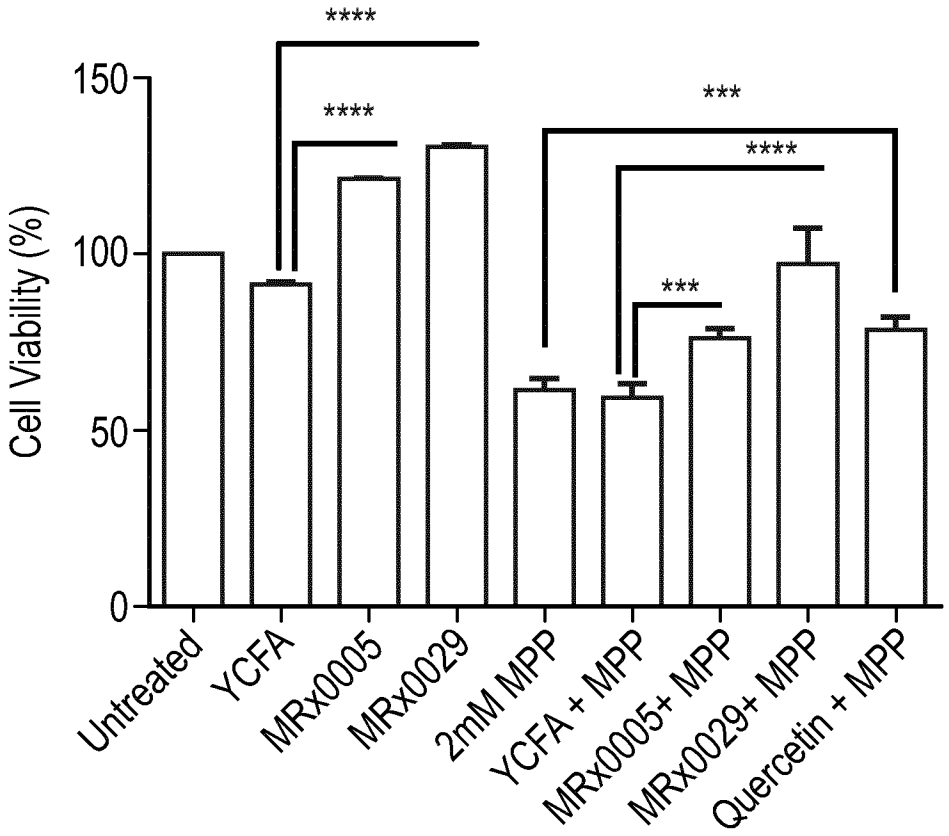


FIG. 2 Secretion of IL-6 from U373

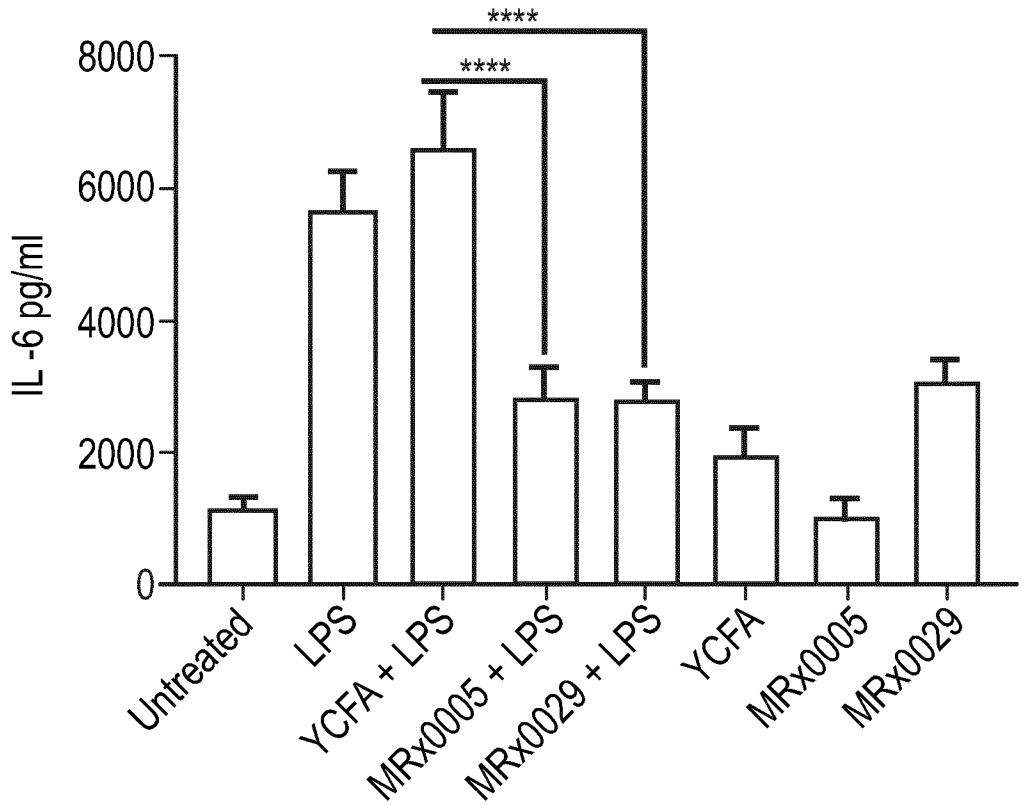


FIG. 3 Secretion of IL-8 from U373

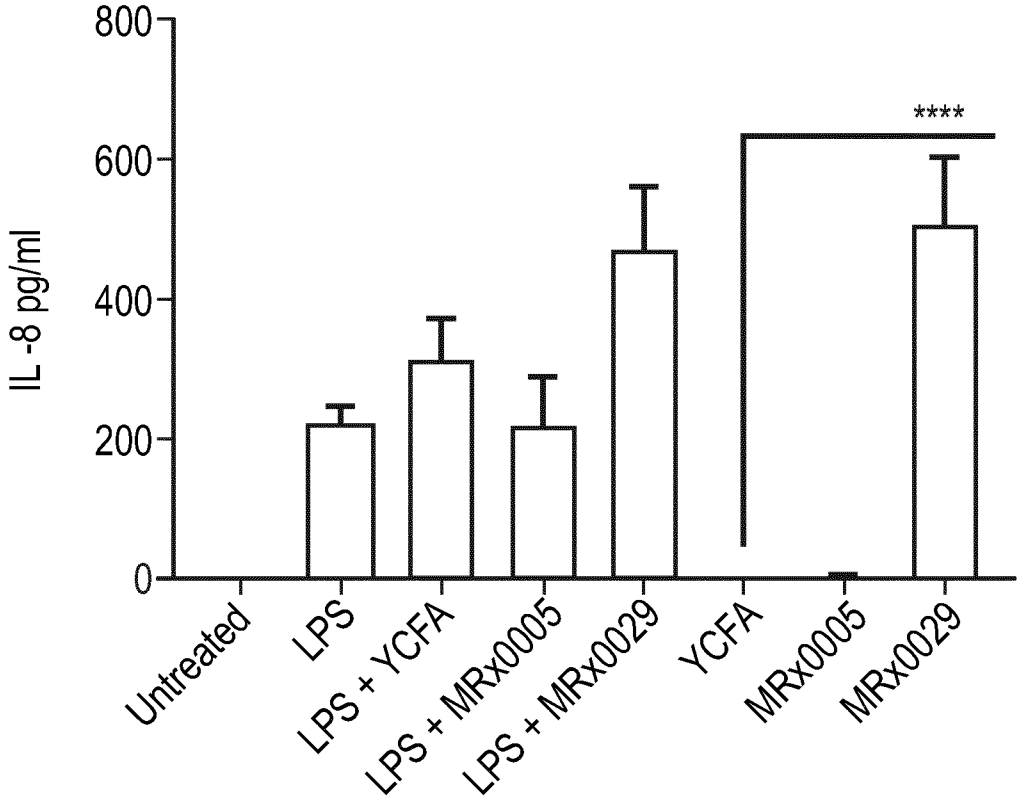


FIG. 5 Inhibition of a-synuclein-induced NFkB-AP1 activation in HEK-TLR4

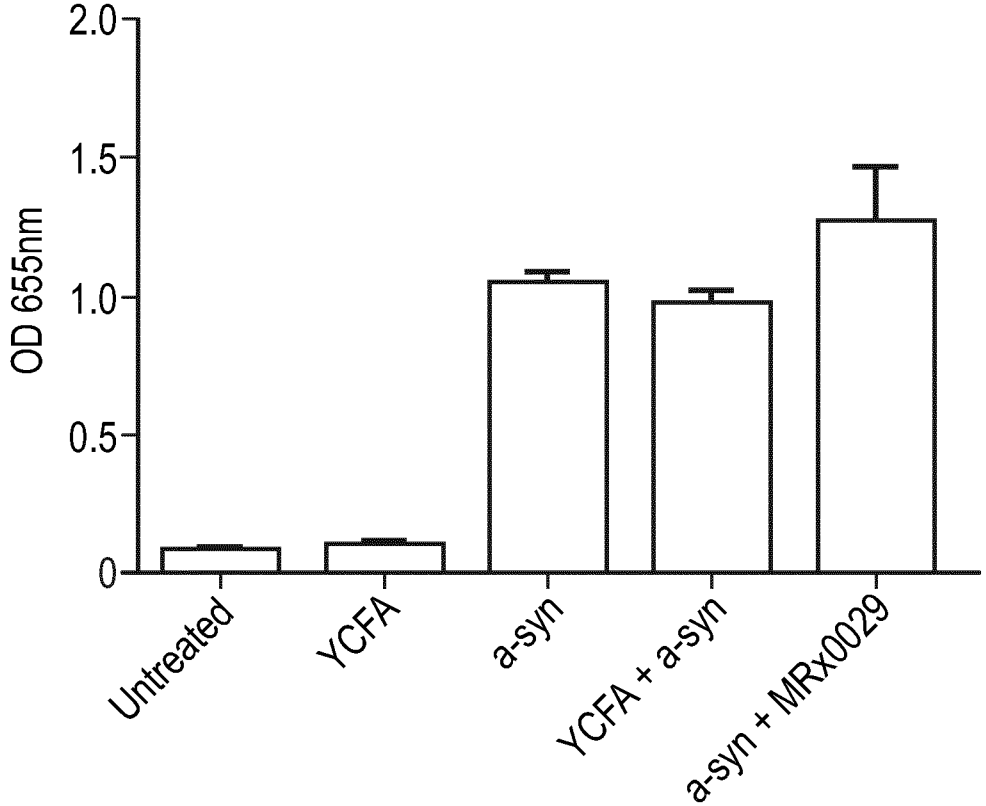


FIG. 4A Secretion of IL-6 from U373

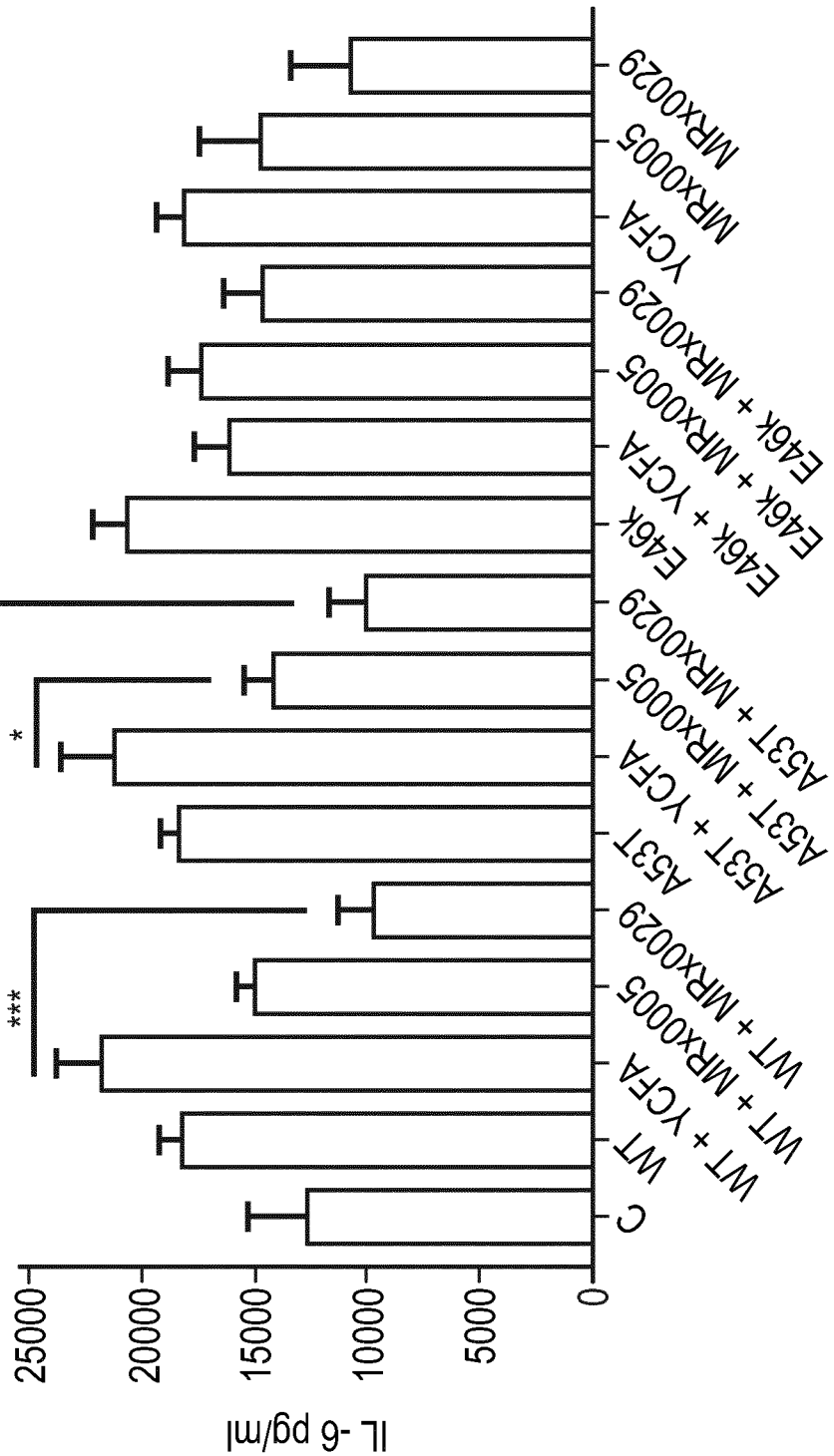


FIG. 4B Secretion of IL-8 from U373

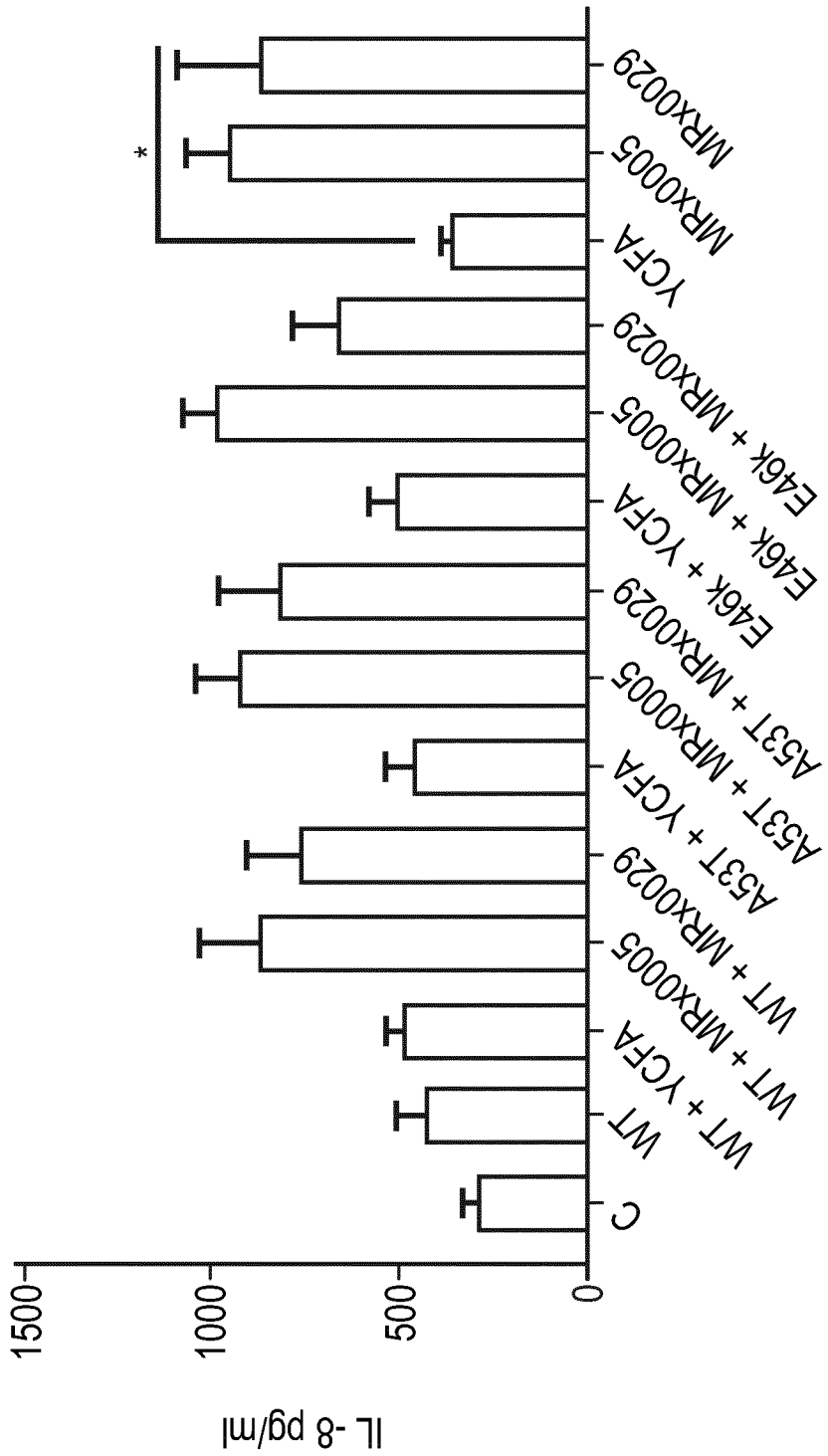


FIG. 6 Inhibition of LPS-induced NFkB-AP1 activation in HEK-TLR4

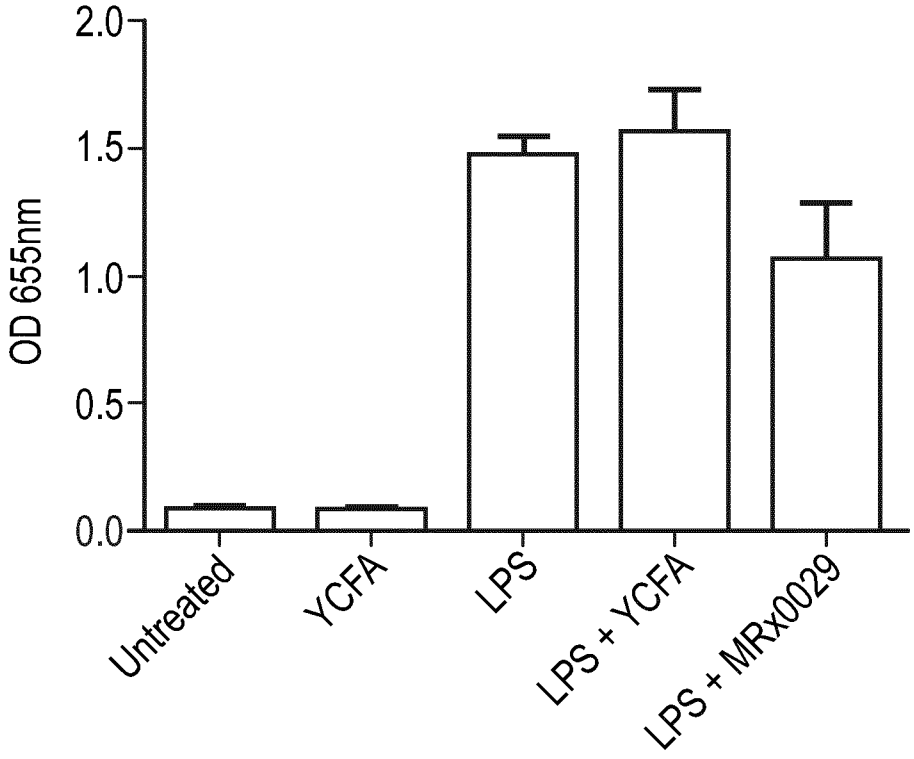
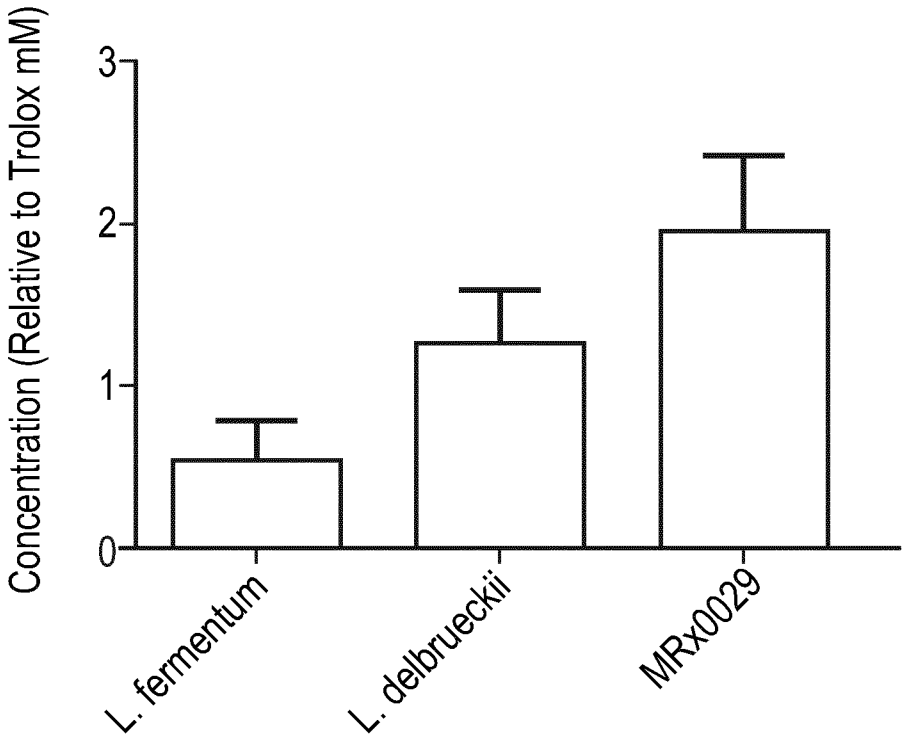


FIG. 8 Antioxidant Capacity Assay



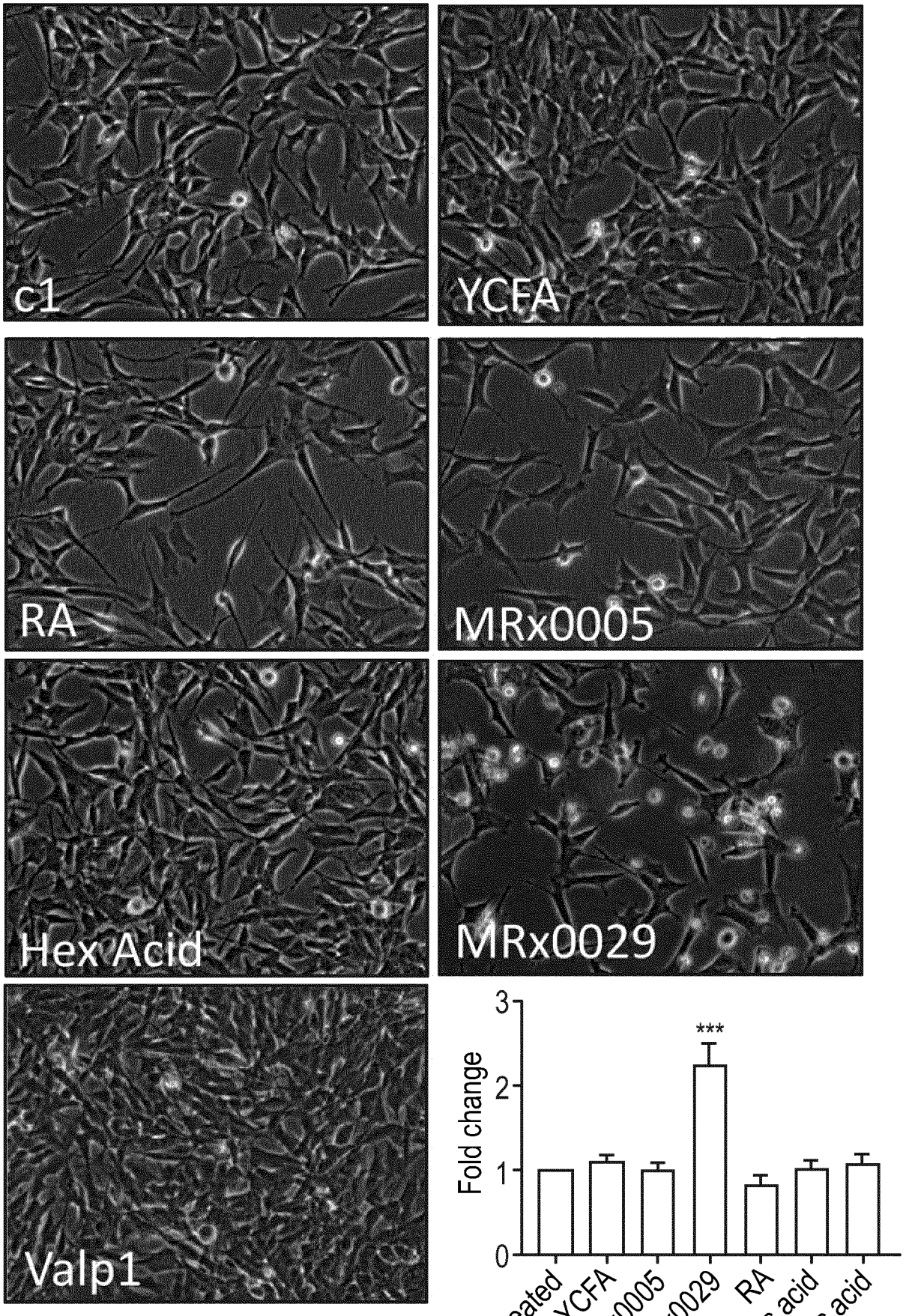


FIG. 7A Neurite outgrowth

FIG. 7B

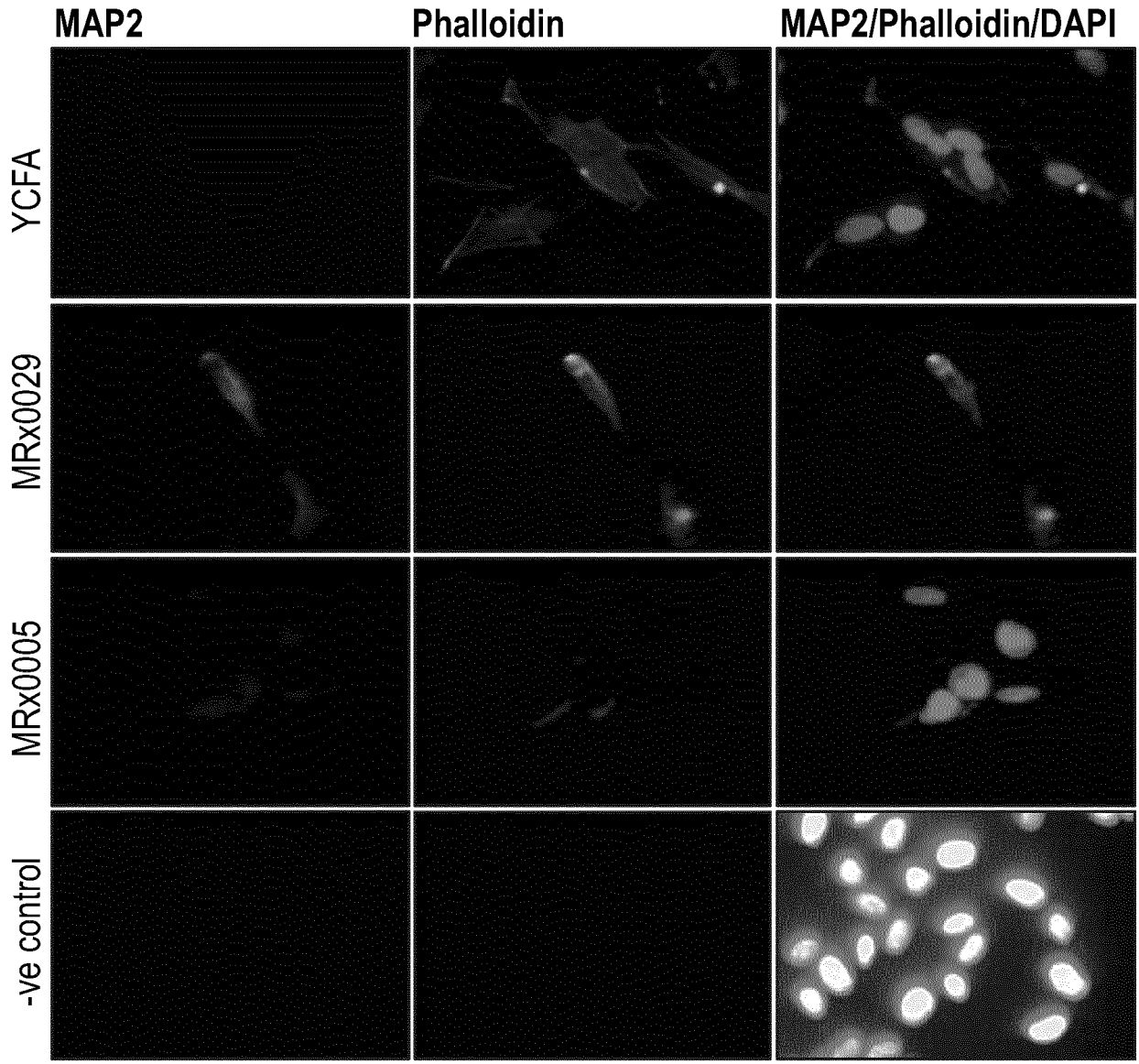

MAP2
Phalloidin
MAP2/Phalloidin/DAPI
YCFA
MRx0029
MRx0005
-ve control

FIG. 7B (contd.)

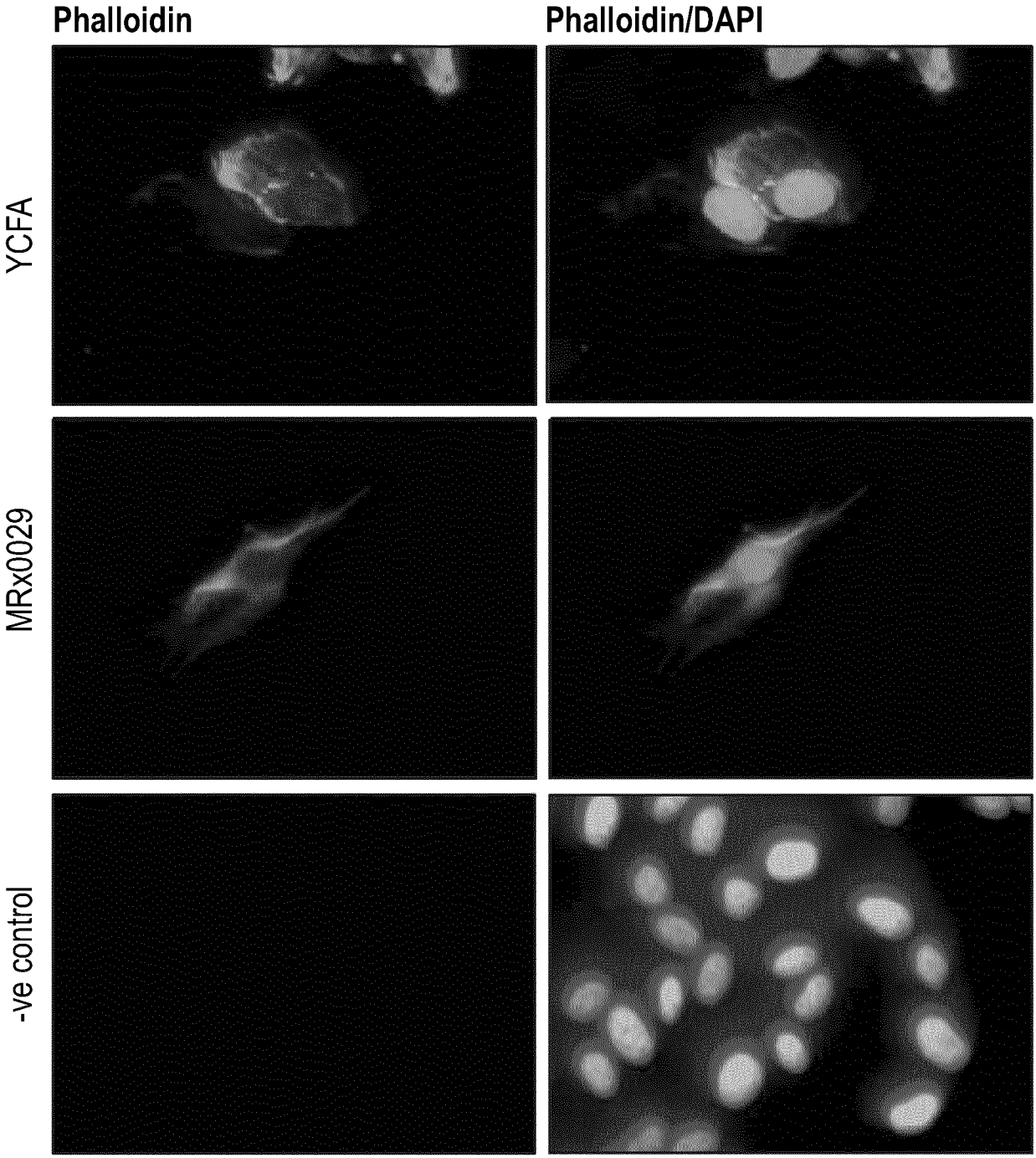


FIG. 9 Total Antioxidant Capacity

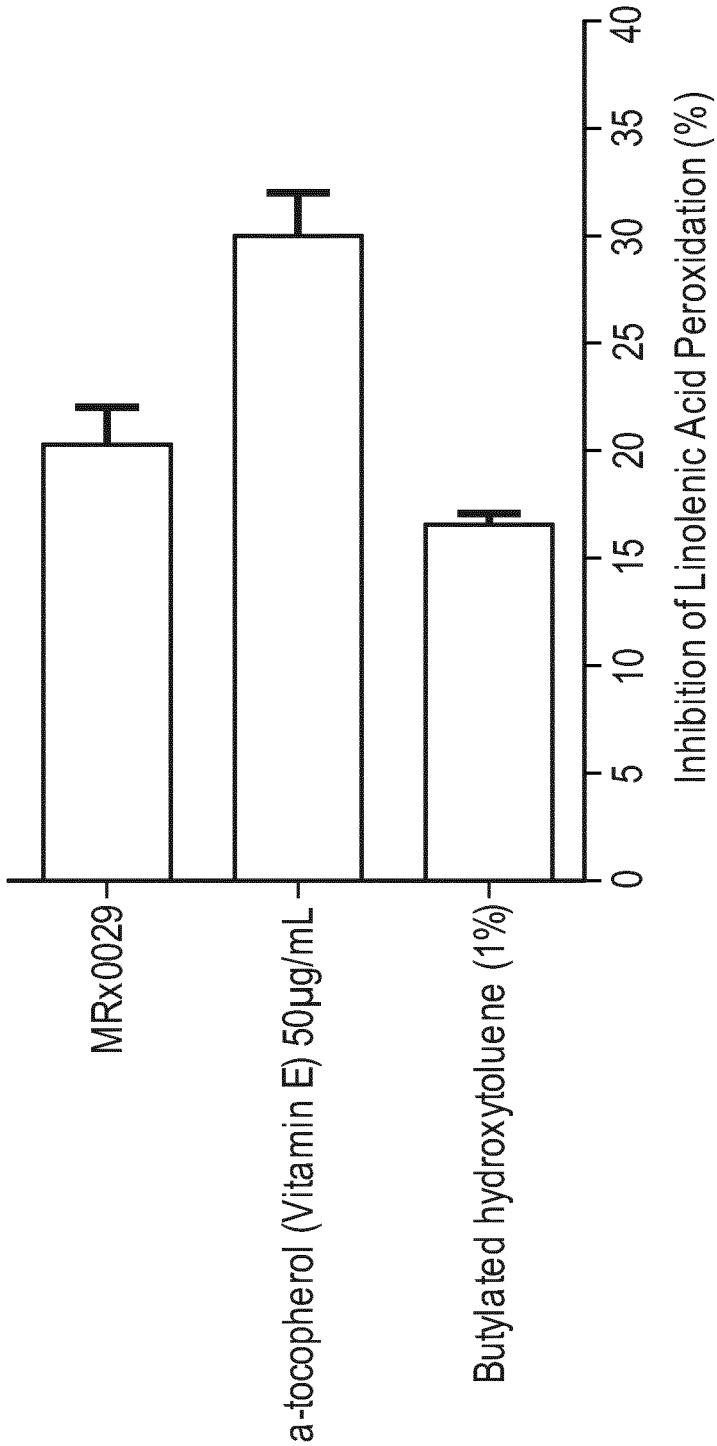


FIG. 10A Total ROS production

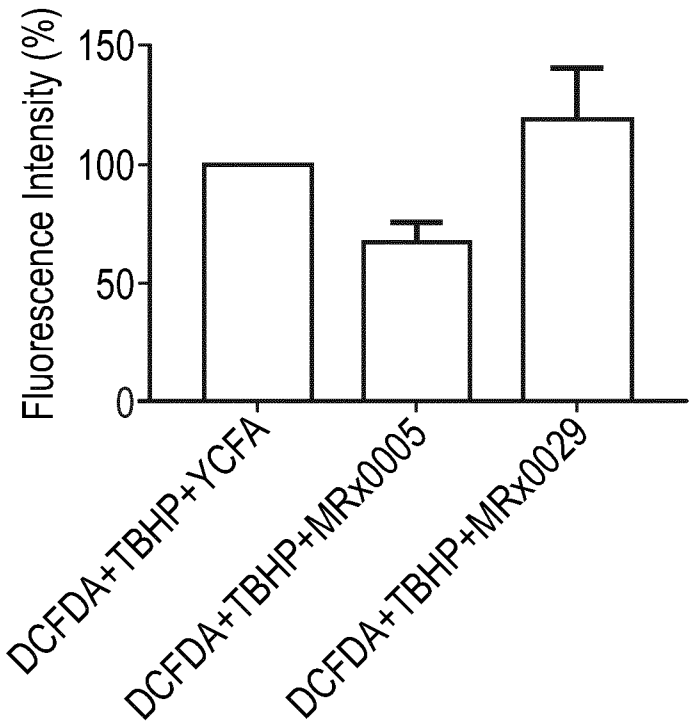


FIG. 10B Total ROS production

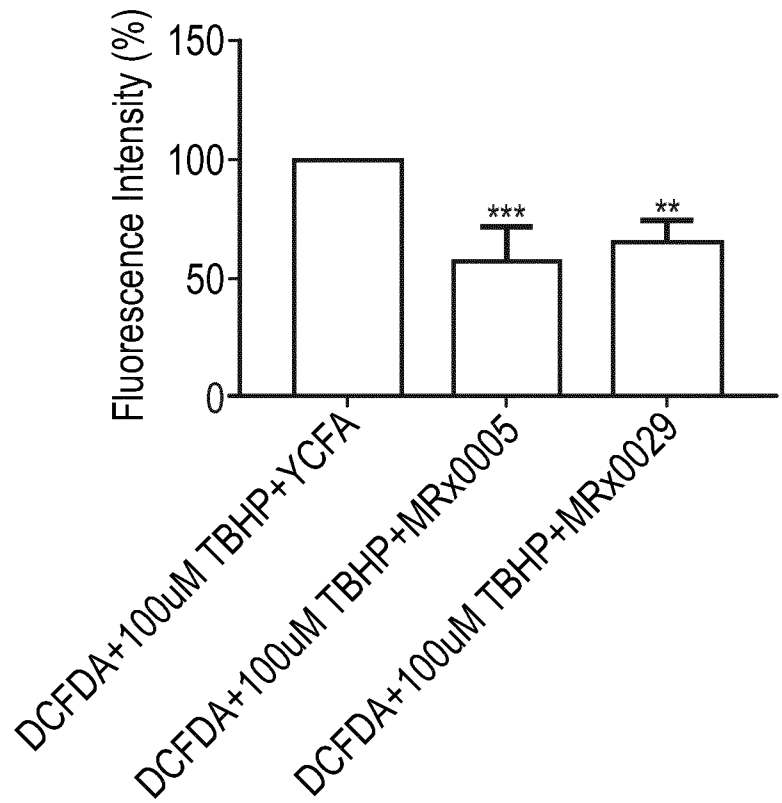


FIG. 11 Neuroprotection – cell viability

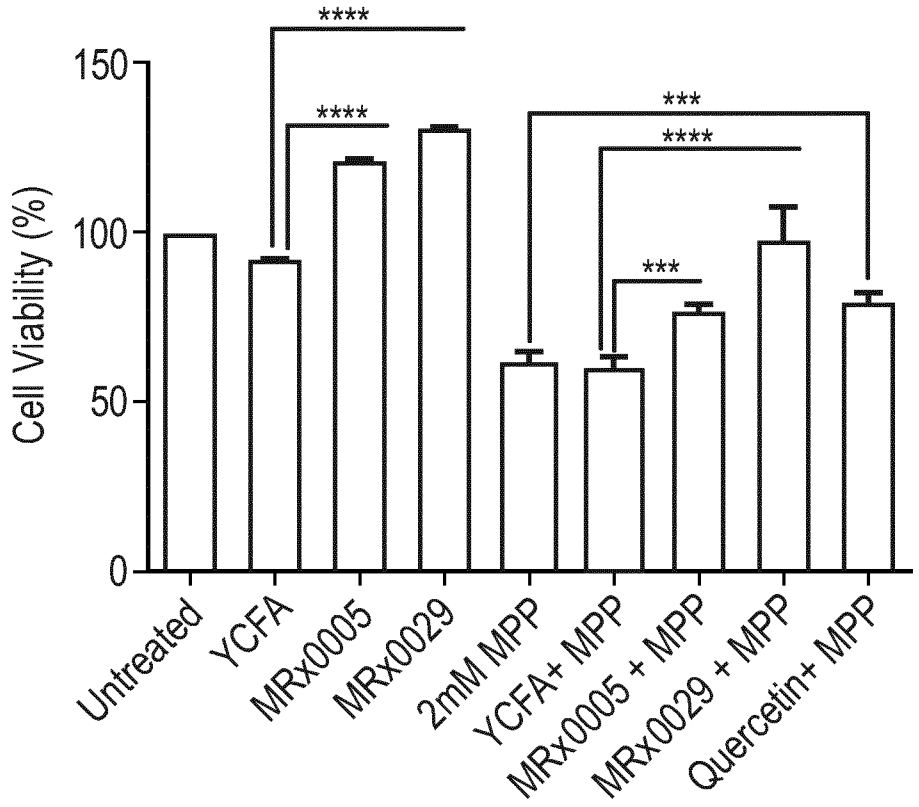


FIG. 12 HDAC activity assay

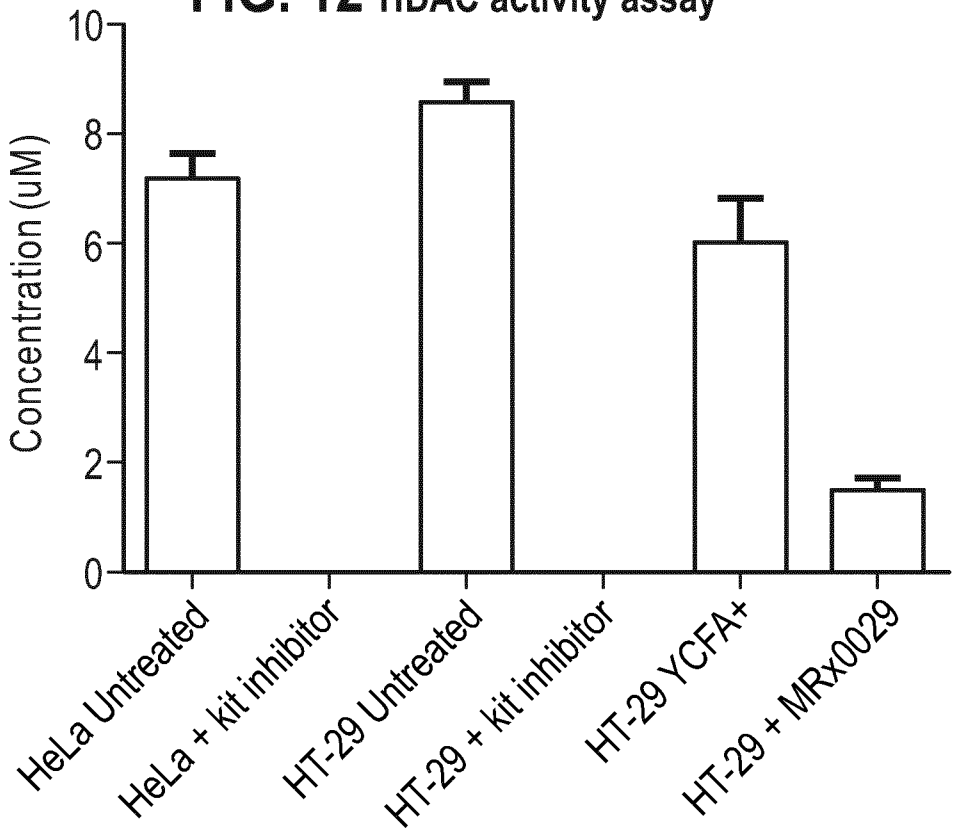


FIG. 13A

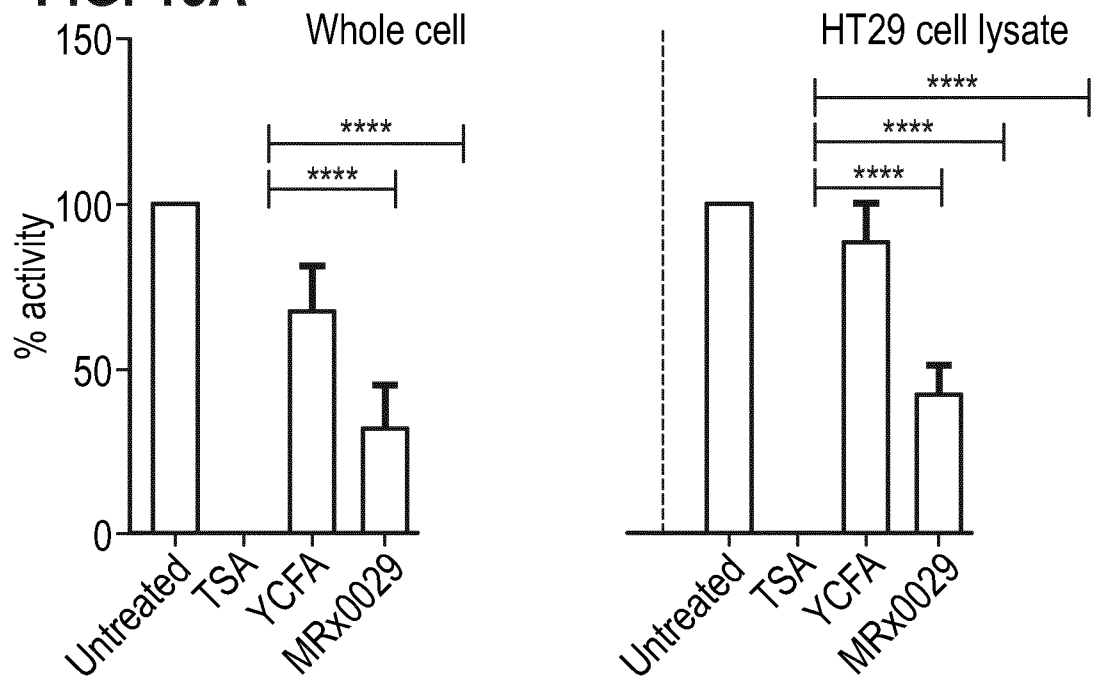


FIG. 13B

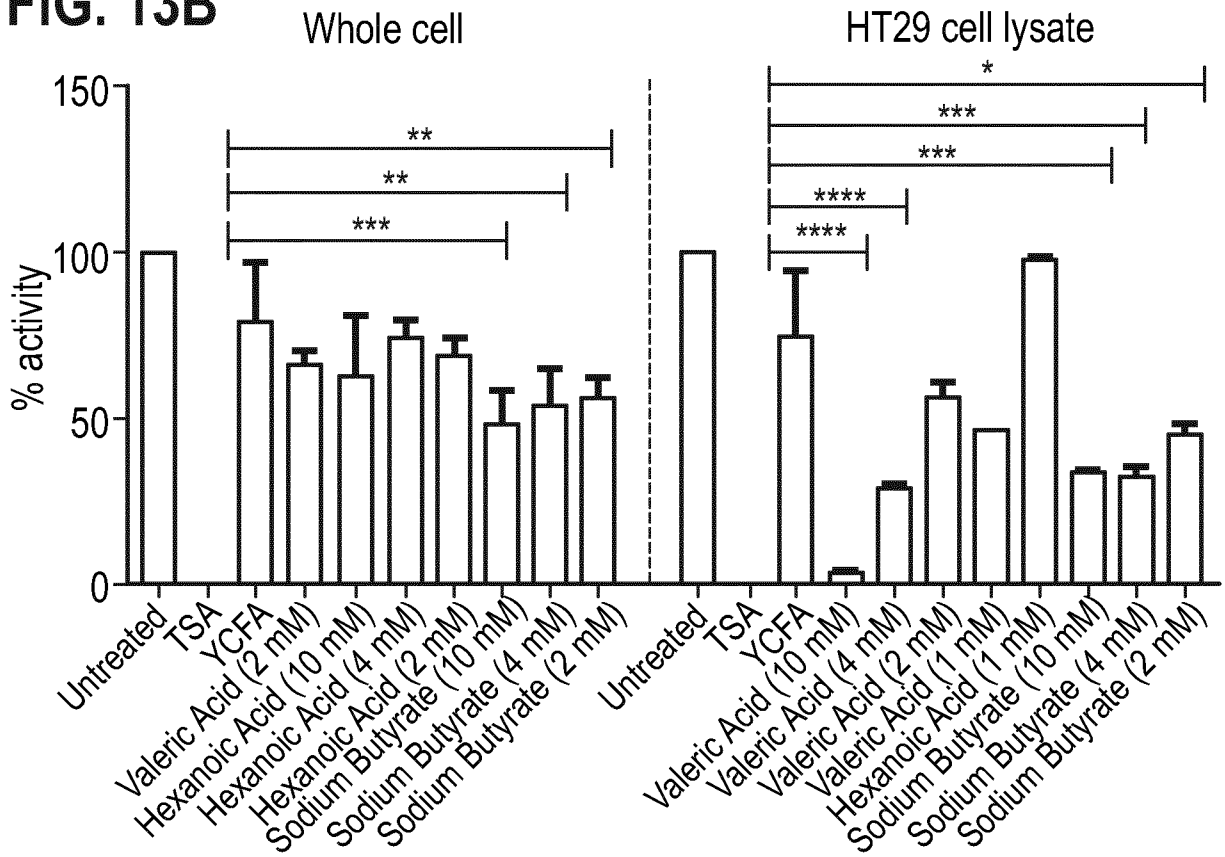
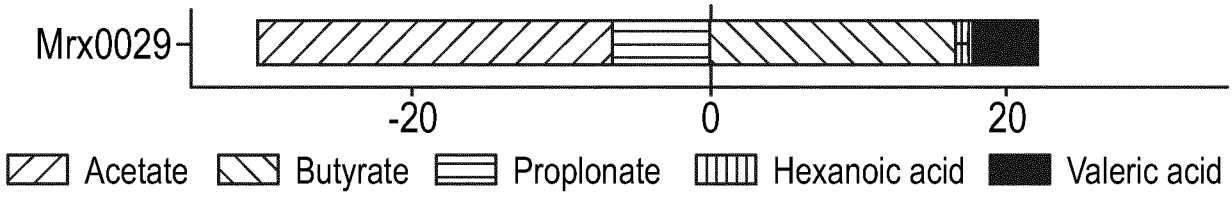


FIG. 13C



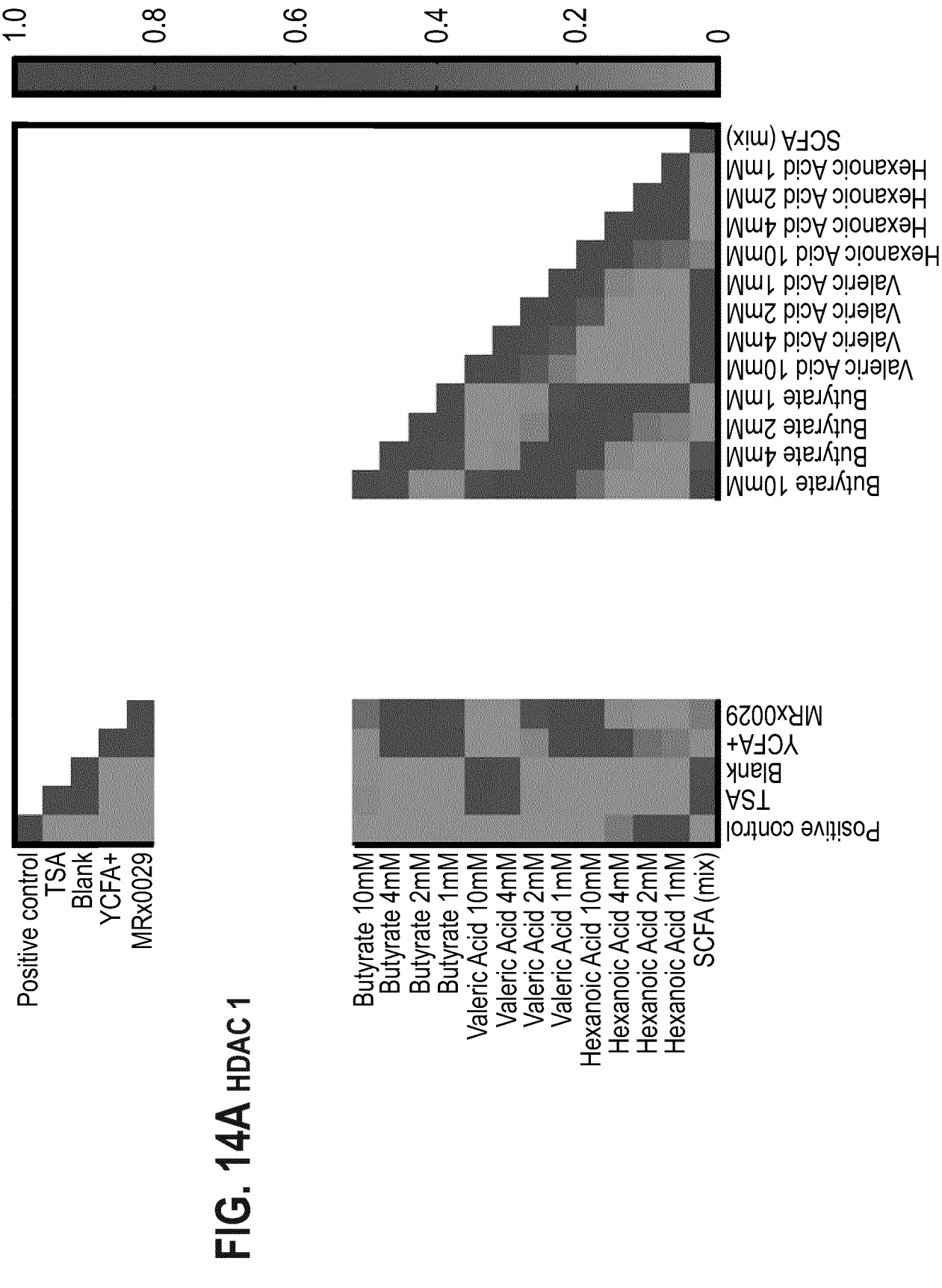


FIG. 14A HDAC 1

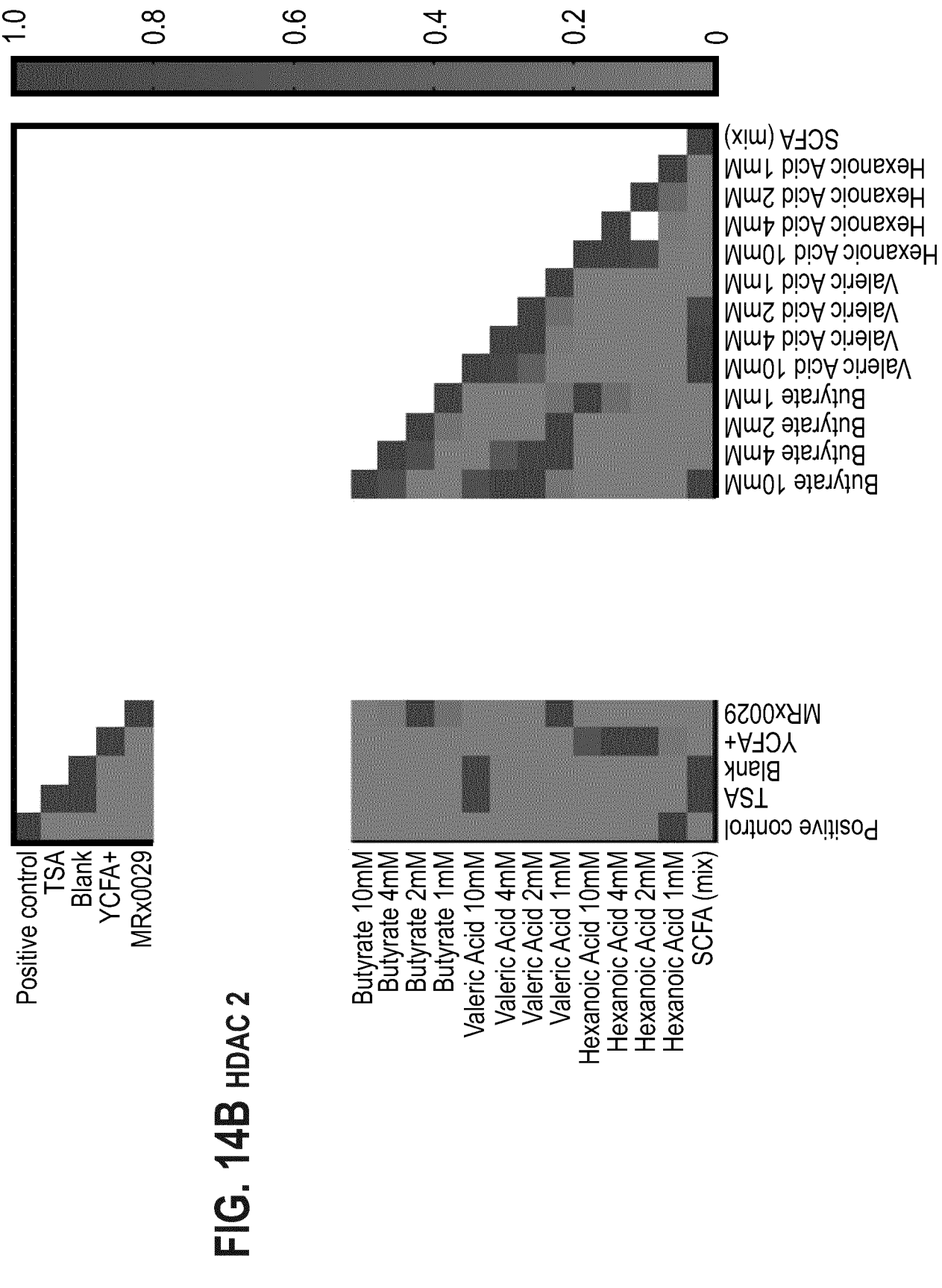


FIG. 14B HDAC 2

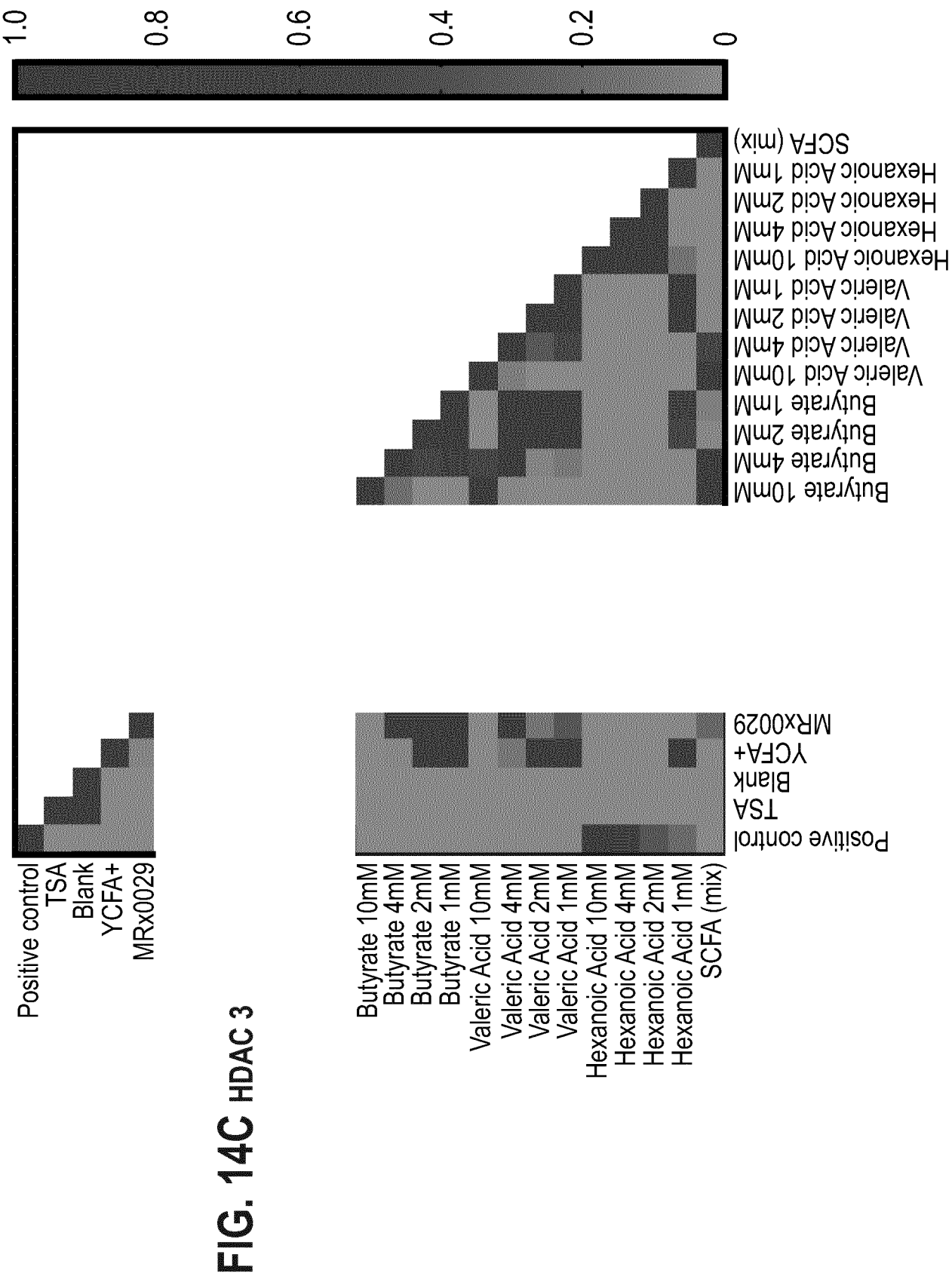


FIG. 14C HDAC 3

FIG. 15A

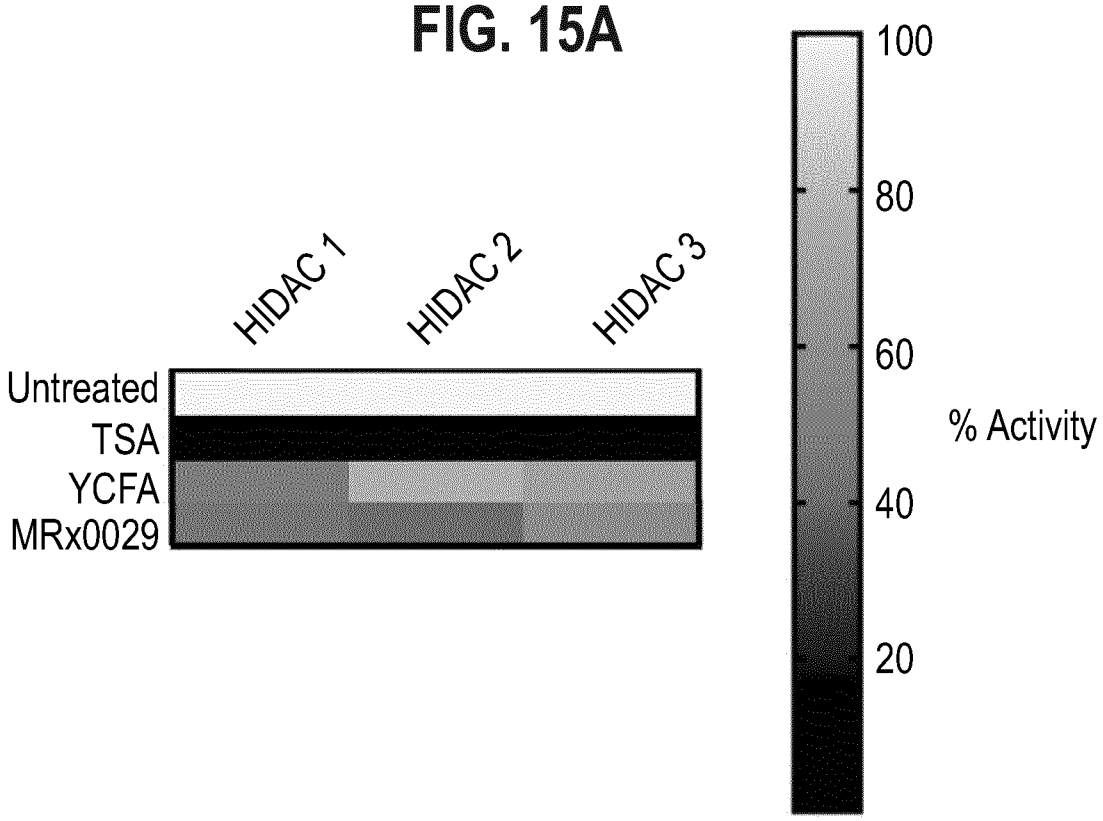


FIG. 15B

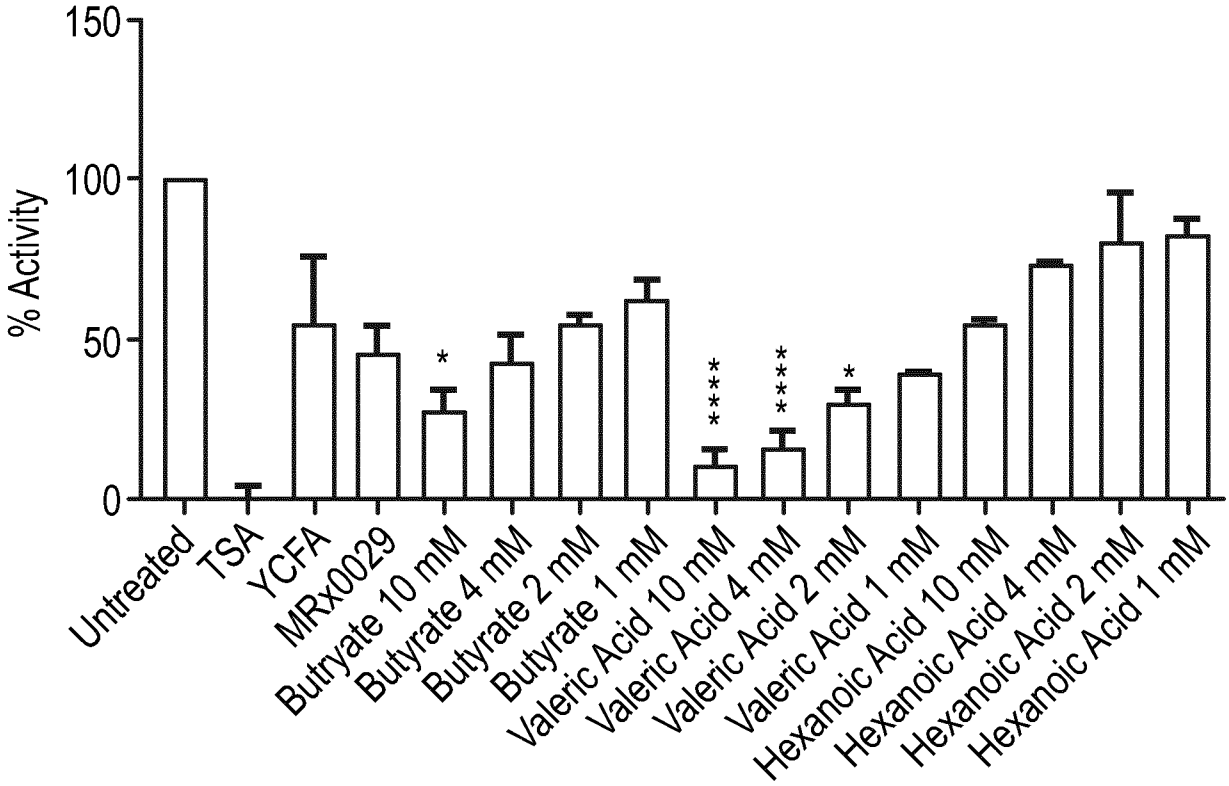


FIG. 15C

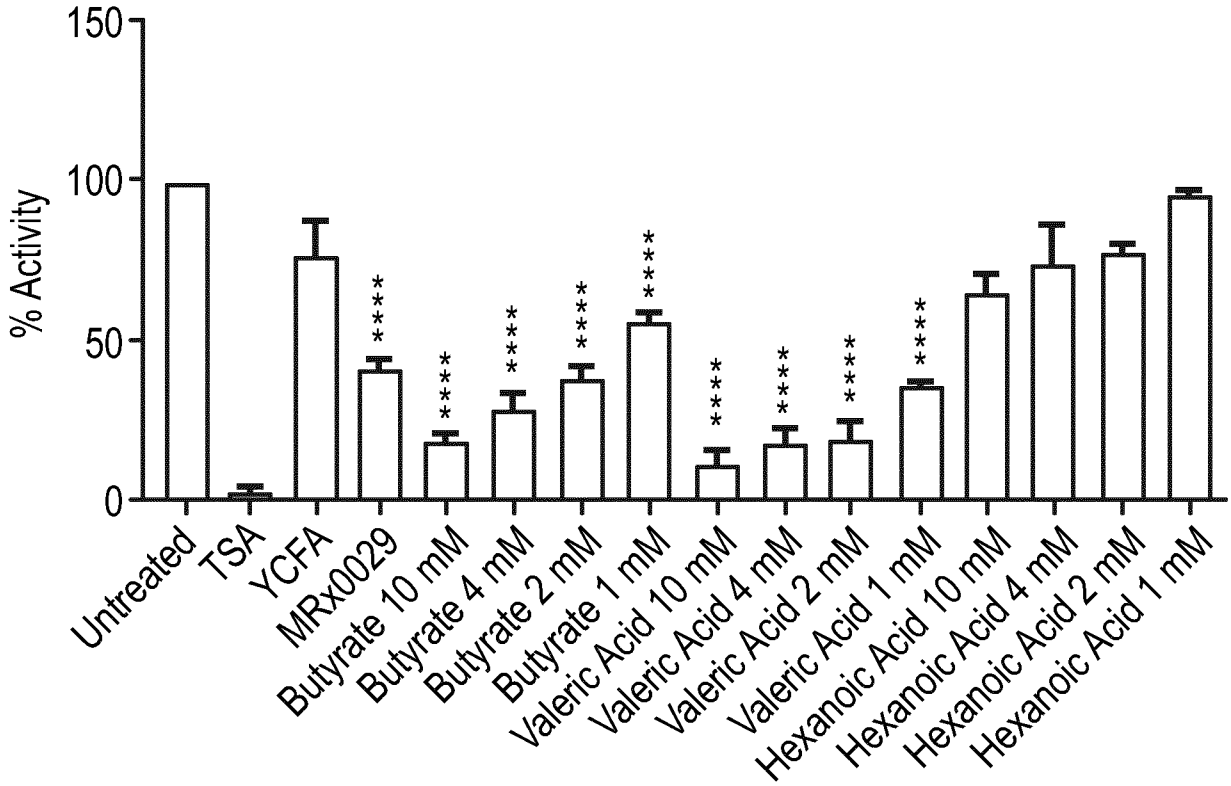
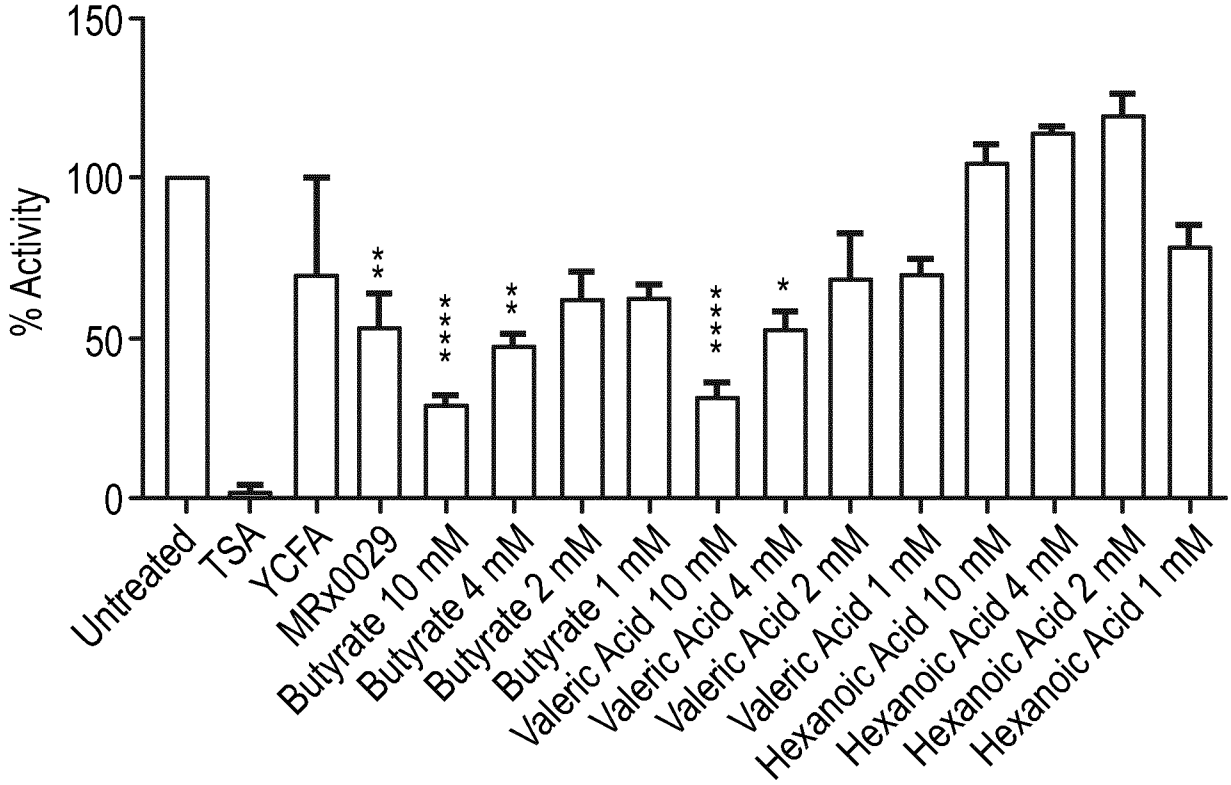


FIG. 15D



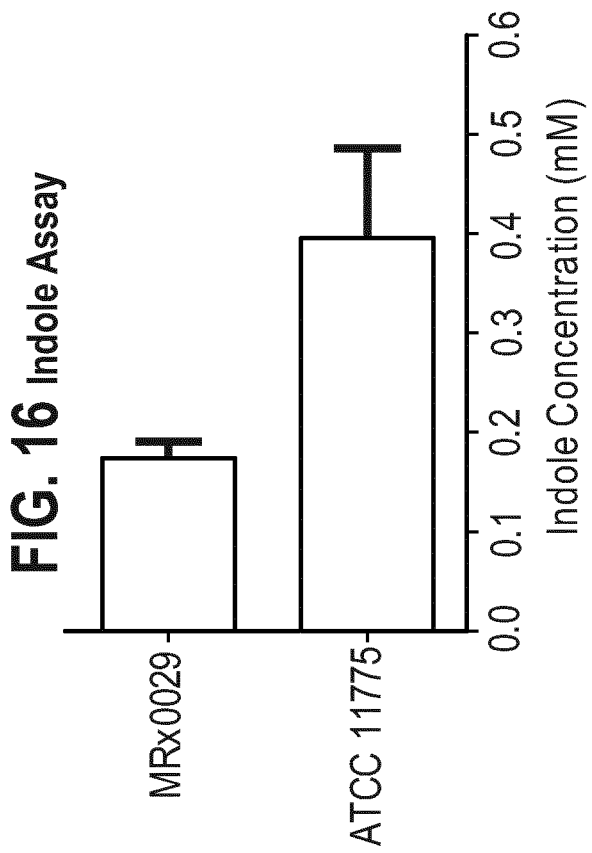


FIG. 16 Indole Assay

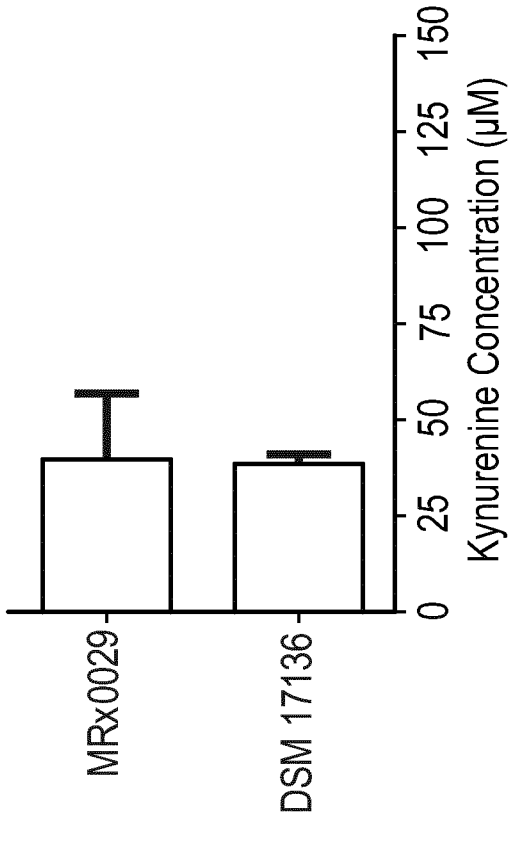


FIG. 17 Kynurenine Assay

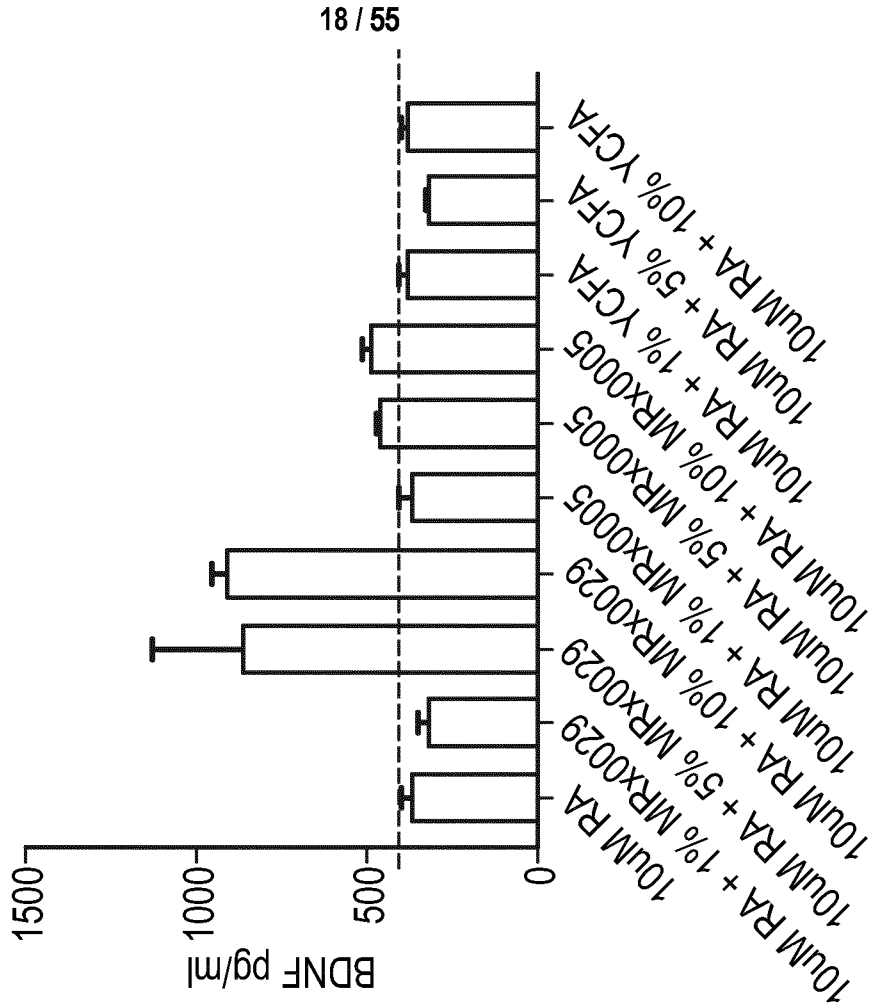


FIG. 18 BDNF secretion from SH-SY-5Y

FIG. 19 Production of neurotransmitters in the brain

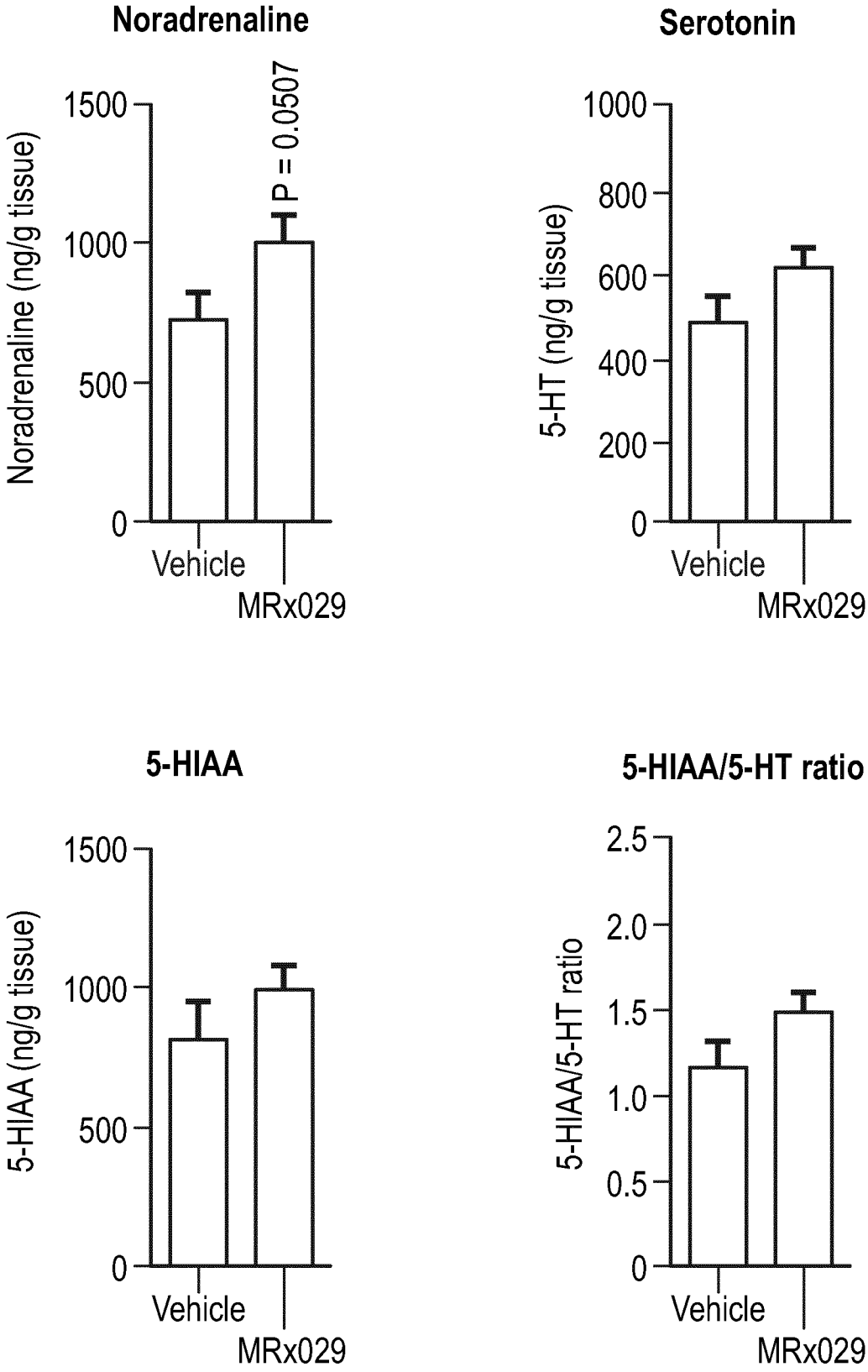


FIG. 20 Bacterial metabolites in the supernatant

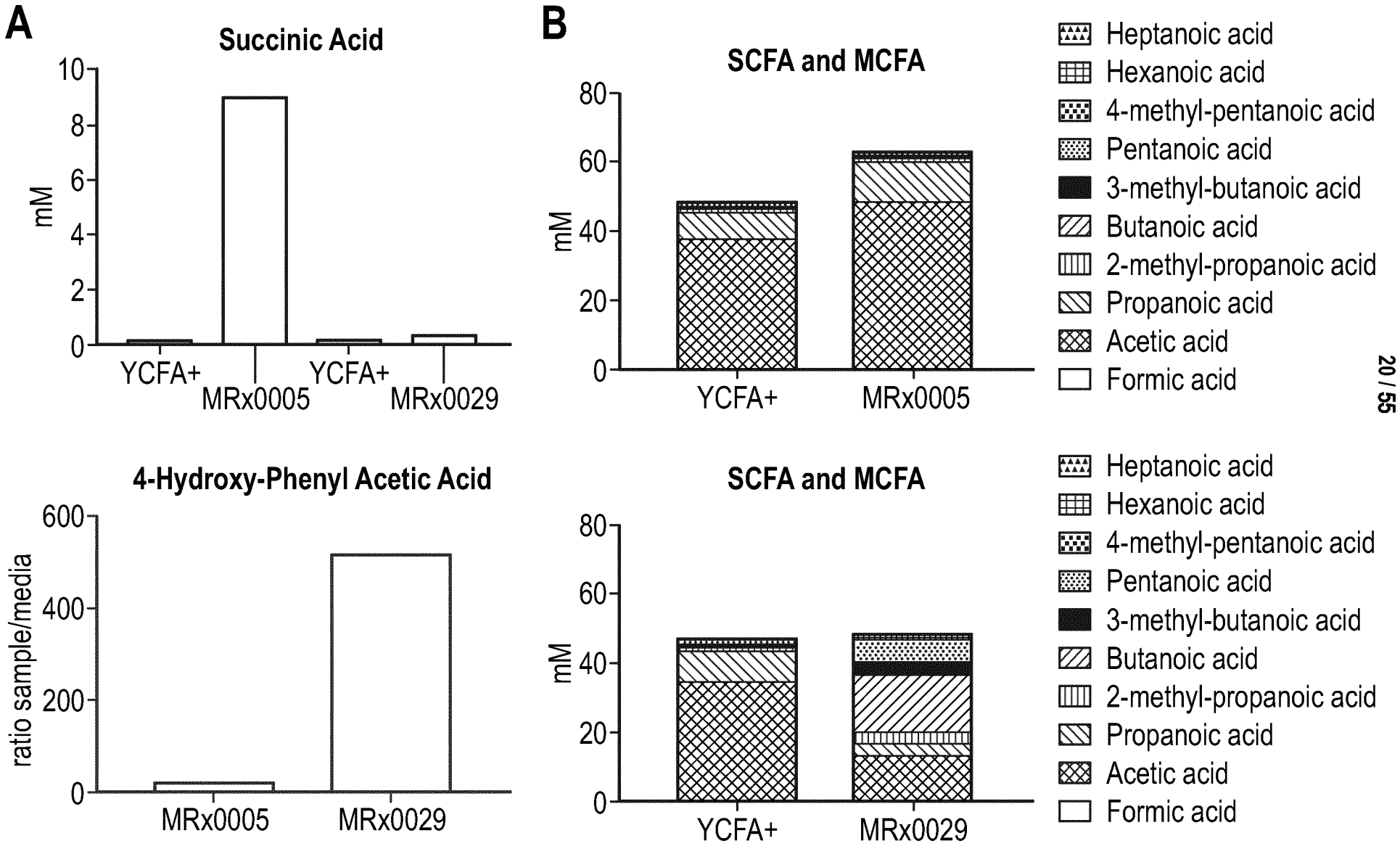


FIG. 21A DA

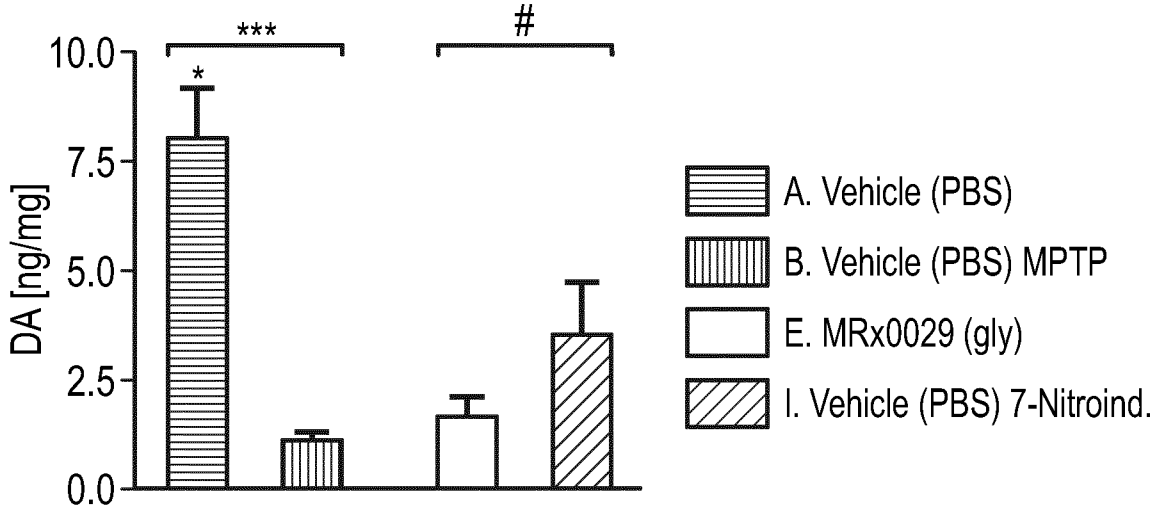


FIG. 21B DOPAC

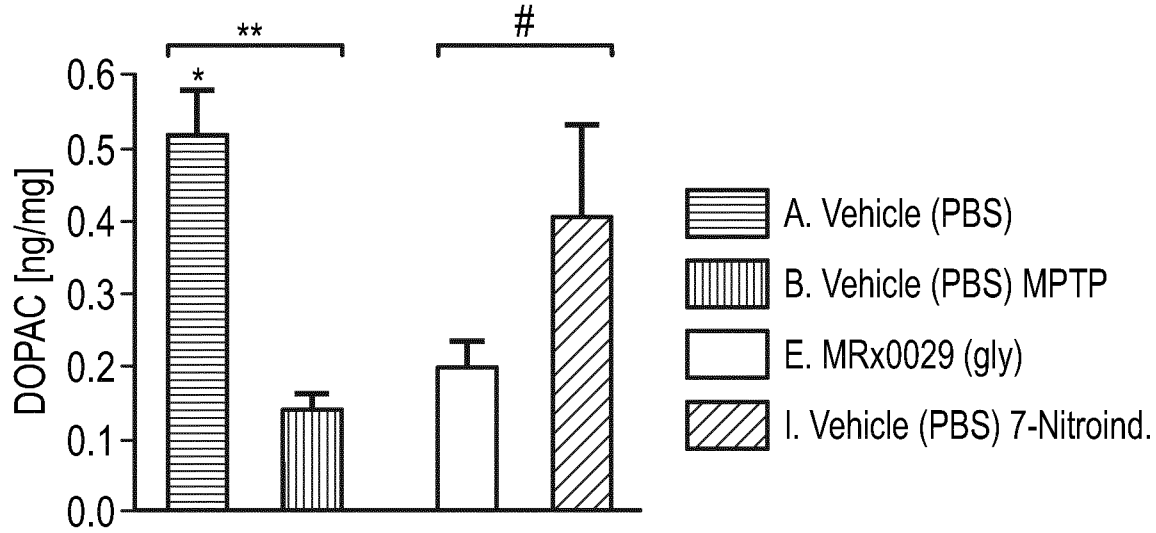


FIG. 21C HVA

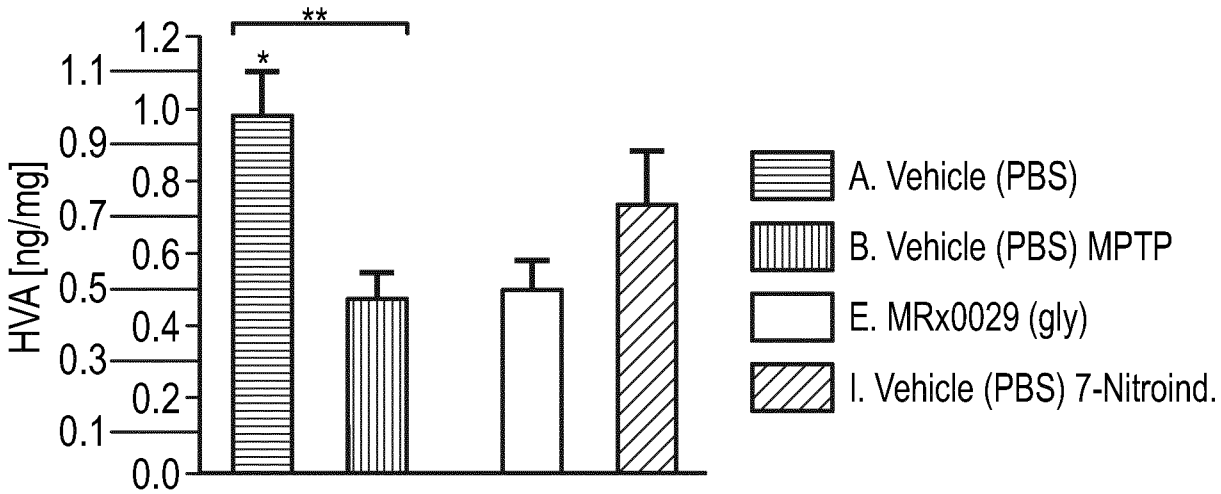
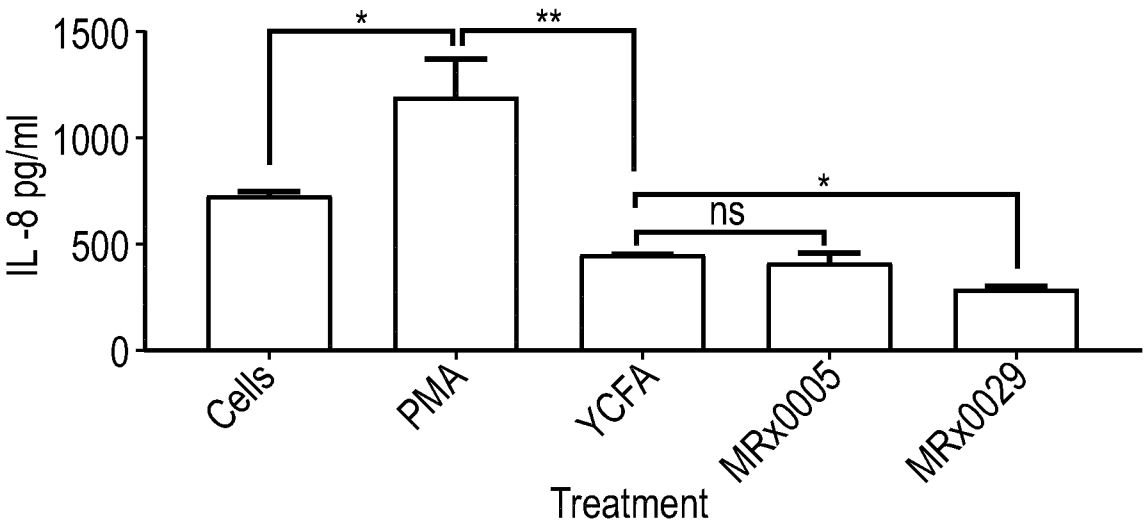


FIG. 22A


1500
1000
500
0
IL -8 pg/ml
*
**
*
ns
Cells
PMA
YCFA
MRx0005
MRx0029
Treatment

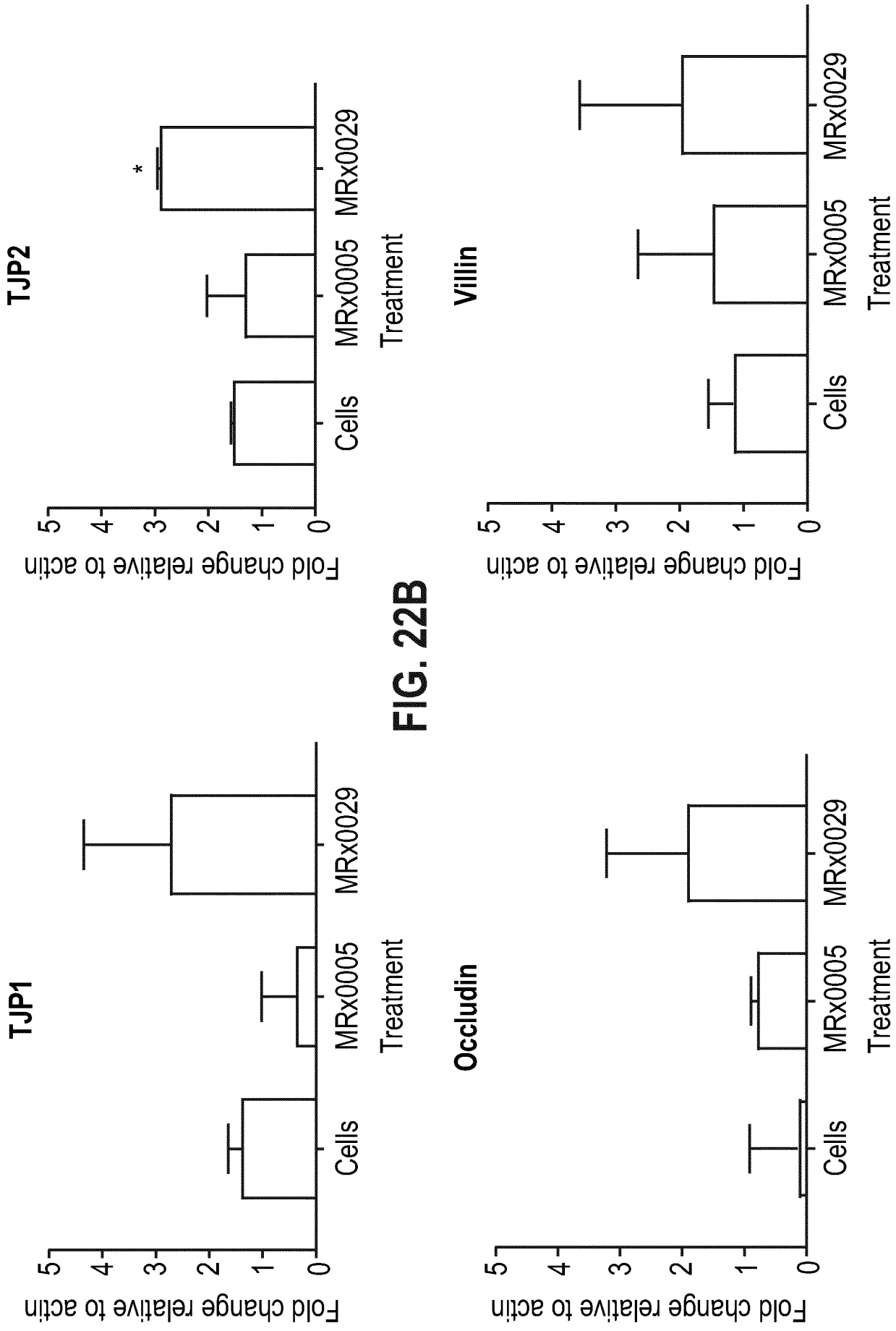

TJP1
Fold change relative to actin
0
1
2
3
4
5
Cells
MRx0005
MRx0029
Treatment
TJP2
*
Villin
Occludin

FIG. 22B

FIG. 22C

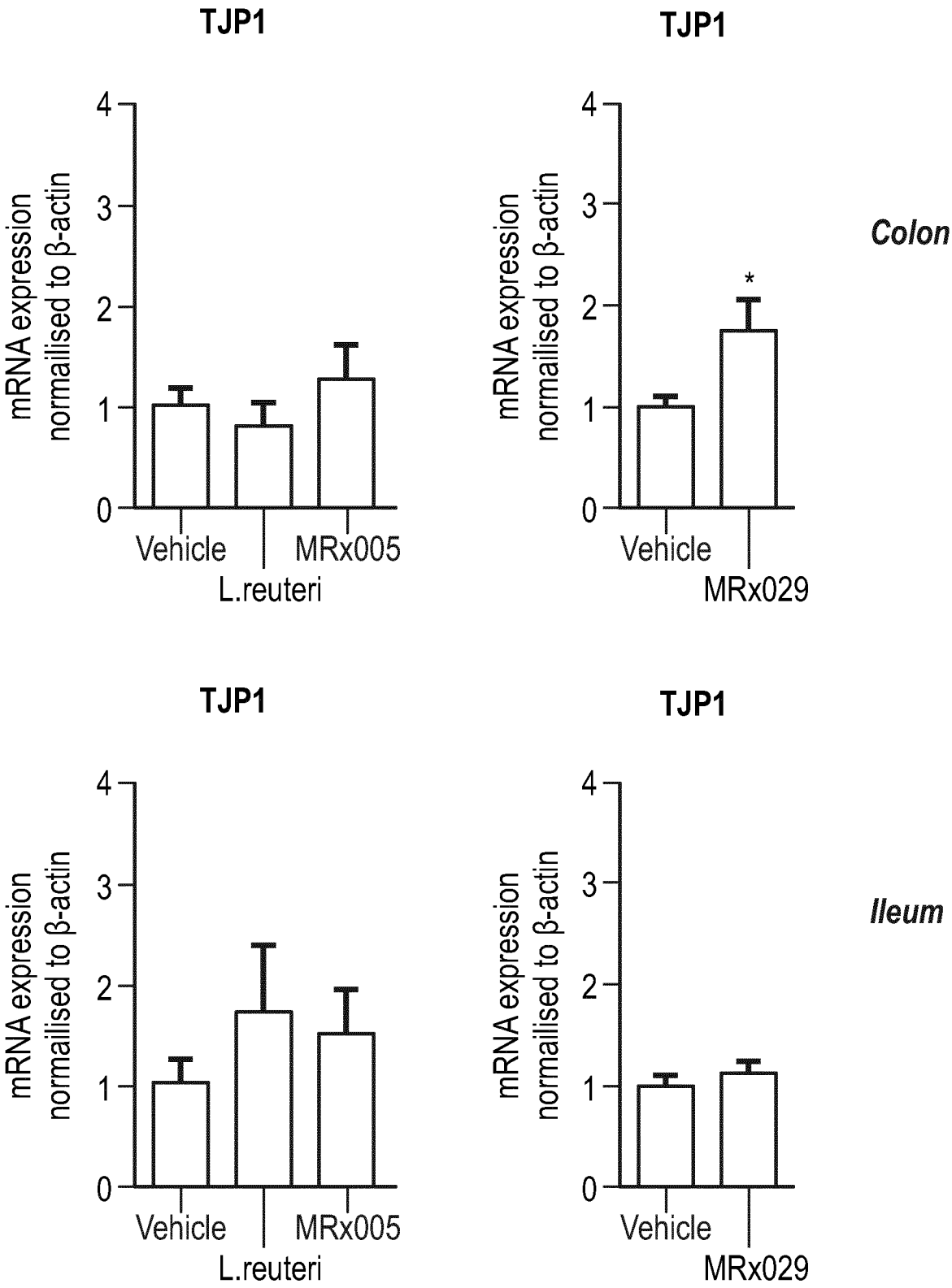

TJP1
mRNA expression normalised to β-actin
4
3
2
1
0
Vehicle
MRx005
L.reuteri
TJP1
mRNA expression normalised to β-actin
*
Vehicle
MRx029
Colon
TJP1
mRNA expression normalised to β-actin
Vehicle
MRx005
L.reuteri
TJP1
mRNA expression normalised to β-actin
Vehicle
MRx029
Ileum

FIG. 22D

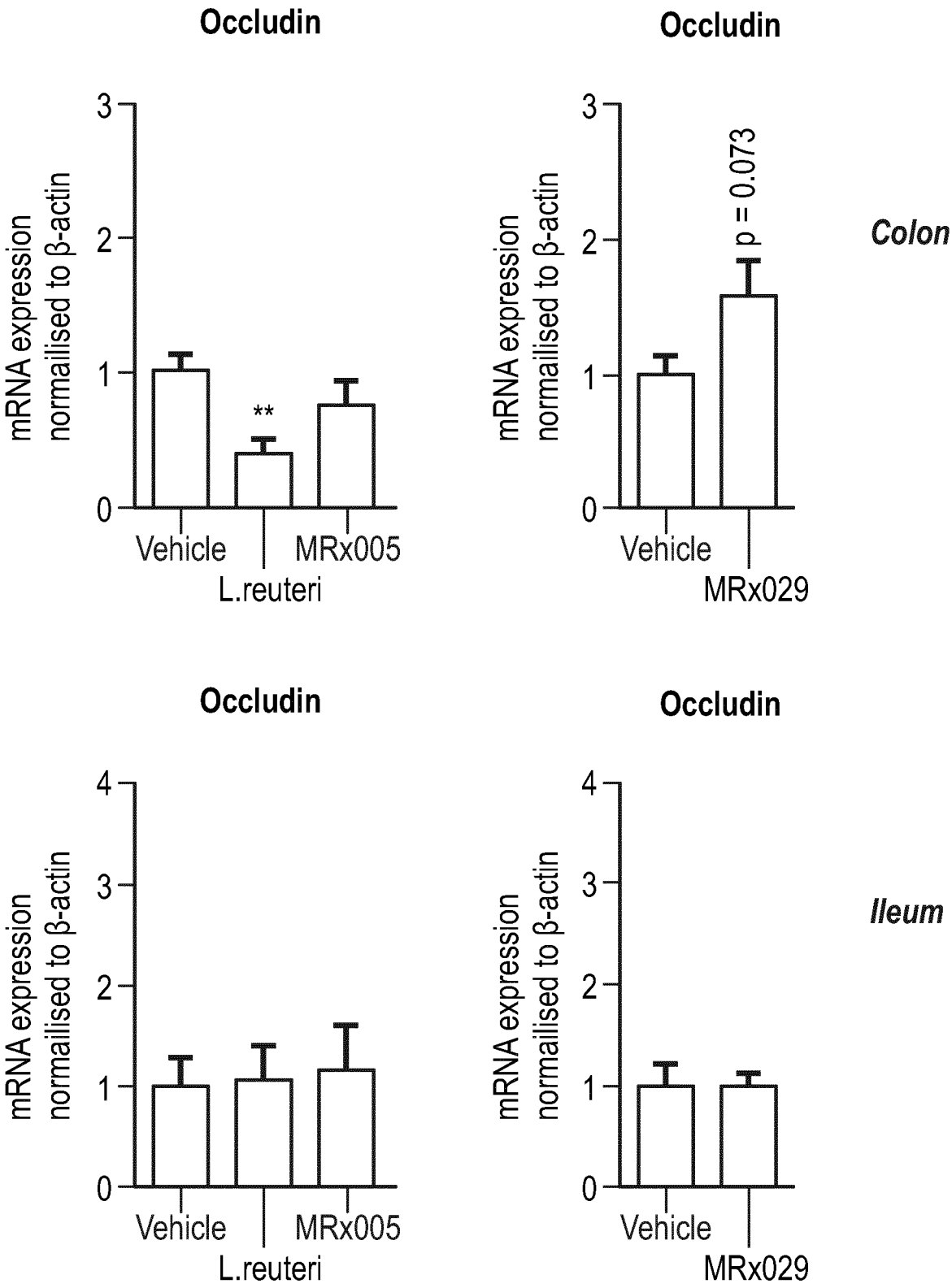
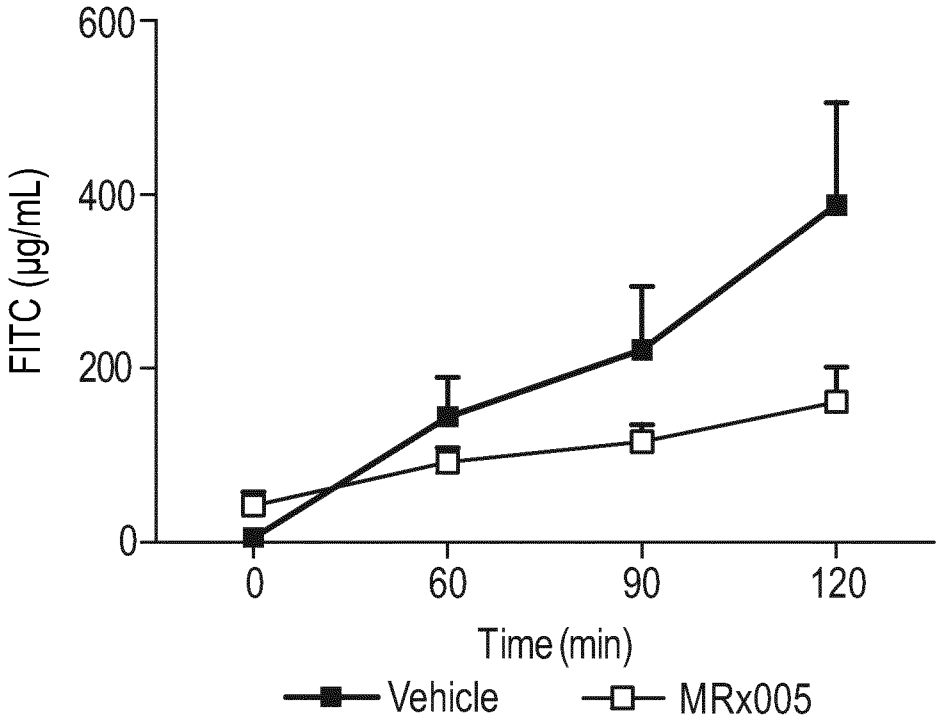

Occludin
mRNA expression normalised to β-actin
3
2
1
0
**
Vehicle
MRx005
L.reuteri
Occludin
mRNA expression normalised to β-actin
p = 0.073
Vehicle
MRx029
Colon
Occludin
mRNA expression normalised to β-actin
4
3
2
1
0
Vehicle
MRx005
L.reuteri
Occludin
mRNA expression normalised to β-actin
Vehicle
MRx029
Ileum

FIG. 22E Permeability in the Ileum



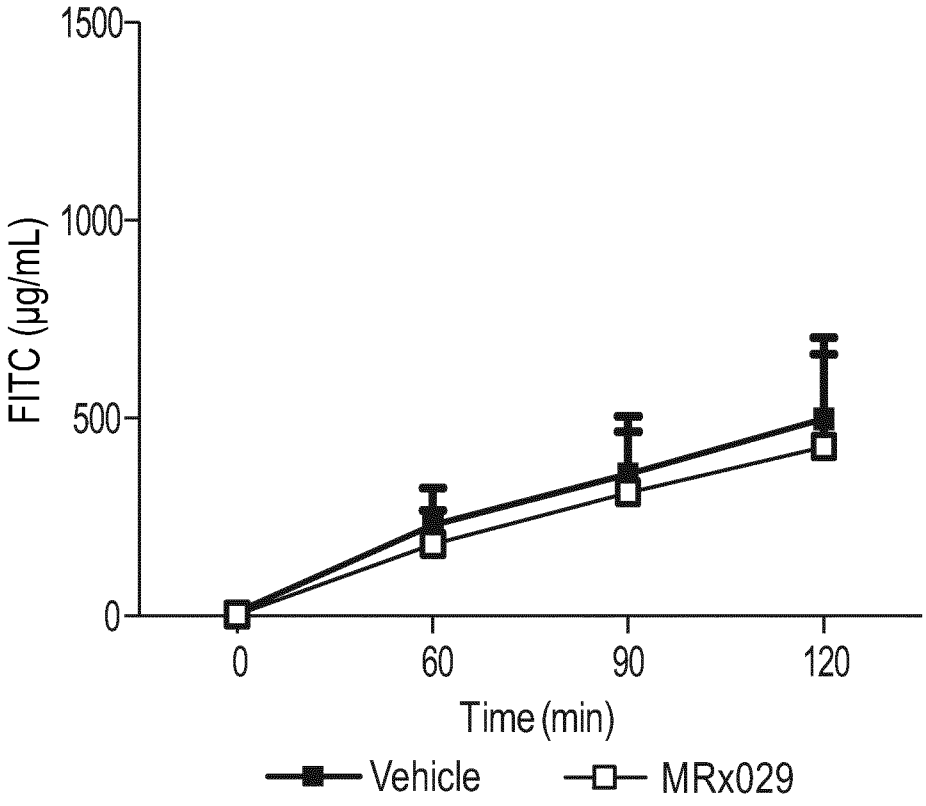
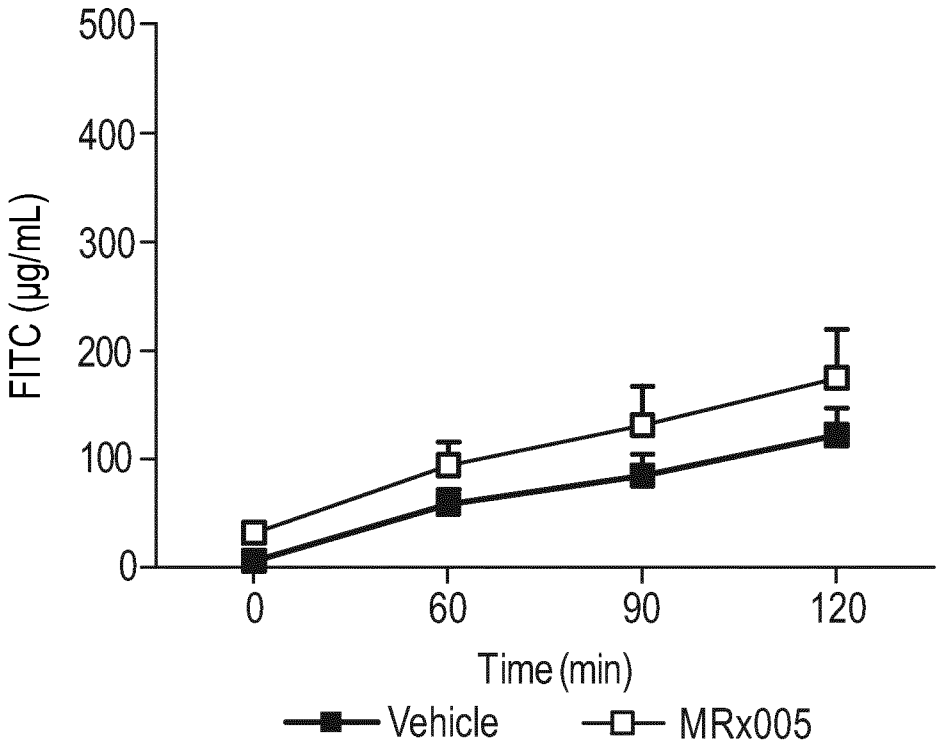
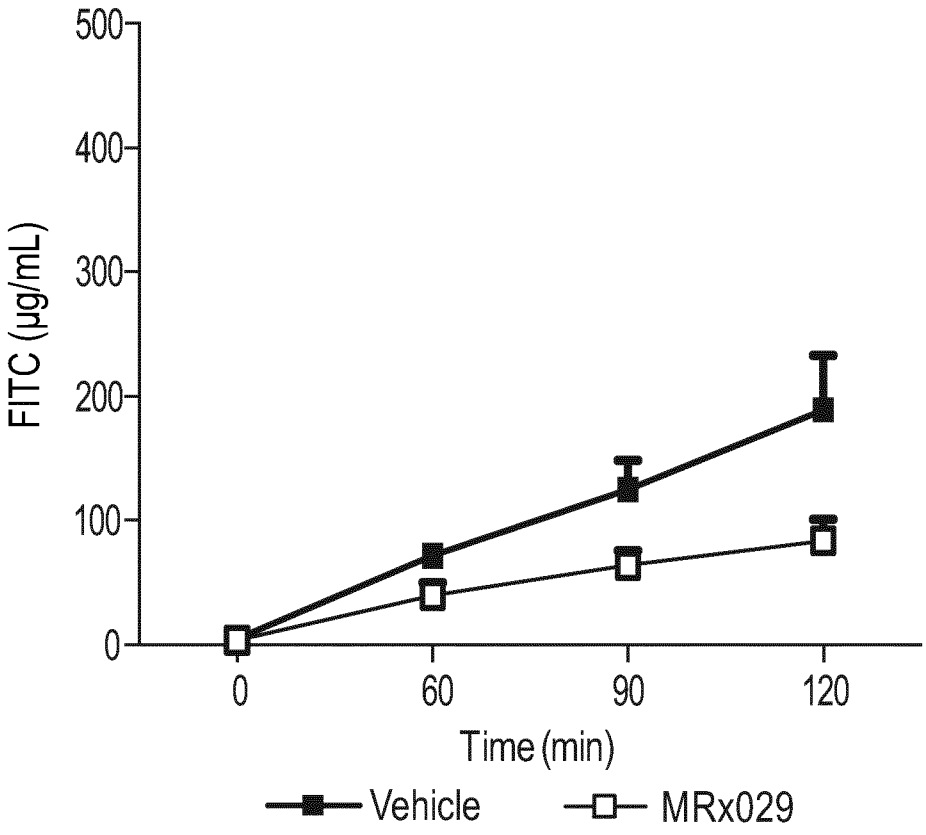


FIG. 22F Permeability in the colon





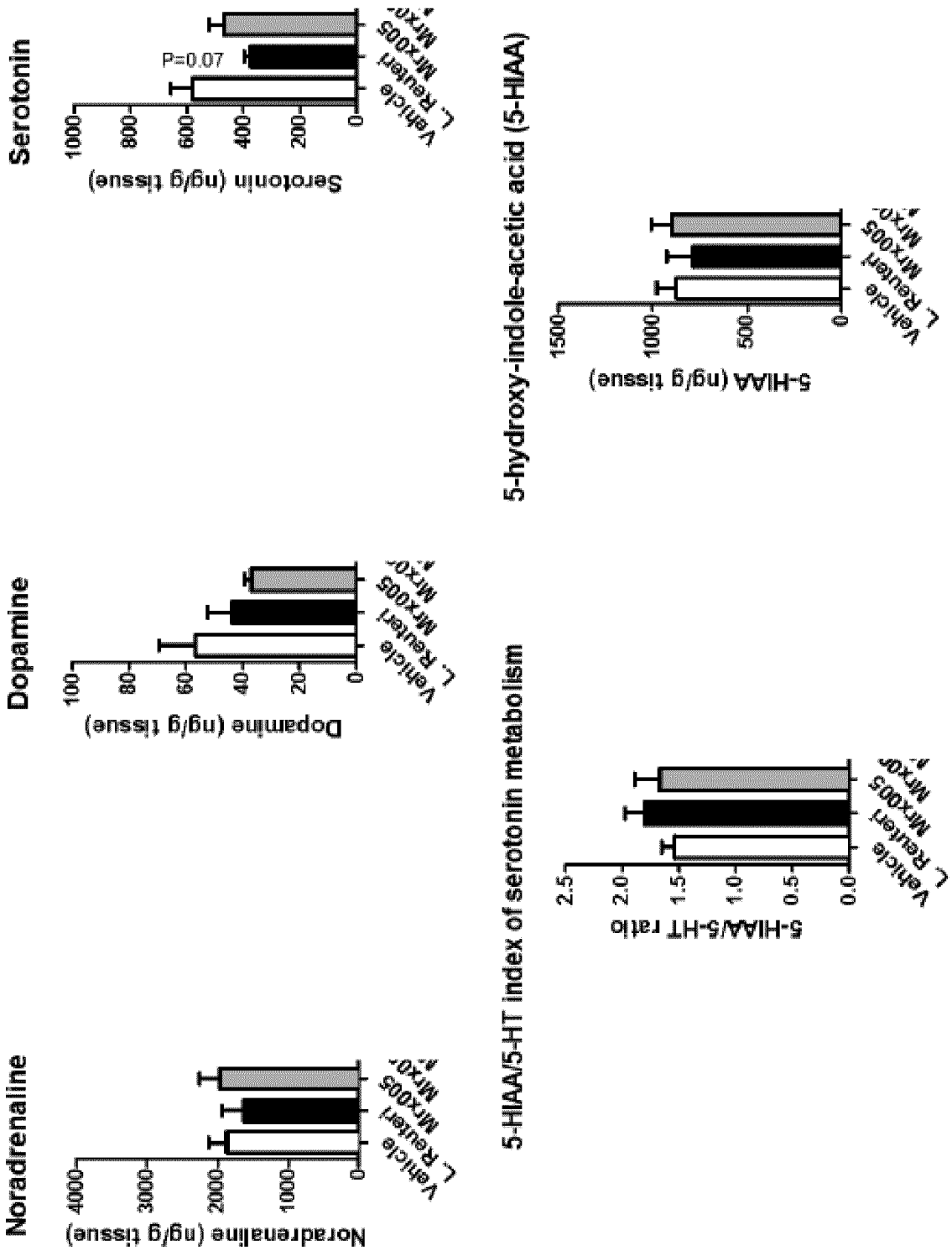
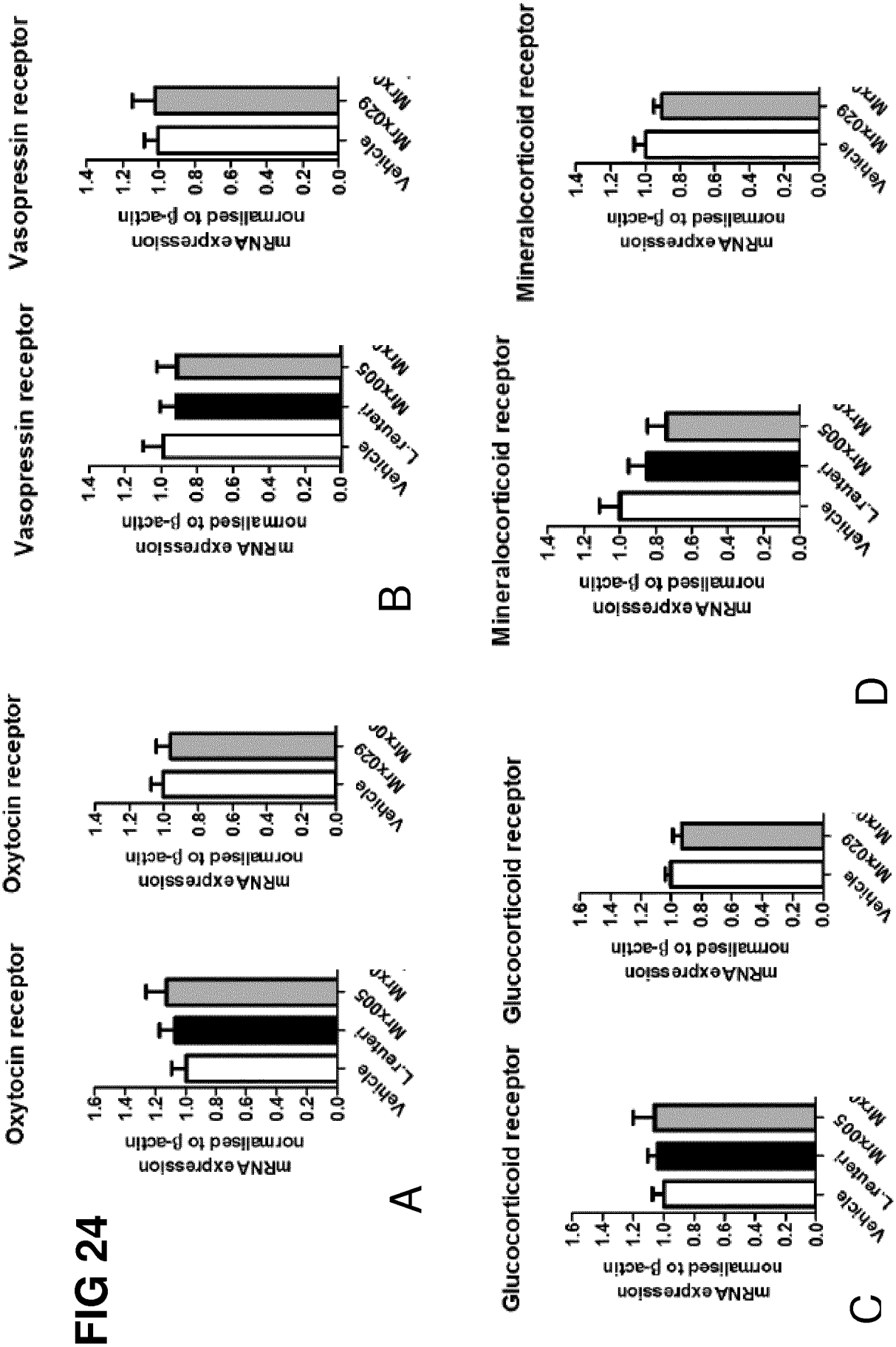

Noradrenaline
Noradrenaline (ng/g tissue)
4000
3000
2000
1000
0
Vehicle
L. Reuteri
MRx005
Dopamine
Dopamine (ng/g tissue)
100
80
60
40
20
0
Serotonin
Serotonin (ng/g tissue)
P=0.07
1000
800
600
400
200
0
5-HIAA/5-HT index of serotonin metabolism
5-HIAA/5-HT ratio
2.5
2.0
1.5
1.0
0.5
0.0
5-hydroxy-indole-acetic acid (5-HIAA)
5-HIAA (ng/g tissue)
1500
1000
500
0

FIG 23

FIG 24


Oxytocin receptor
Oxytocin receptor
Vasopressin receptor
Vasopressin receptor
Mineralocorticoid receptor
Mineralocorticoid receptor
Glucocorticoid receptor
Glucocorticoid receptor
mRNA expression
normalised to β-actin
Vehicle
L-reuteri
MRx005
MRxF
MRx029
MRx0F
A
B
C
D

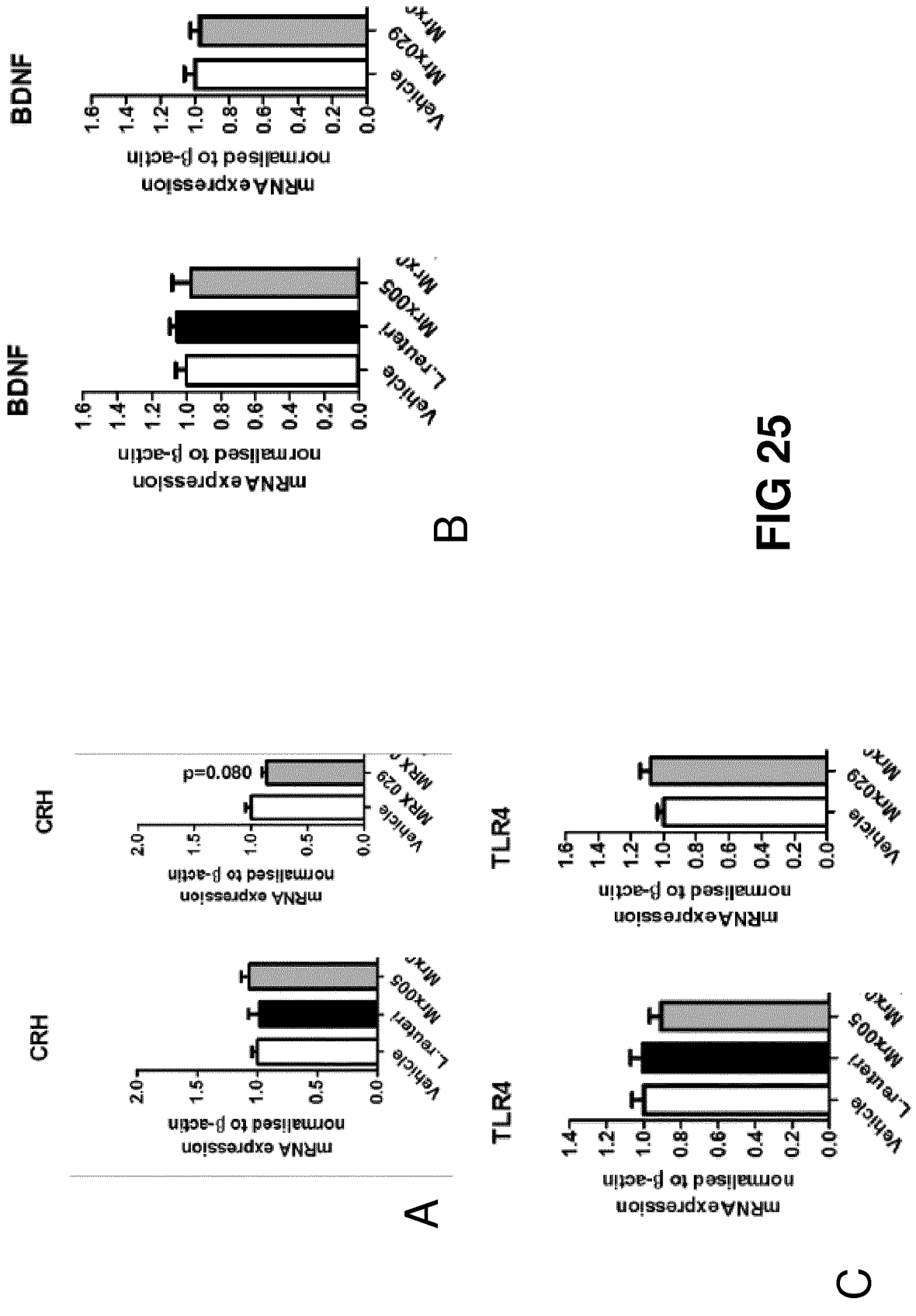

A
CRH
mRNA expression
normalised to β-actin
2.0
1.5
1.0
0.5
0.0
Vehicle
L_reuteri
MrX005
MrXF
CRH
p=0.080
Vehicle
MRX 029
MRX
TLR4
mRNAexpression
normalised to β-actin
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Vehicle
L_reuteri
MrX005
MrXF
TLR4
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Vehicle
MrX029
MrXF
B
BDNF
mRNA expression
normalised to β-actin
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Vehicle
L_reuteri
MrX005
MrXF
BDNF
mRNAexpression
normalised to β-actin
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Vehicle
MrX029
MrXF
C

FIG 25

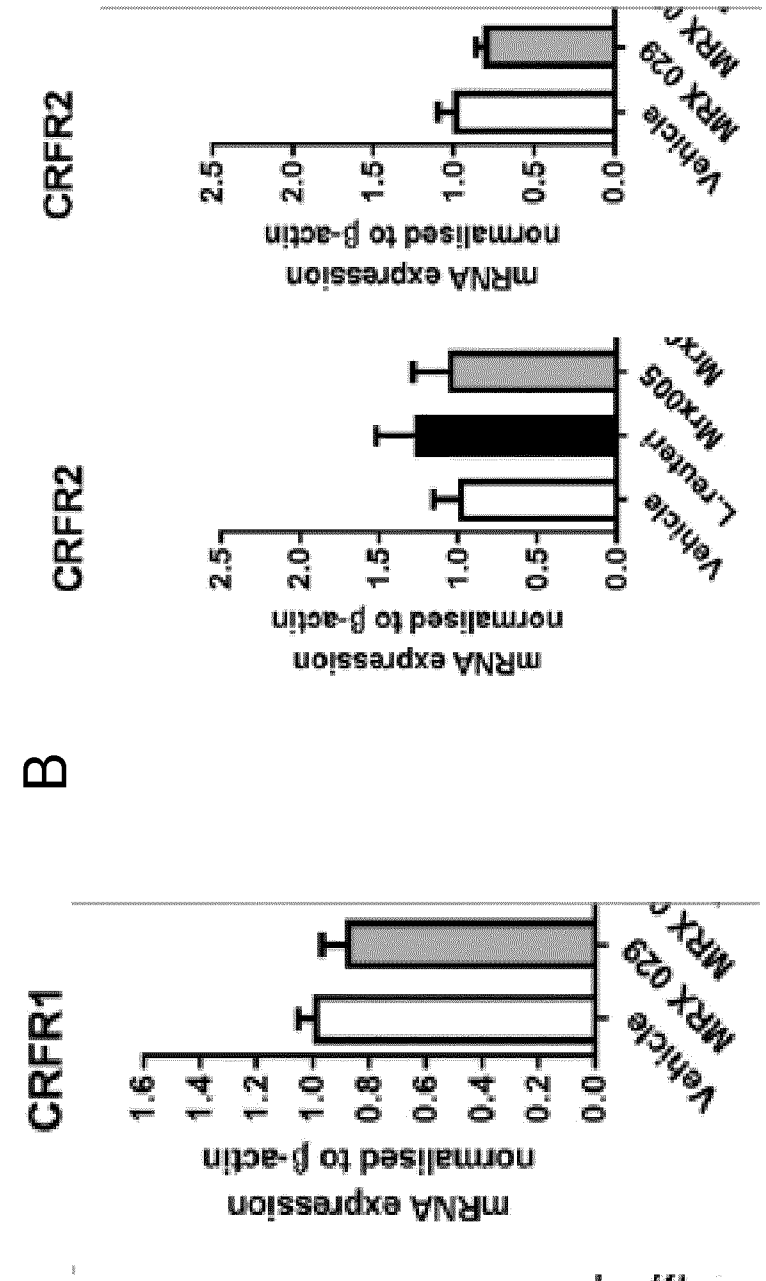

A
CRFR1
mRNA expression
normalised to β-actin
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Vehicle
L_feuteri
MRx005
MRx
CRFR1
mRNA expression
normalised to β-actin
Vehicle
MRX 029
MRX
B
CRFR2
mRNA expression
normalised to β-actin
2.5
2.0
1.5
1.0
0.5
0.0
Vehicle
L_feuteri
MRx005
MRx
CRFR2
mRNA expression
normalised to β-actin
Vehicle
MRX 029
MRX

FIG 26

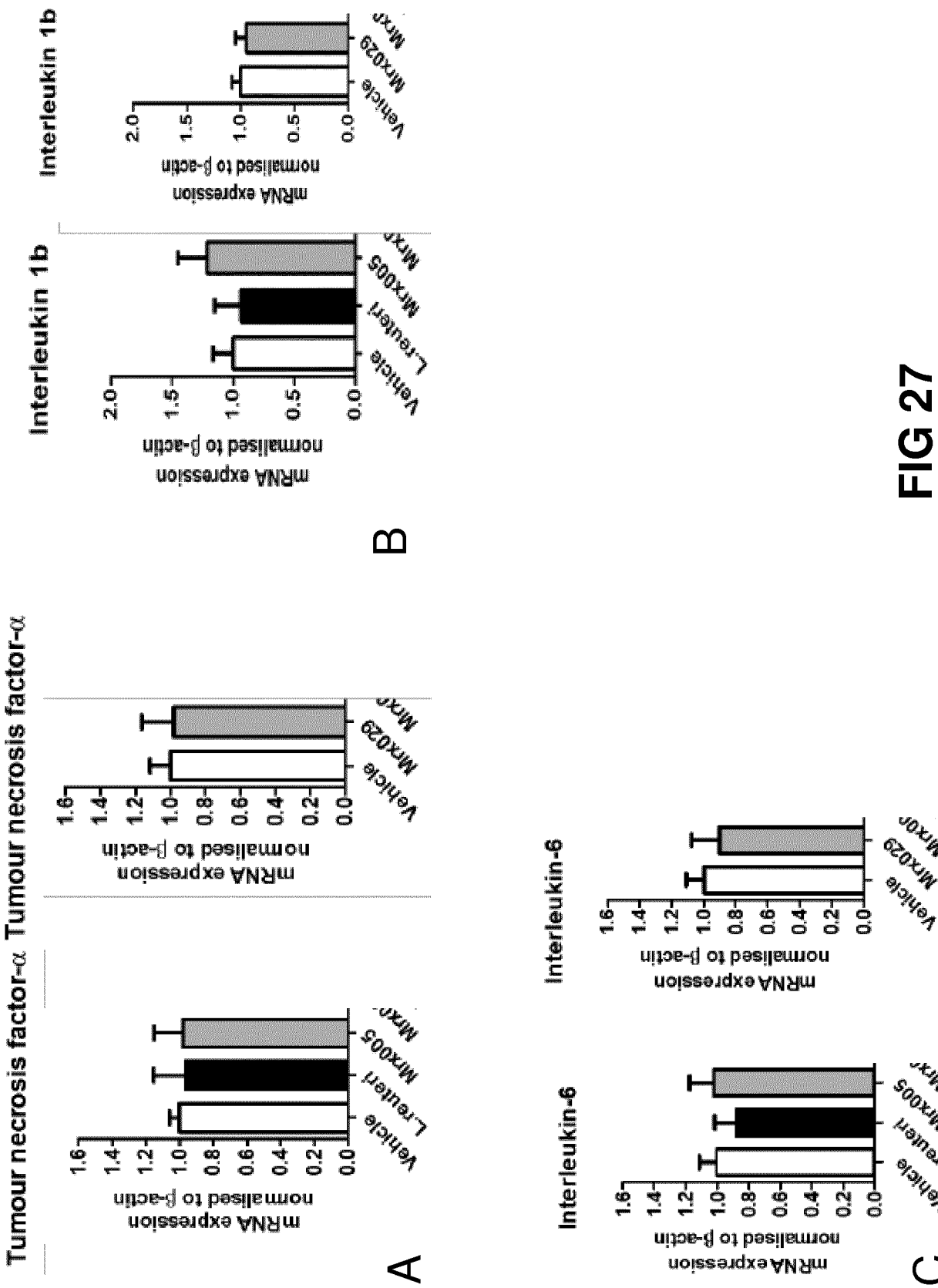

Tumour necrosis factor-α
mRNA expression normalised to β-actin
Vehicle
Mrx029
Mrx
A
Tumour necrosis factor-α
mRNA expression normalised to β-actin
Vehicle
L-feuleri
Mrx005
Mrx
B
Interleukin 1b
mRNA expression normalised to β-actin
Vehicle
Mrx029
Mrx
Interleukin 1b
mRNA expression normalised to β-actin
Vehicle
L-feuleri
Mrx005
Mrx
Interleukin-6
mRNA expression normalised to β-actin
Vehicle
Mrx029
Mrx
Interleukin-6
mRNA expression normalised to β-actin
Vehicle
L-feuleri
Mrx005
Mrx
C

FIG 27

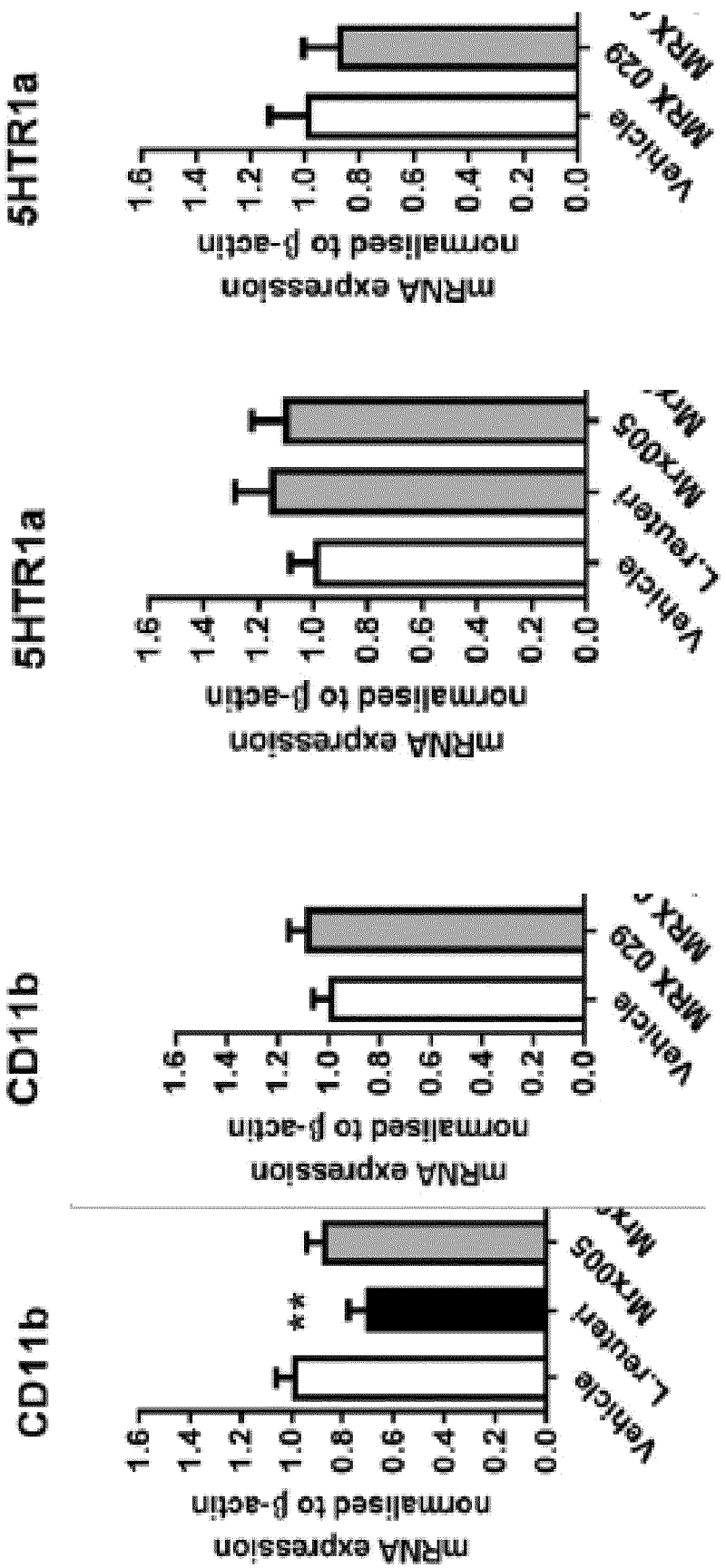

CD11b
mRNA expression
normalised to β-actin
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
**
Vehicle
L-reuteri
MrX005
MrX
A
CD11b
mRNA expression
normalised to β-actin
Vehicle
MRX 029
MRX
5HTR1a
mRNA expression
normalised to β-actin
Vehicle
L-reuteri
MrX005
MrX
B
5HTR1a
mRNA expression
normalised to β-actin
Vehicle
MRX 029
MRX

FIG 28

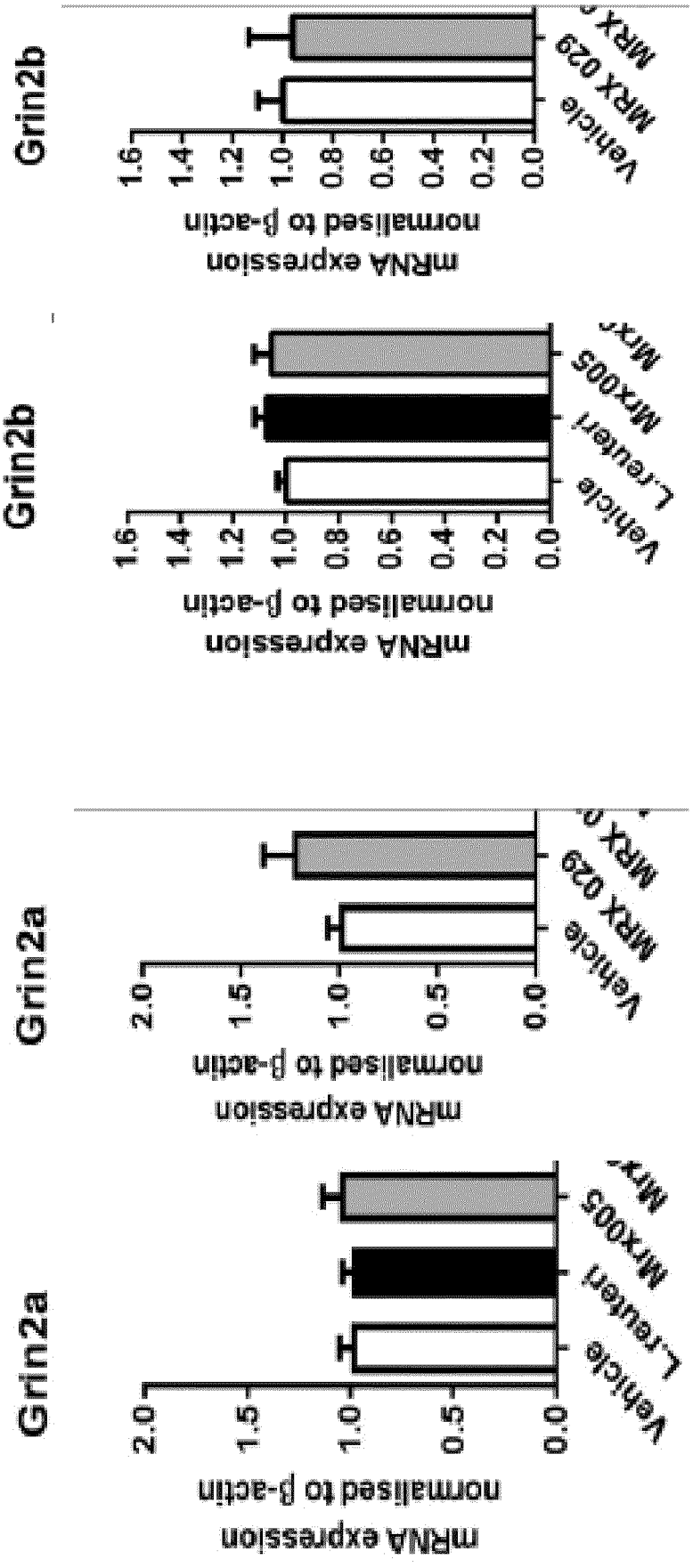

Grin2a
mRNA expression
normalised to β-actin
2.0
1.5
1.0
0.5
0.0
Vehicle
L-reuteri
MRx005
MRx
Grin2a
mRNA expression
normalised to β-actin
2.0
1.5
1.0
0.5
0.0
Vehicle
MRX 029
MRX
A
Grin2b
mRNA expression
normalised to β-actin
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Vehicle
L-reuteri
MRx005
MRx
Grin2b
mRNA expression
normalised to β-actin
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Vehicle
MRX 029
MRX
B

FIG 29

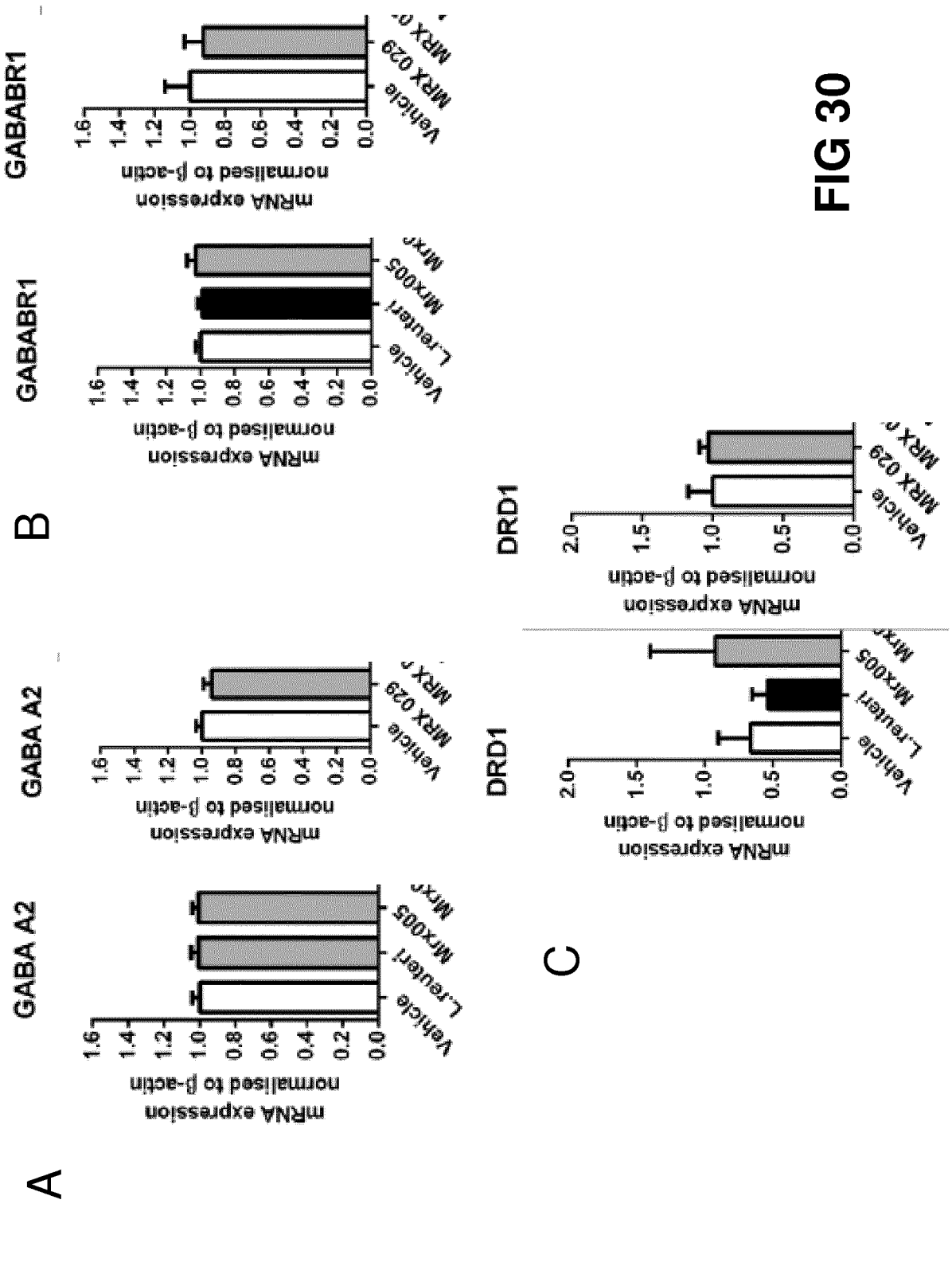

A
GABA A2
mRNA expression
normalised to β-actin
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Vehicle
L-reuteri
MRX005
MRX
GABA A2
mRNA expression
normalised to β-actin
Vehicle
MRX 029
MRX
B
GABABR1
mRNA expression
normalised to β-actin
Vehicle
L-reuteri
MRX005
MRX
GABABR1
mRNA expression
normalised to β-actin
Vehicle
MRX 029
MRX
C
DRD1
mRNA expression
normalised to β-actin
2.0
1.5
1.0
0.5
0.0
Vehicle
L-reuteri
MRX005
MRX
DRD1
mRNA expression
normalised to β-actin
Vehicle
MRX 029
MRX

FIG 30

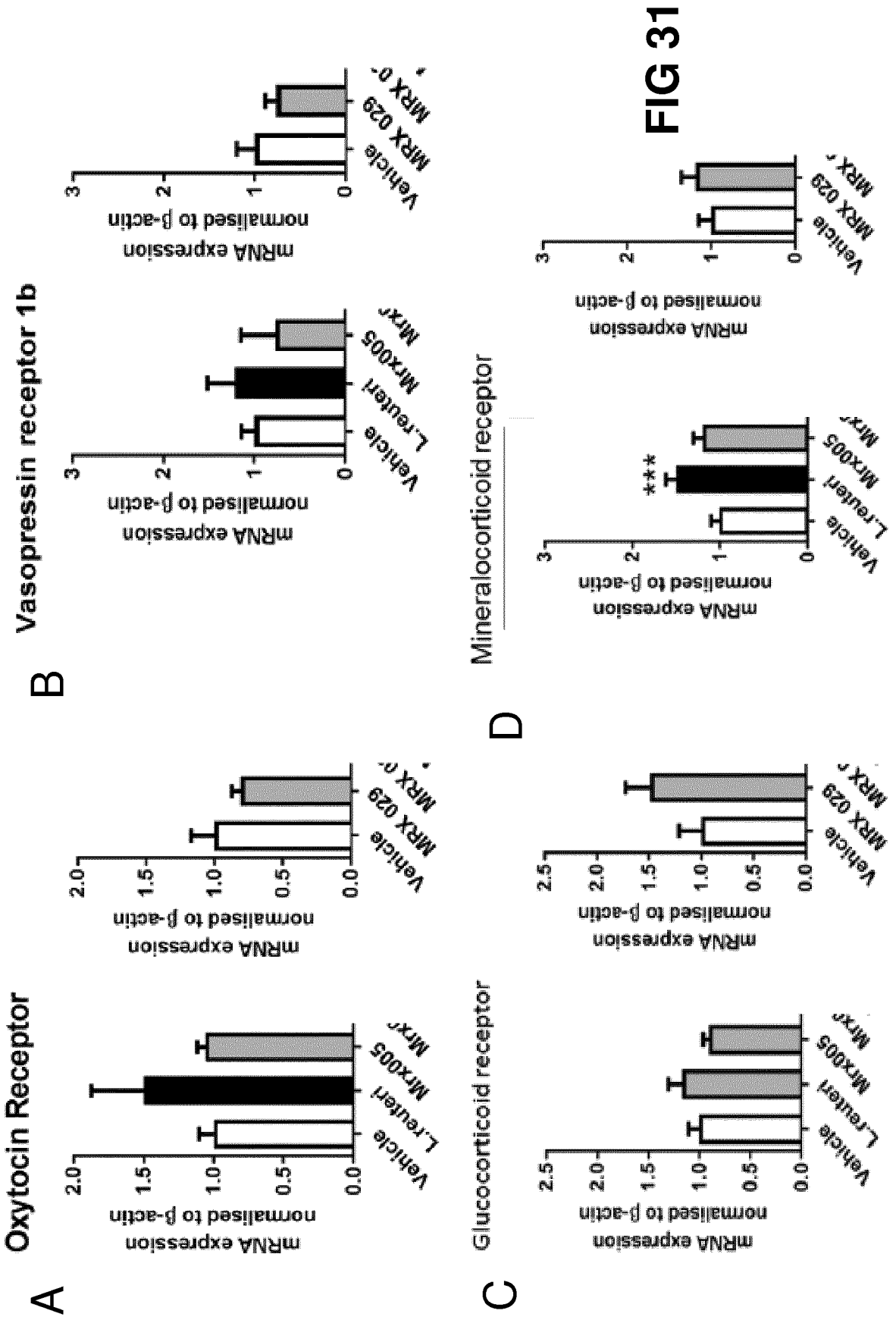
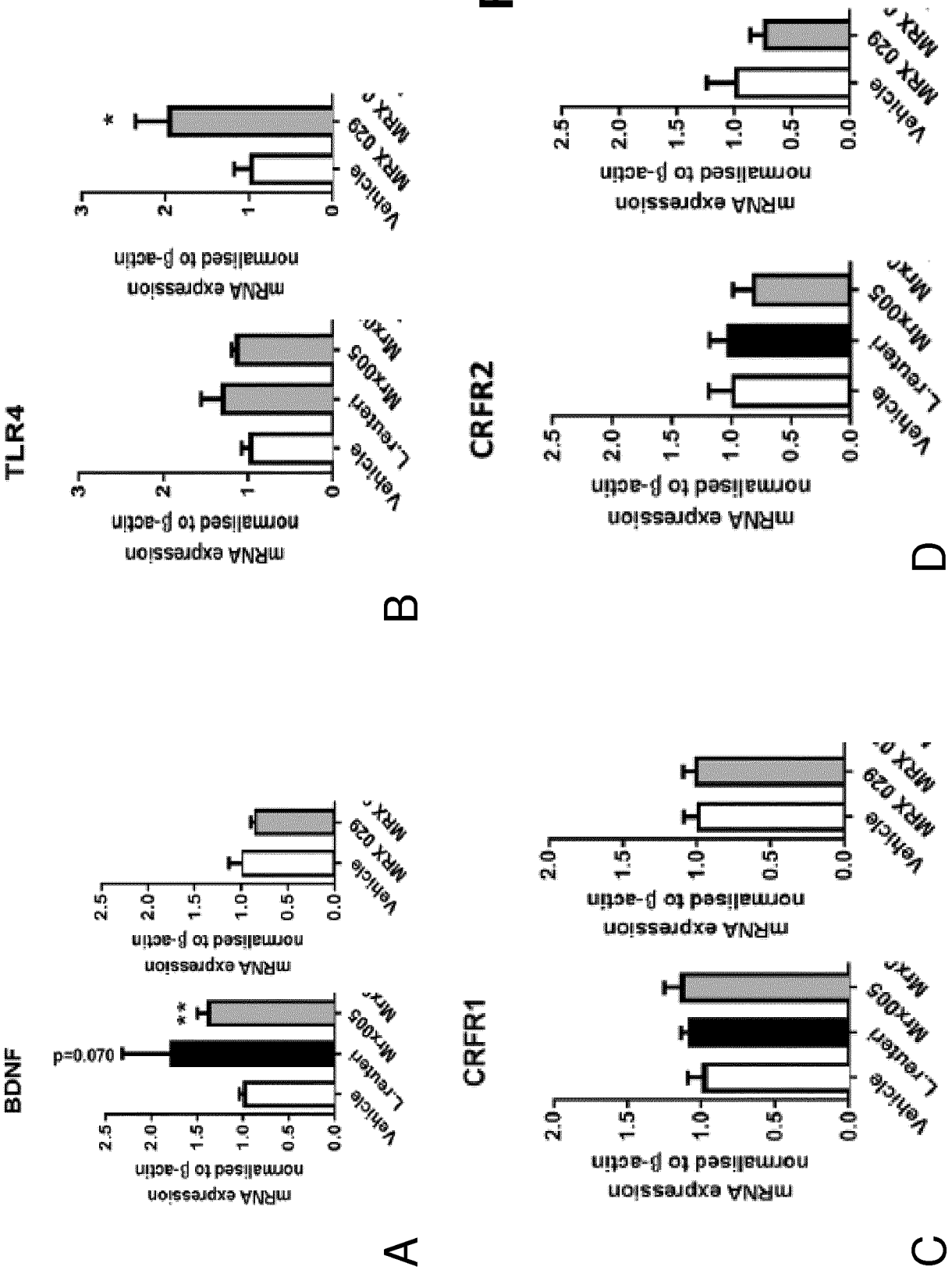

A
Oxytocin Receptor
mRNA expression
normalised to β-actin
Vehicle
L-reuteri
MrX005
MrXf
B
Vasopressin receptor 1b
mRNA expression
normalised to β-actin
Vehicle
MRX 029
C
Glucocorticoid receptor
D
Mineralocorticoid receptor
***

FIG 31

FIG 32


A
BDNF
mRNA expression
normalised to β-actin
2.5
2.0
1.5
1.0
0.5
0.0
p=0.070
**
Vehicle
L-reuteri
MRX005
MRX
B
TLR4
mRNA expression
normalised to β-actin
3
2
1
0
*
Vehicle
MRX 029
MRX
C
CRFR1
mRNA expression
normalised to β-actin
2.0
1.5
1.0
0.5
0.0
Vehicle
L-reuteri
MRX005
MRX
D
CRFR2
mRNA expression
normalised to β-actin
2.5
2.0
1.5
1.0
0.5
0.0
Vehicle
L-reuteri
MRX005
MRX

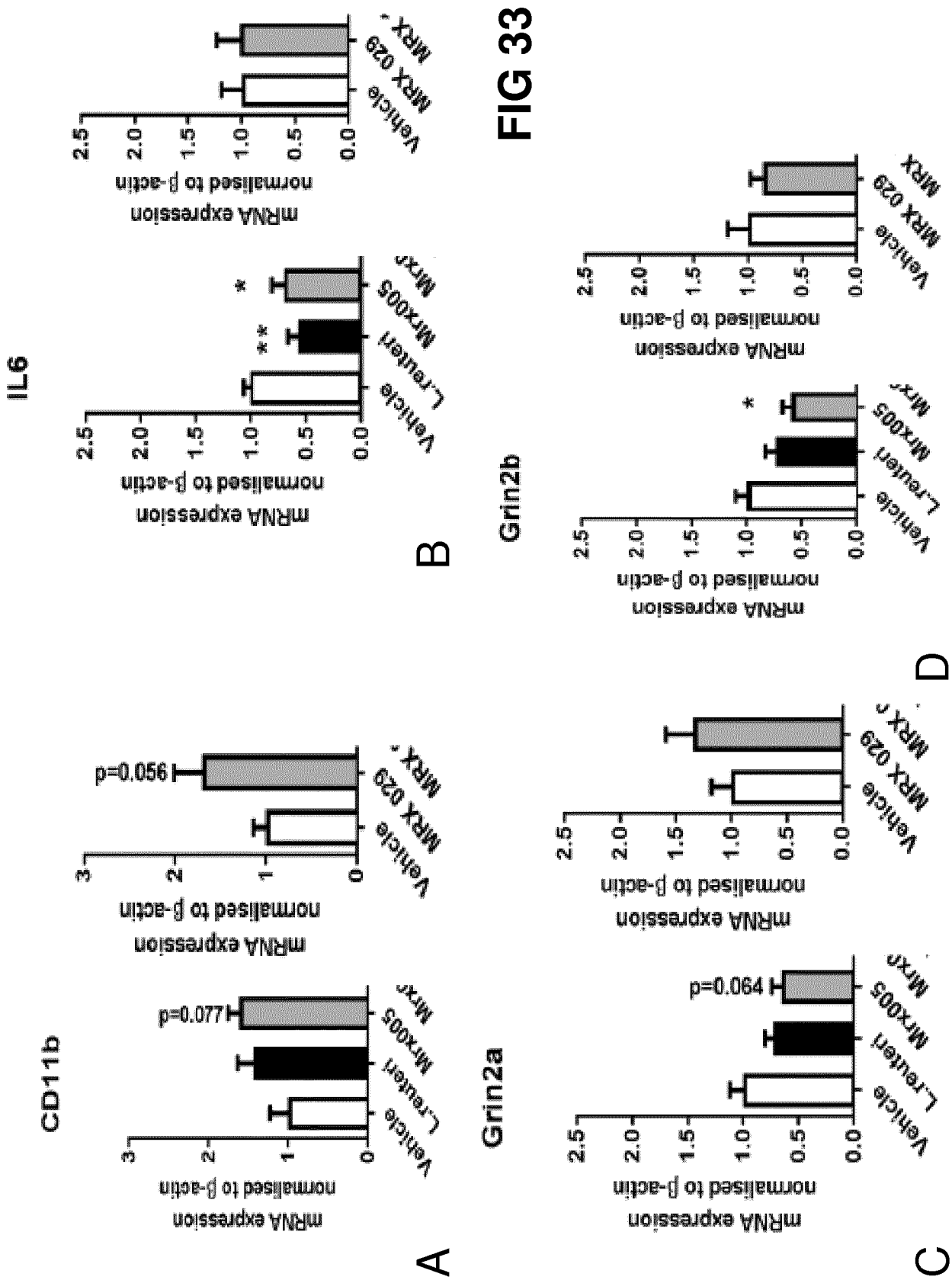
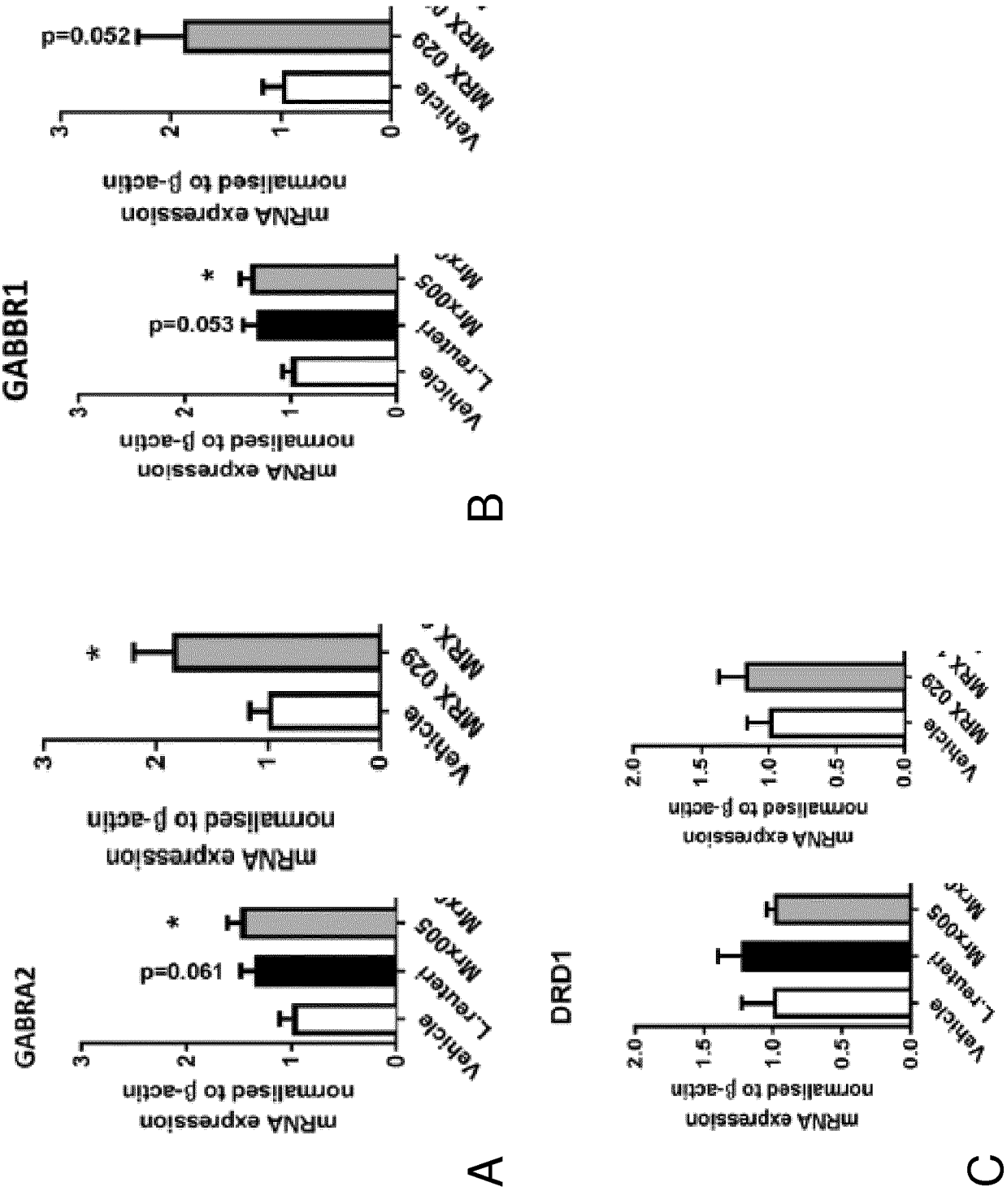

A
CD11b
mRNA expression
normalised to β-actin
p=0.077
p=0.056
Vehicle
L-reuteri
MRX005
MRXF
MRX 029
B
IL6
**
*
C
Grin2a
p=0.064
D
Grin2b
*

FIG 33

FIG 34


A
GABRA2
mRNA expression
normalised to β-actin
Vehicle
MRX 029
L-reuteri
MRX005
p=0.061
*
B
GABBR1
mRNA expression
normalised to β-actin
Vehicle
MRX 029
L.reuteri
MRX005
p=0.053
p=0.052
*
C
DRD1
mRNA expression
normalised to β-actin
Vehicle
MRX 029
L.reuteri
MRX005

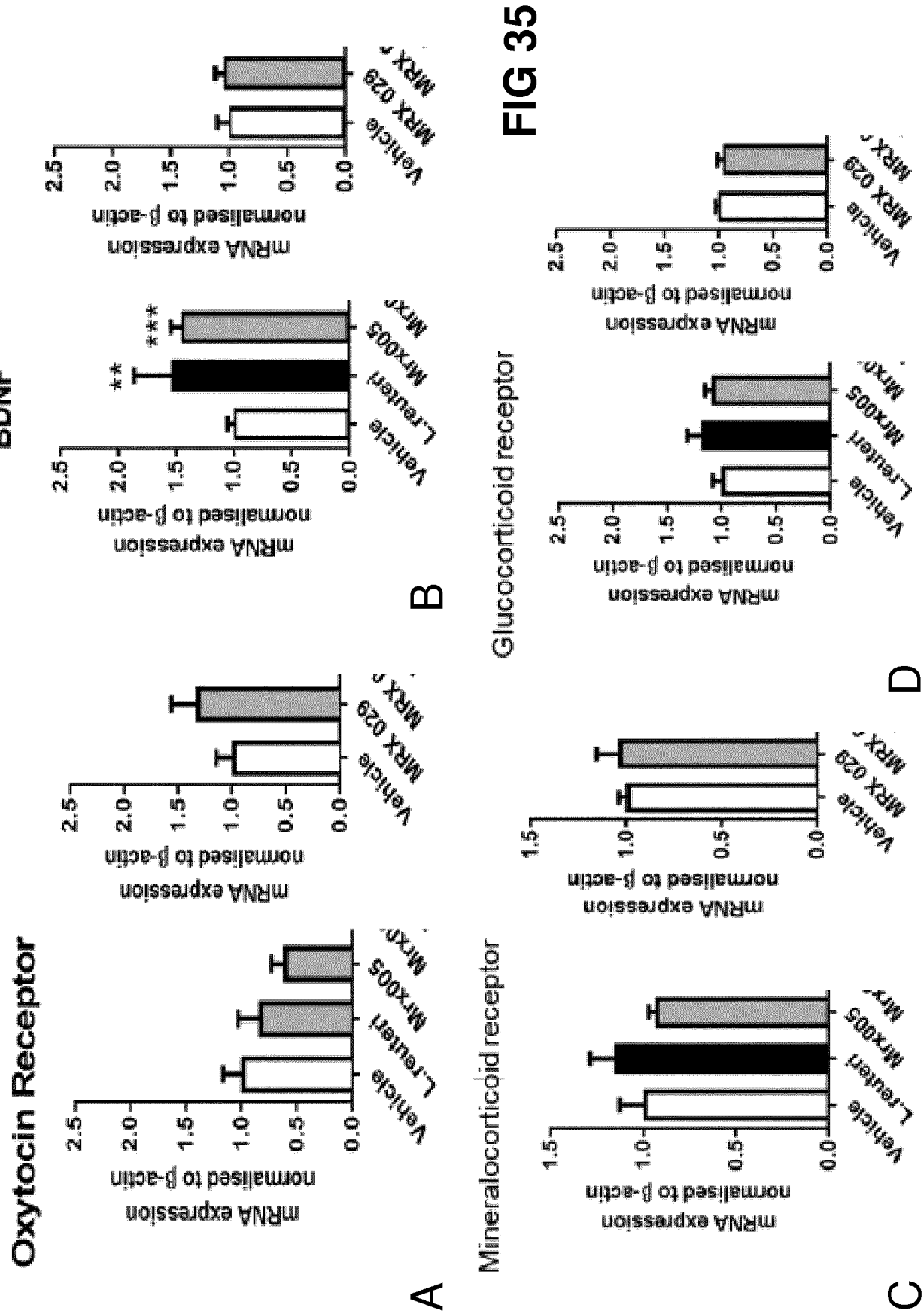

A
Oxytocin Receptor
mRNA expression
normalised to β-actin
2.5
2.0
1.5
1.0
0.5
0.0
Vehicle
L_reuteri
MrX005
MRX 029
B
BDNF
**
***
C
Mineralocorticoid receptor
1.5
D
Glucocorticoid receptor

FIG 35

FIG 36

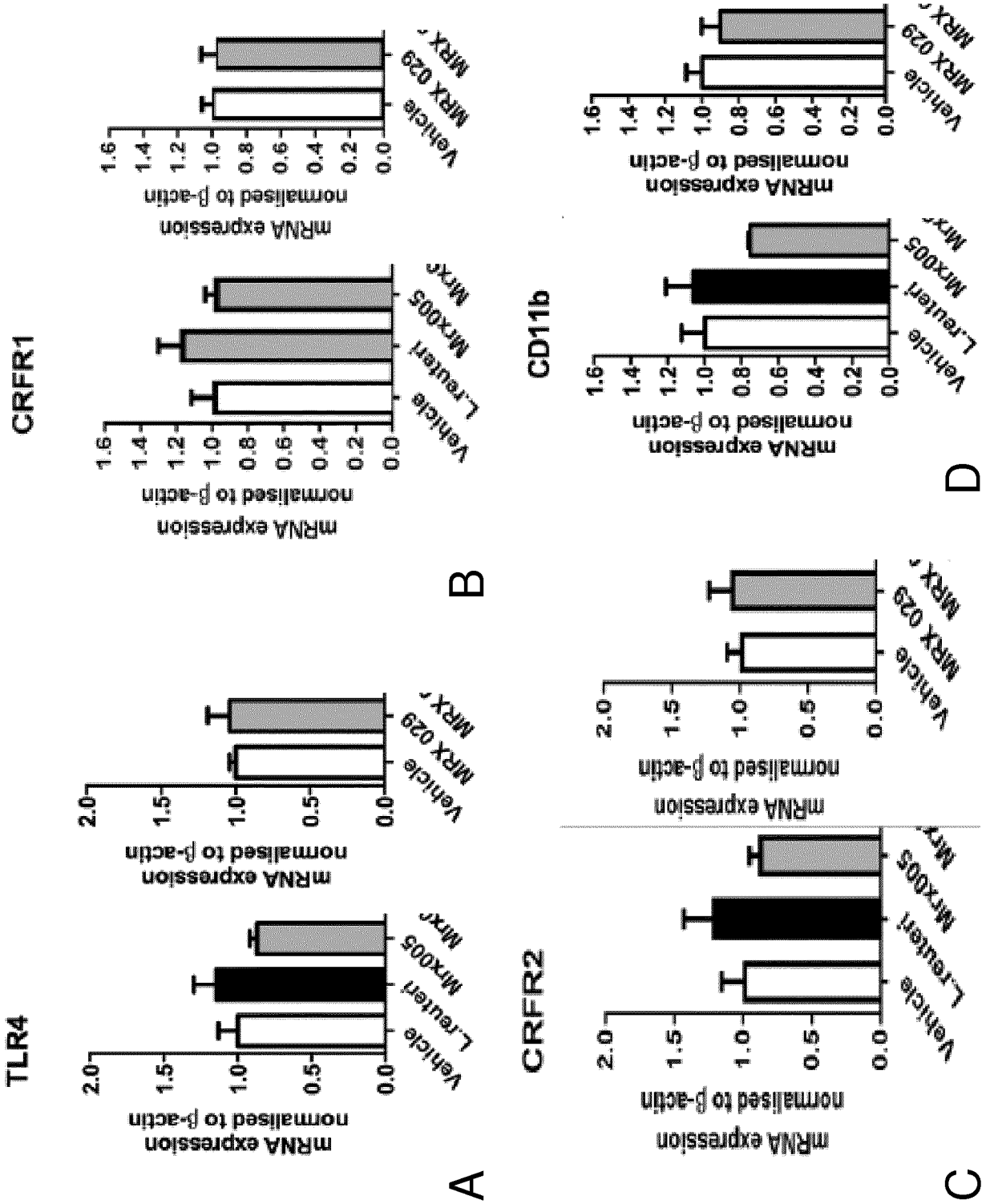

TLR4
CRFR1
CD11b
CRFR2
A
B
C
D
mRNA expression normalised to β-actin
Vehicle
MRX 029
L.reuteri
MRX005

FIG 37

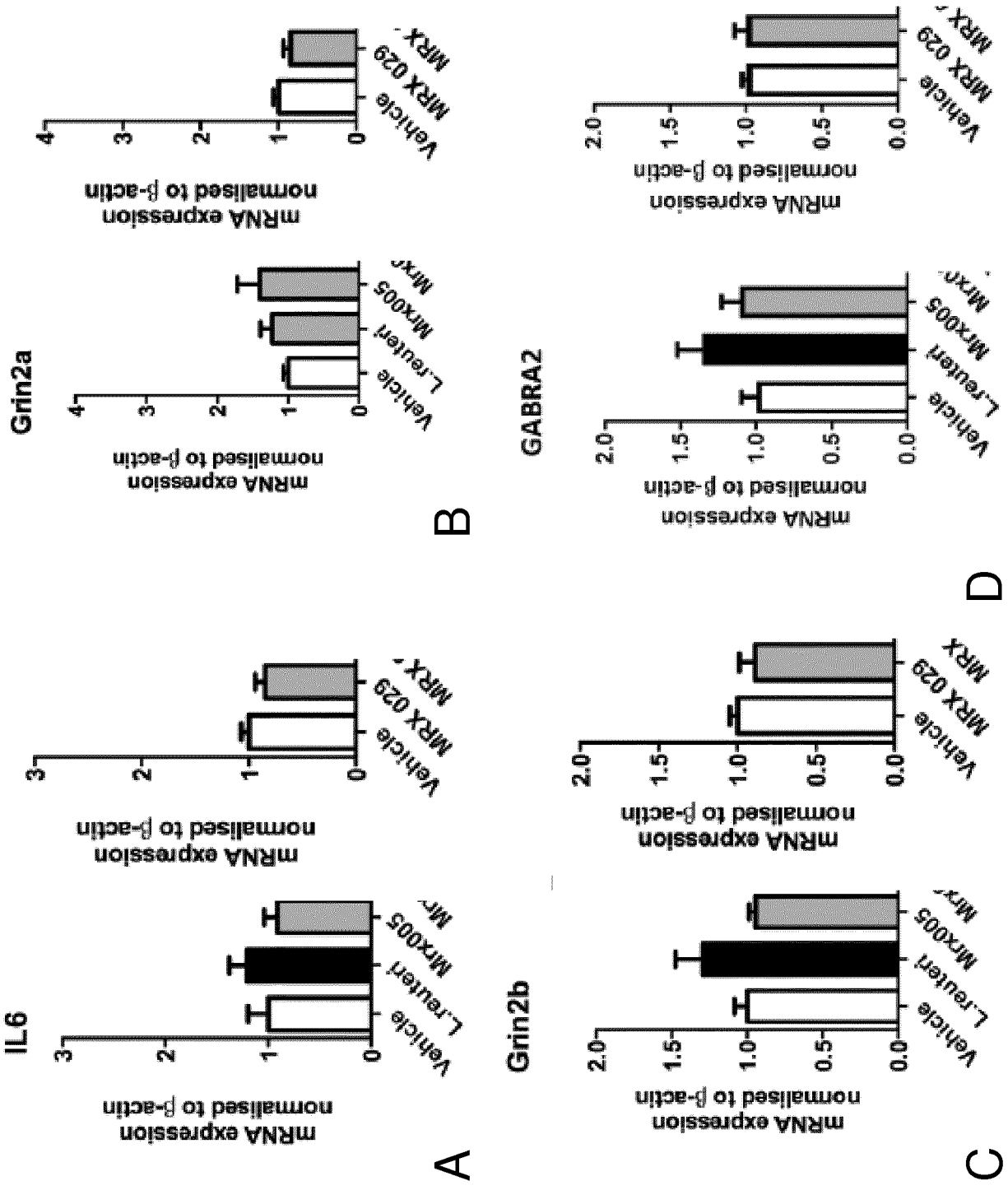

A
IL6
mRNA expression
normalised to β-actin
Vehicle
MRX 029
MRX
B
Grin2a
mRNA expression
normalised to β-actin
Vehicle
L_reuteri
MrX005
C
Grin2b
mRNA expression
normalised to β-actin
Vehicle
L_reuteri
MrX005
D
GABRA2
mRNA expression
normalised to β-actin
Vehicle
L_reuteri
MrX005

FIG 38

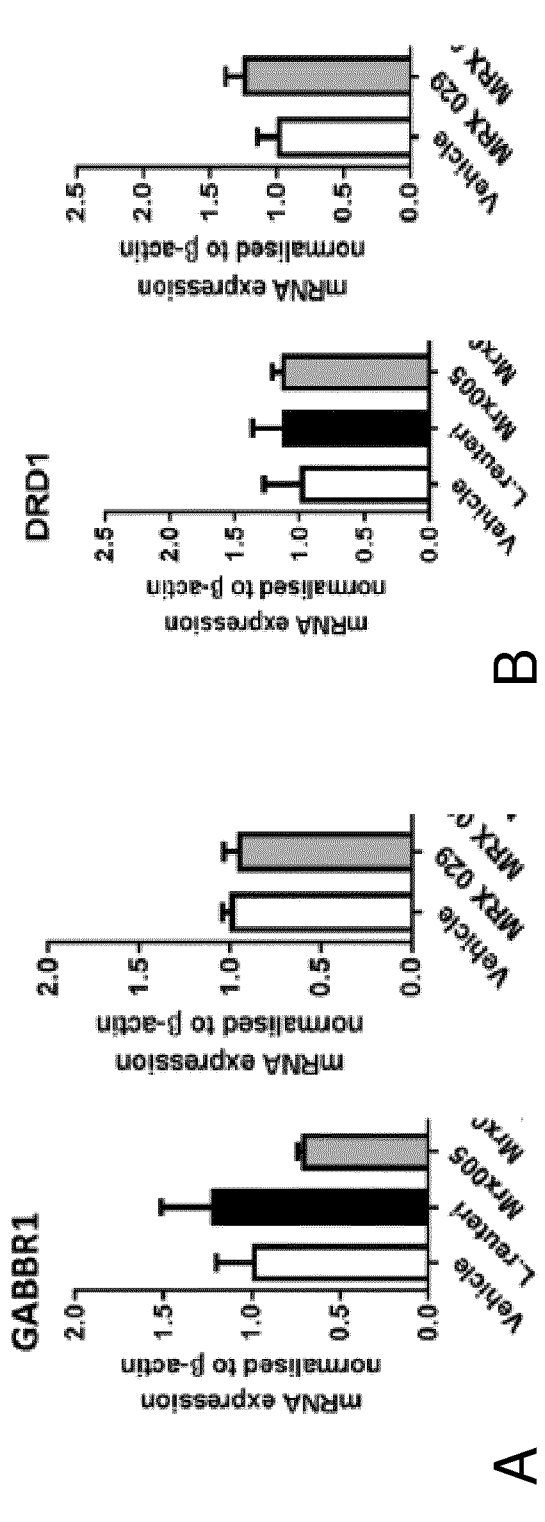

A
GABBR1
mRNA expression
normalised to β-actin
2.0
1.5
1.0
0.5
0.0
Vehicle
L-reuteri
MRx005
MRx
B
DRD1
mRNA expression
normalised to β-actin
2.5
2.0
1.5
1.0
0.5
0.0
Vehicle
L-reuteri
MRx005
MRx
Vehicle
MRX 029
MRX

FIG 39

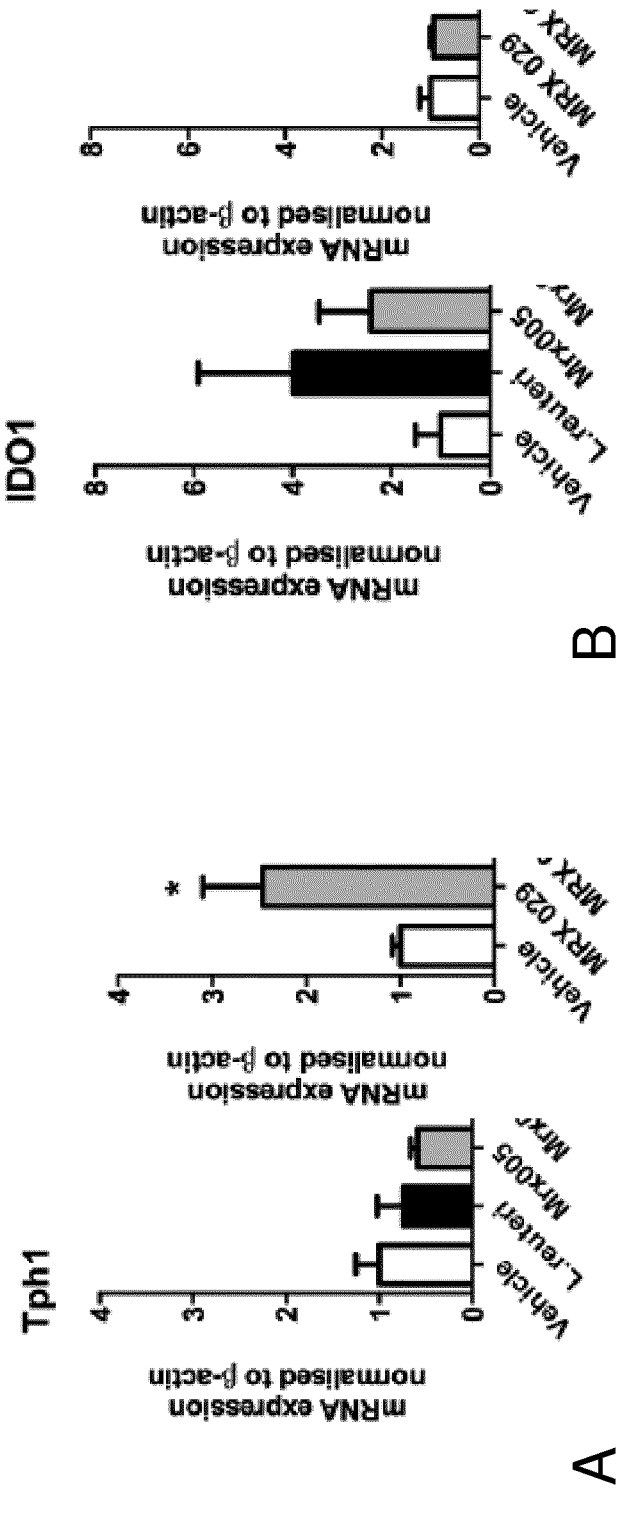
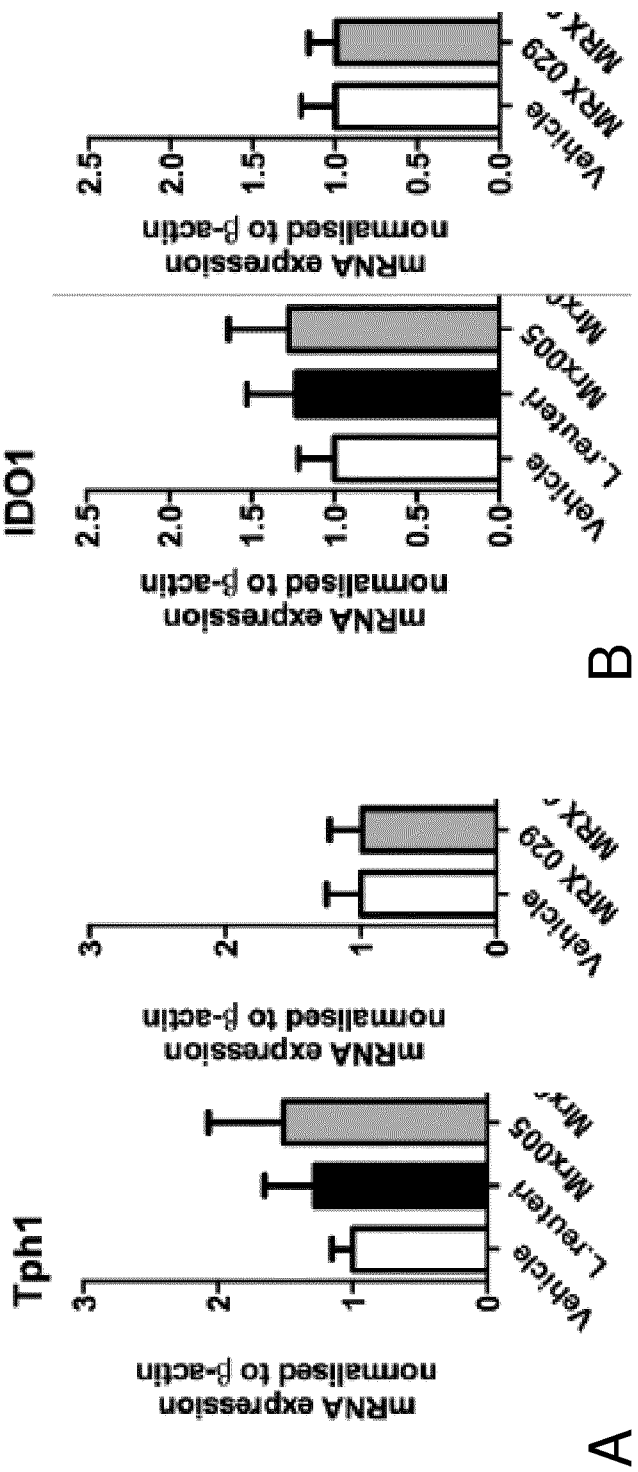

A
Tph1
mRNA expression
normalised to β-actin
4
3
2
1
0
Vehicle
L-reuteri
MRx005
MRx
*
Vehicle
MRX 029
MRX
B
IDO1
mRNA expression
normalised to β-actin
8
6
4
2
0
Vehicle
L-reuteri
MRx005
MRx
mRNA expression
normalised to β-actin
Vehicle
MRX 029
MRX

FIG 40


A
Tph1
mRNA expression
normalised to β-actin
3
2
1
0
Vehicle
L.reuteri
MrX005
MRX
B
IDO1
mRNA expression
normalised to β-actin
2.5
2.0
1.5
1.0
0.5
0.0
Vehicle
L.reuteri
MrX005
MRX 029
MRX

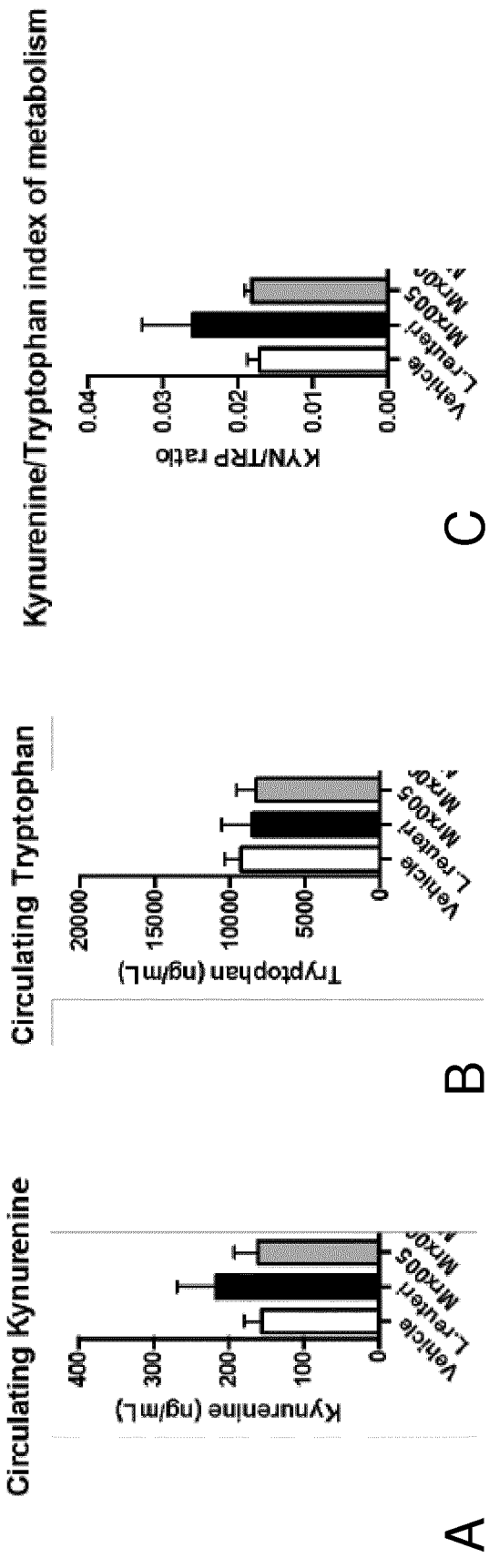

Circulating Kynurenine
Kynurenine (ng/mL)
400
300
200
100
0
Vehicle
L-reuteri
MRx005
MRx0
A
Circulating Tryptophan
Tryptophan (ng/mL)
20000
15000
10000
5000
0
Vehicle
L-reuteri
MRx005
MRx0
B
Kynurenine/Tryptophan index of metabolism
KYN/TRP ratio
0.04
0.03
0.02
0.01
0.00
Vehicle
L-reuteri
MRx005
MRx0
C

FIG 41

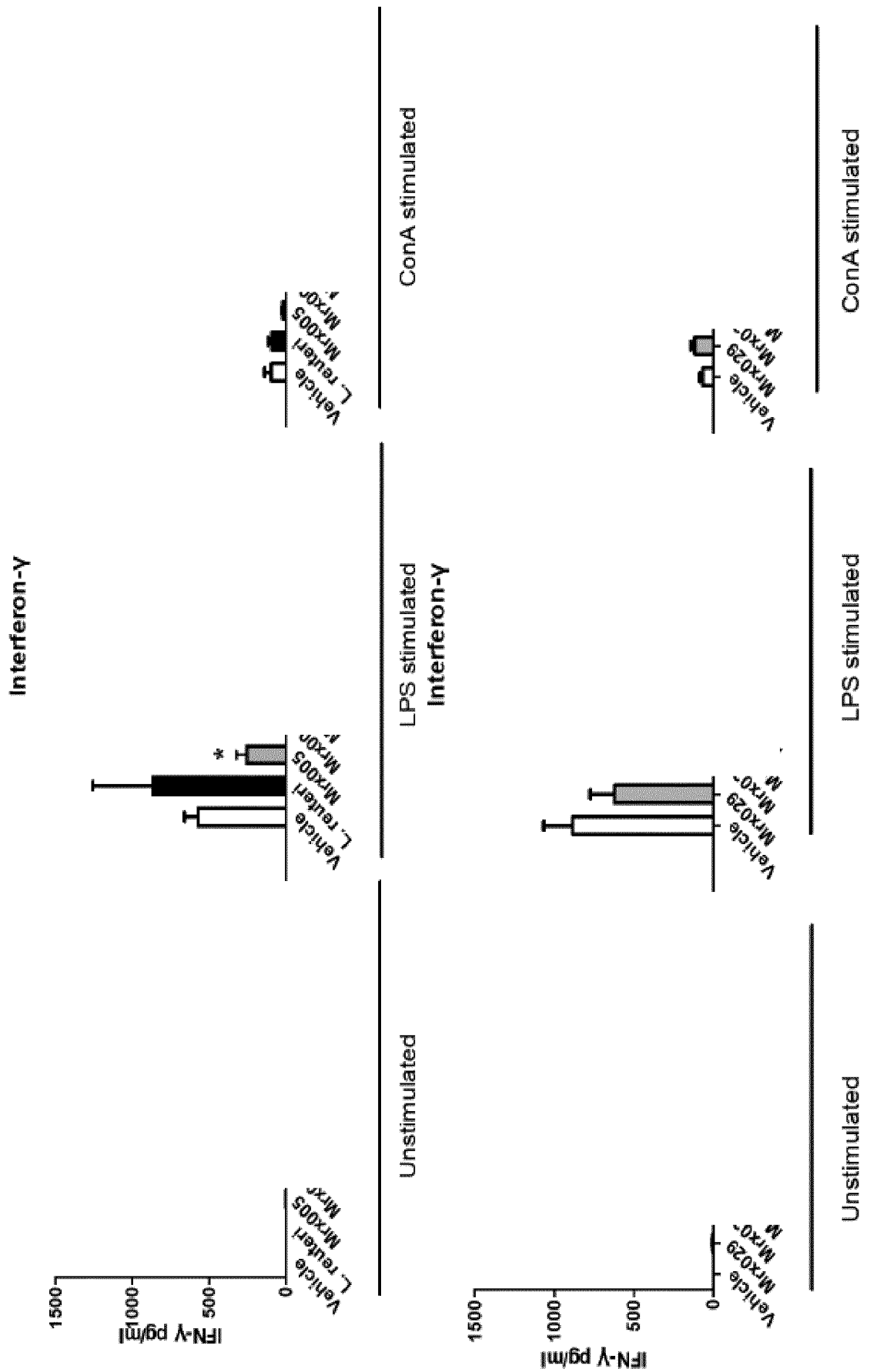

Interferon-γ
IFN-γ pg/ml
1500
1000
500
0
Vehicle
L. reuteri Mrx005
Mrx0F
*
Unstimulated
LPS stimulated
ConA stimulated
Interferon-γ
IFN-γ pg/ml
1500
1000
500
0
Vehicle
Mrx029
Mrx0-M
Unstimulated
LPS stimulated
ConA stimulated

FIG 42

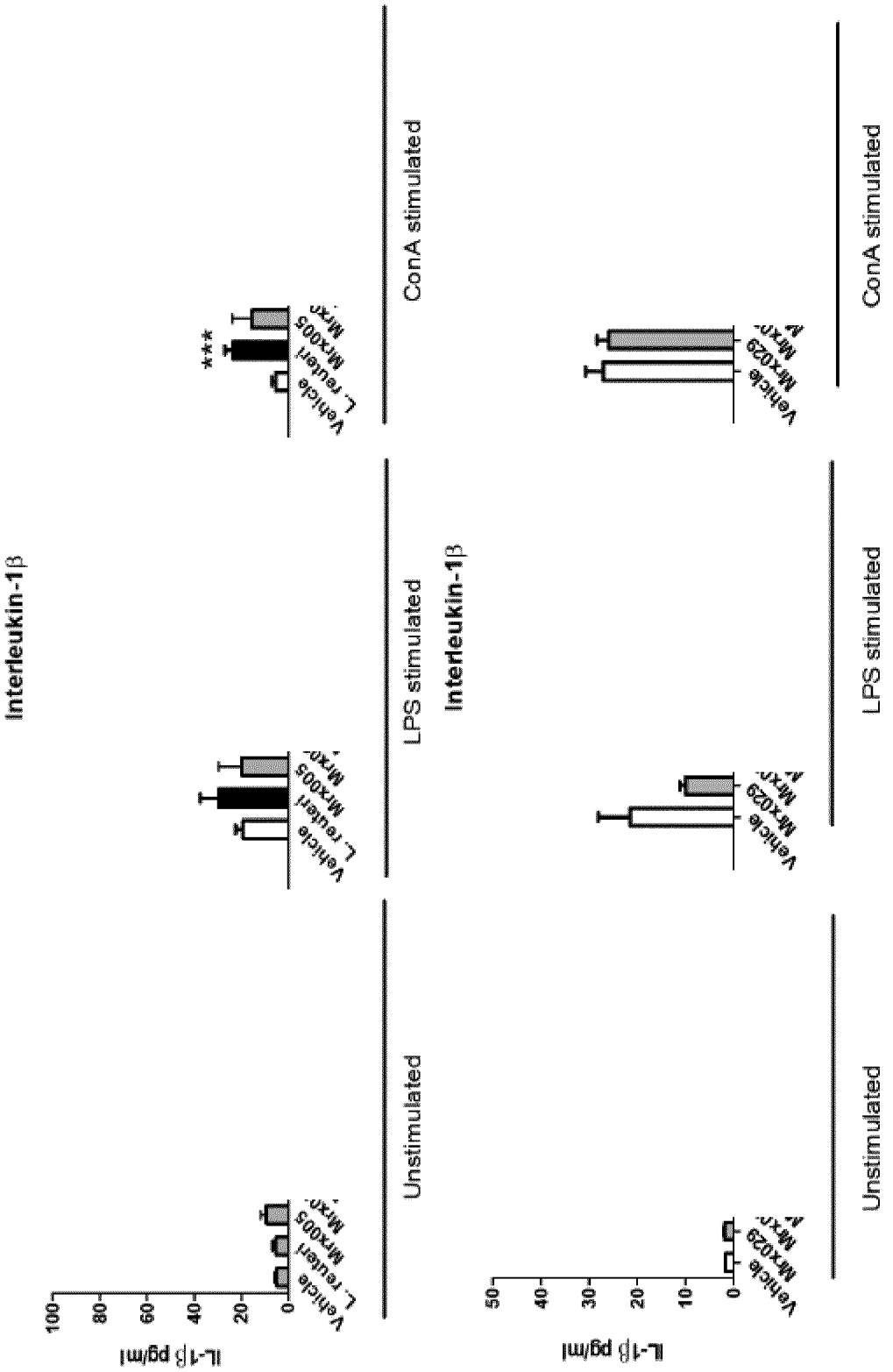

Interleukin-1β
IL-1β pg/ml
100
80
60
40
20
0
Vehicle
L. reuteri MTX005
MTXF
Unstimulated
LPS stimulated
ConA stimulated
***
Interleukin-1β
IL-1β pg/ml
50
40
30
20
10
0
Vehicle
MTX029
MTXF
Unstimulated
LPS stimulated
ConA stimulated

FIG 43

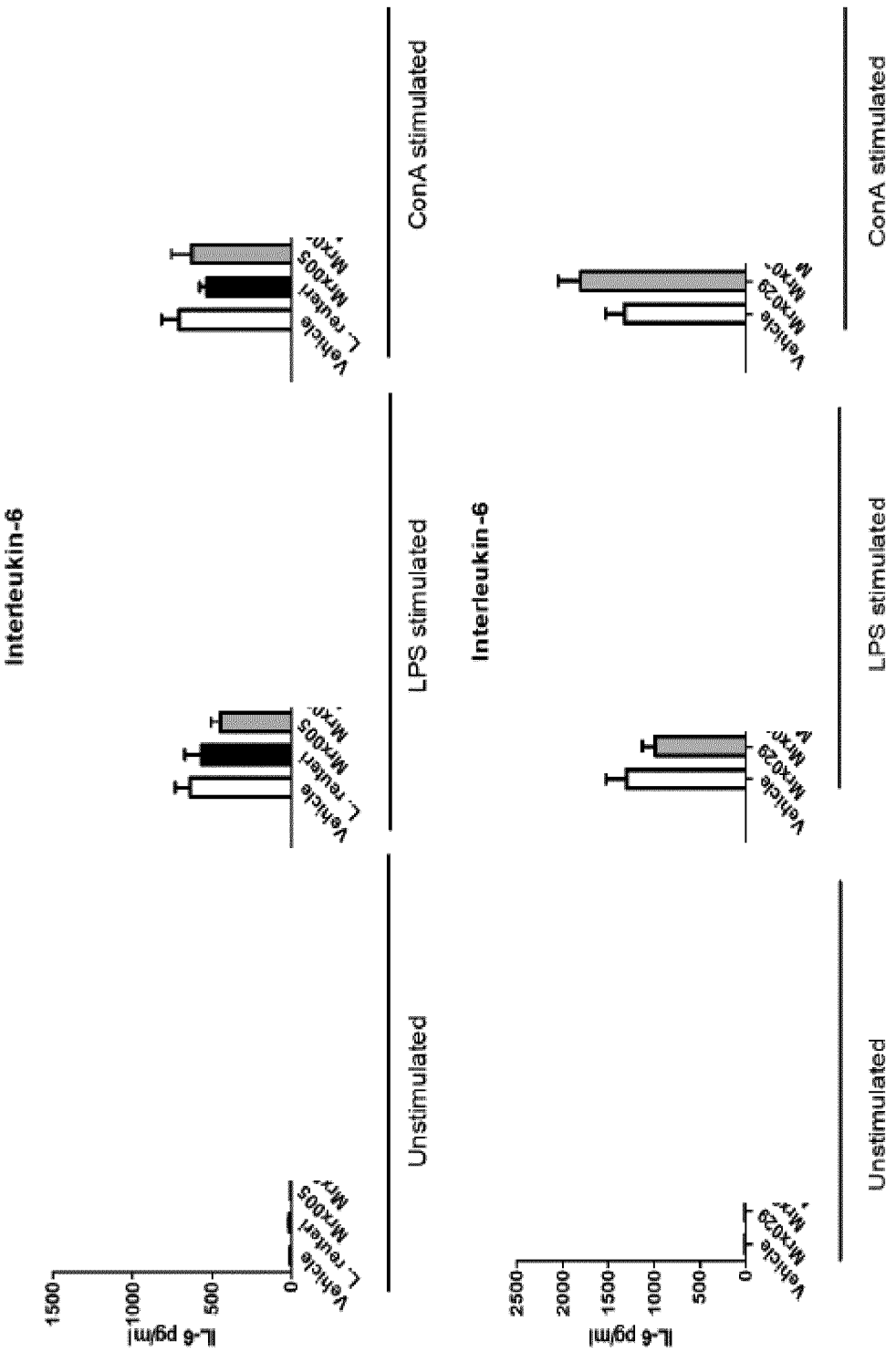

Interleukin-6
IL-6 pg/ml
1500
1000
500
0
Vehicle
L. reuteri
MrX005
MrX
Unstimulated
LPS stimulated
ConA stimulated
Interleukin-6
IL-6 pg/ml
2500
2000
1500
1000
500
0
Vehicle
MrX029
MrX
Unstimulated
LPS stimulated
ConA stimulated

FIG 44

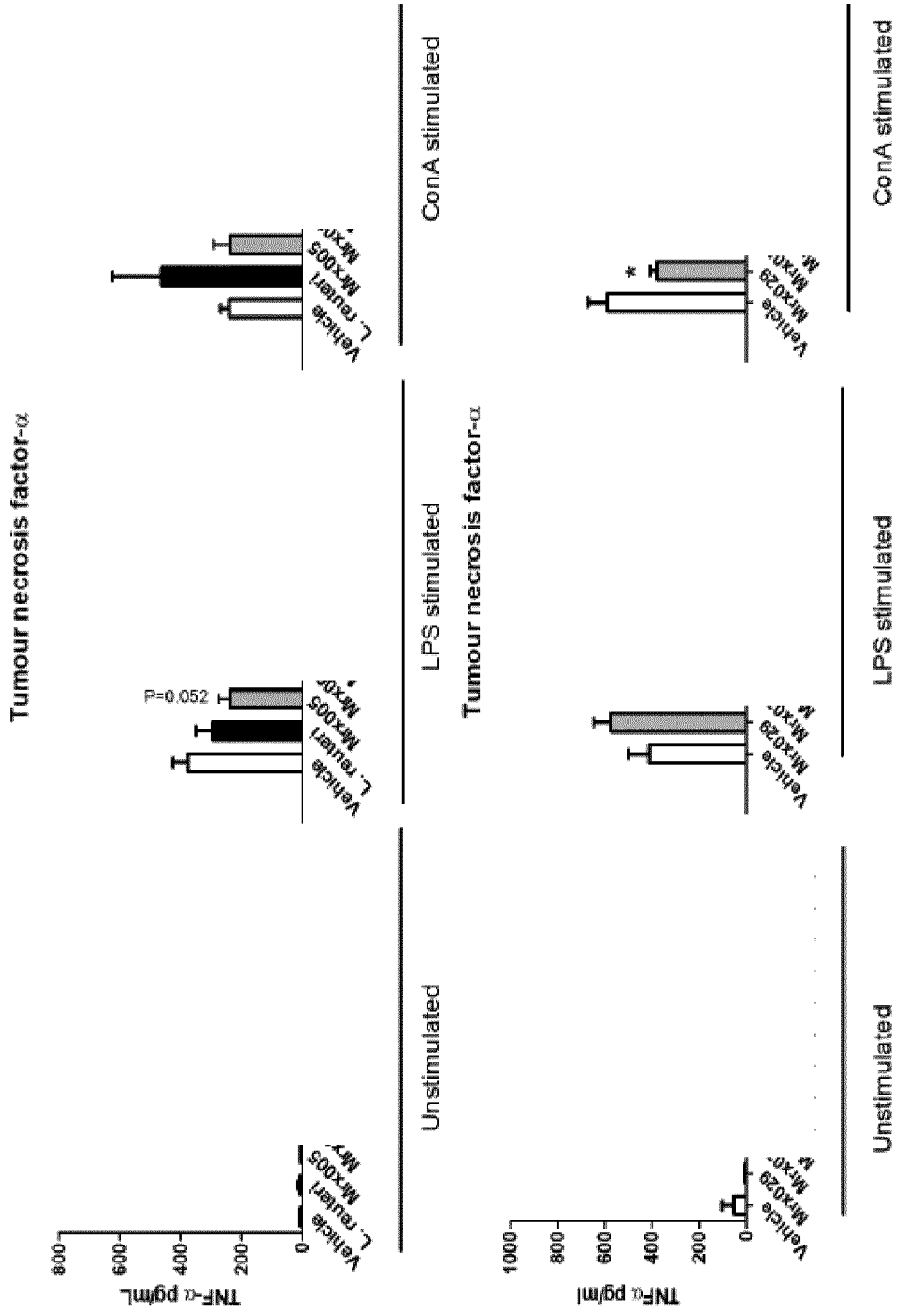

Tumour necrosis factor-α
TNFα pg/mL
800
600
400
200
0
Vehicle
L. reuteri
Mr-X005
Mr-X
Unstimulated
P=0.052
LPS stimulated
ConA stimulated
Tumour necrosis factor-α
TNFα pg/ml
1000
800
600
400
200
0
Vehicle
Mr-X029
Mr-X
*

FIG 45

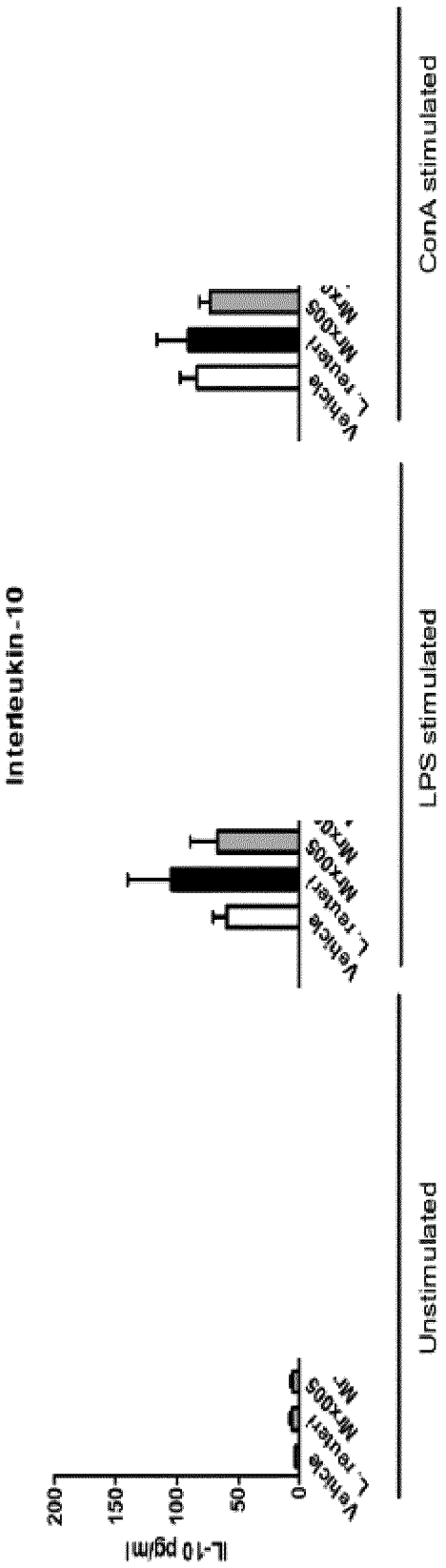

Interleukin-10
IL-10 pg/ml
200
150
100
50
0
Vehicle
L. reuteri
MRX005
MRX
Unstimulated
LPS stimulated
ConA stimulated

FIG 46

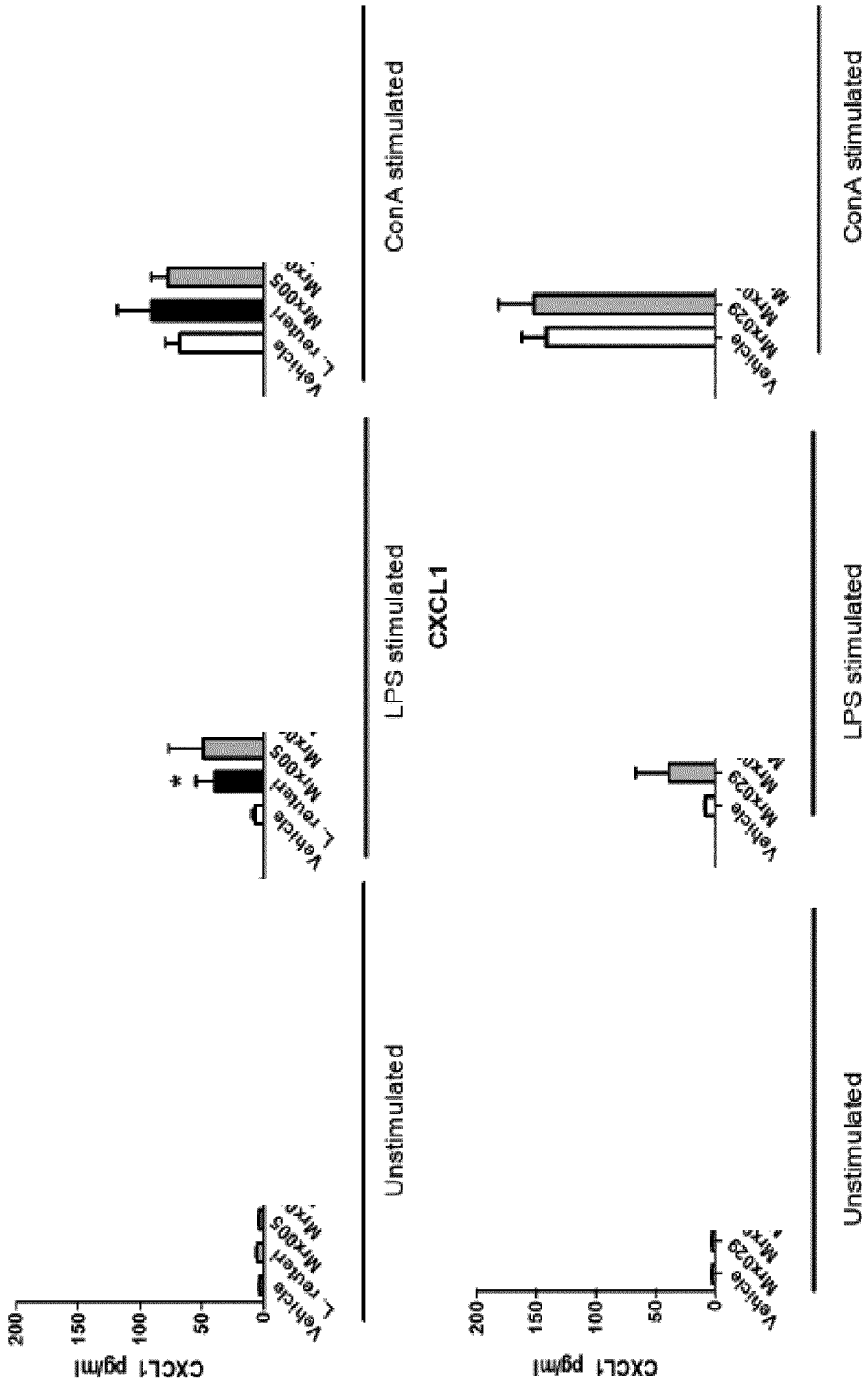

CXCL1
CXCL1 pg/ml
200
150
100
50
0
Vehicle
L. reuteri
Mrx005
Mrx029
*
Unstimulated
LPS stimulated
ConA stimulated

FIG 47

FIG 48

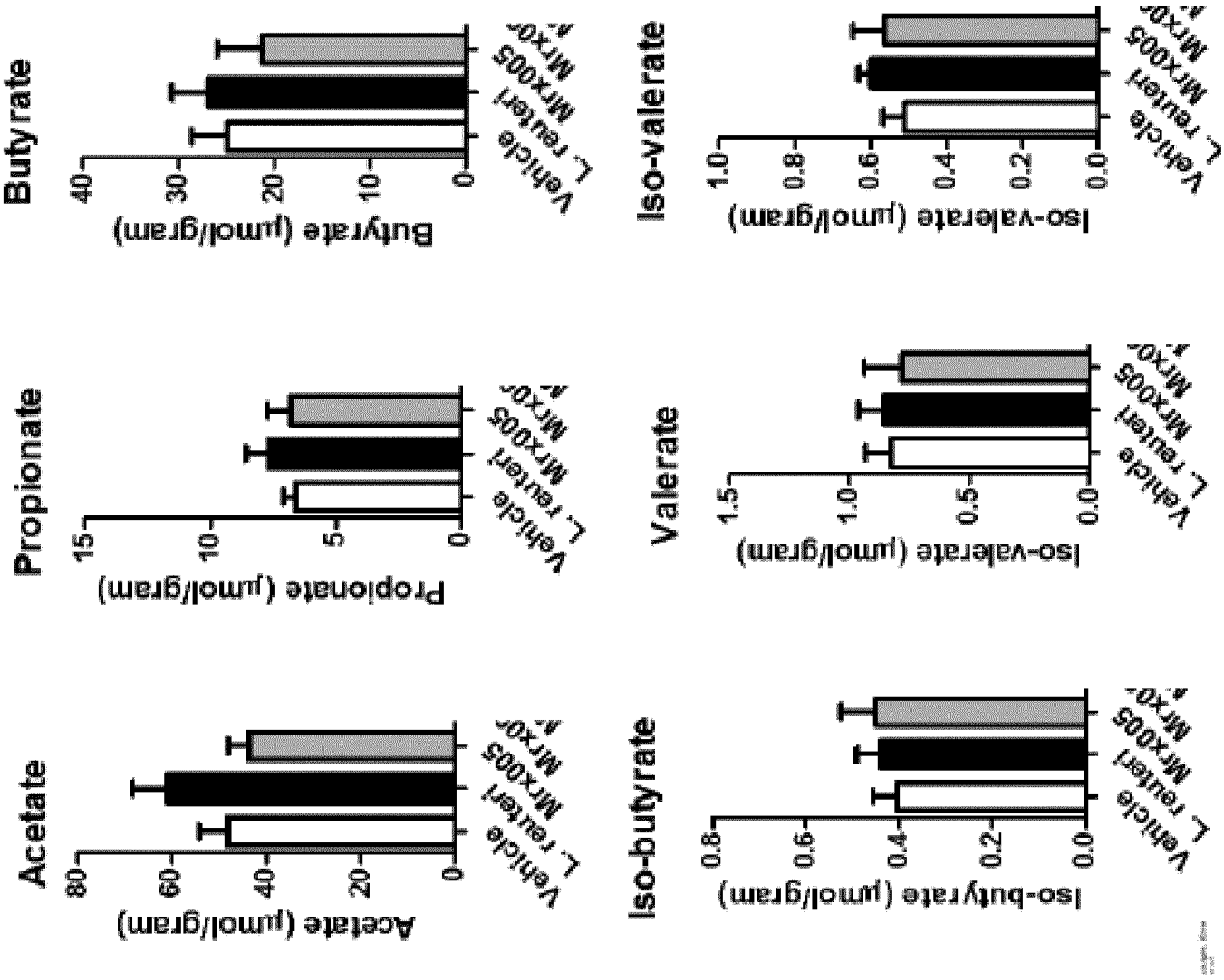

Acetate
Acetate (µmol/gram)
Propionate
Propionate (µmol/gram)
Butyrate
Butyrate (µmol/gram)
Iso-butyrate
Iso-butyrate (µmol/gram)
Valerate
Iso-valerate (µmol/gram)
Iso-valerate
Iso-valerate (µmol/gram)
Vehicle
L. reuteri
MrX005

FIG 49

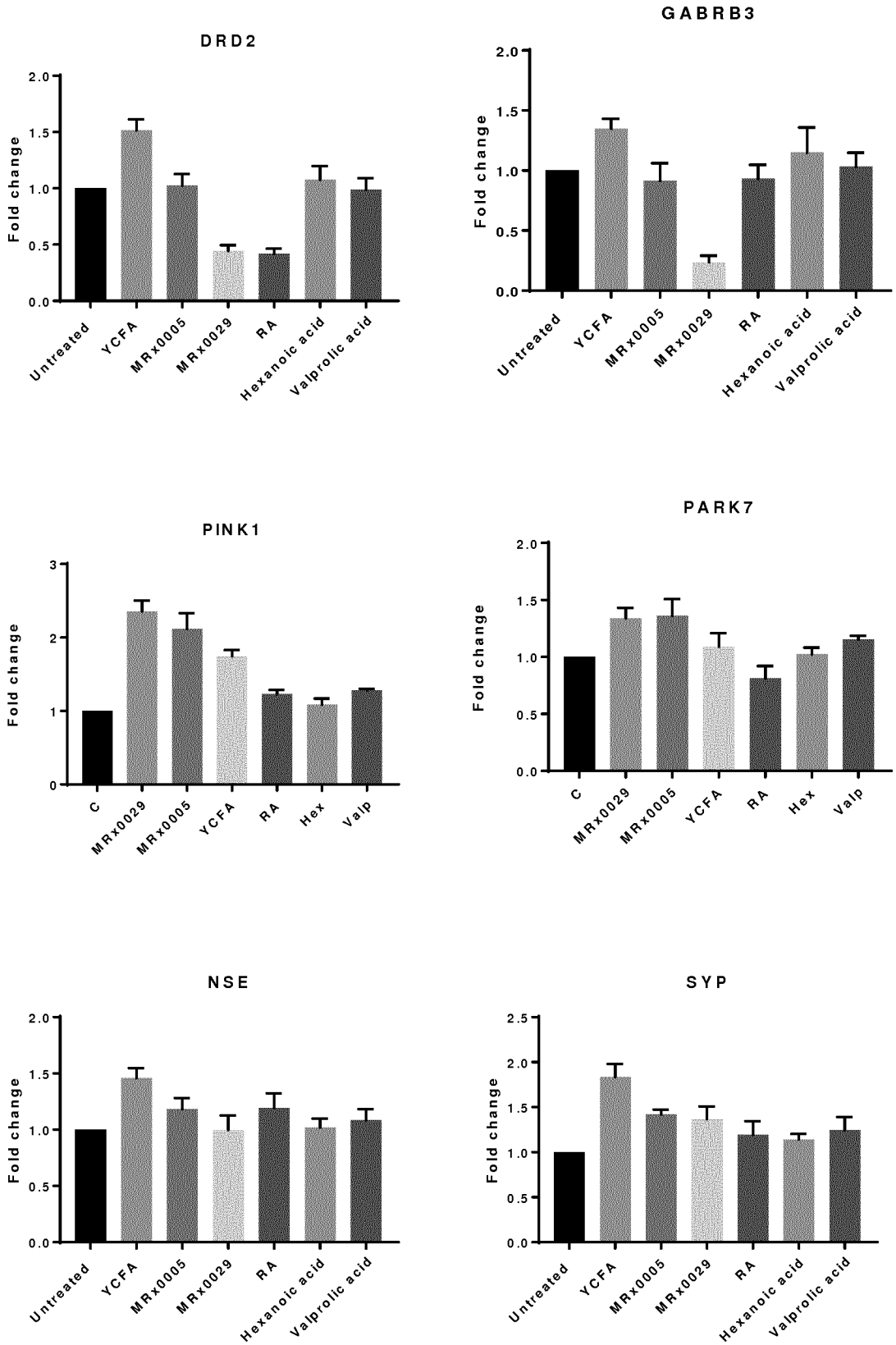

DRD2
Fold change
2.0
1.5
1.0
0.5
0.0
Untreated
YCFA
MRx0005
MRx0029
RA
Hexanoic acid
Valprolic acid
GABRB3
Fold change
2.0
1.5
1.0
0.5
0.0
Untreated
YCFA
MRx0005
MRx0029
RA
Hexanoic acid
Valprolic acid
PINK1
Fold change
3
2
1
0
C
MRx0029
MRx0005
YCFA
RA
Hex
Valp
PARK7
Fold change
2.0
1.5
1.0
0.5
0.0
C
MRx0029
MRx0005
YCFA
RA
Hex
Valp
NSE
Fold change
2.0
1.5
1.0
0.5
0.0
Untreated
YCFA
MRx0005
MRx0029
RA
Hexanoic acid
Valprolic acid
SYP
Fold change
2.5
2.0
1.5
1.0
0.5
0.0
Untreated
YCFA
MRx0005
MRx0029
RA
Hexanoic acid
Valprolic acid

FIG 50

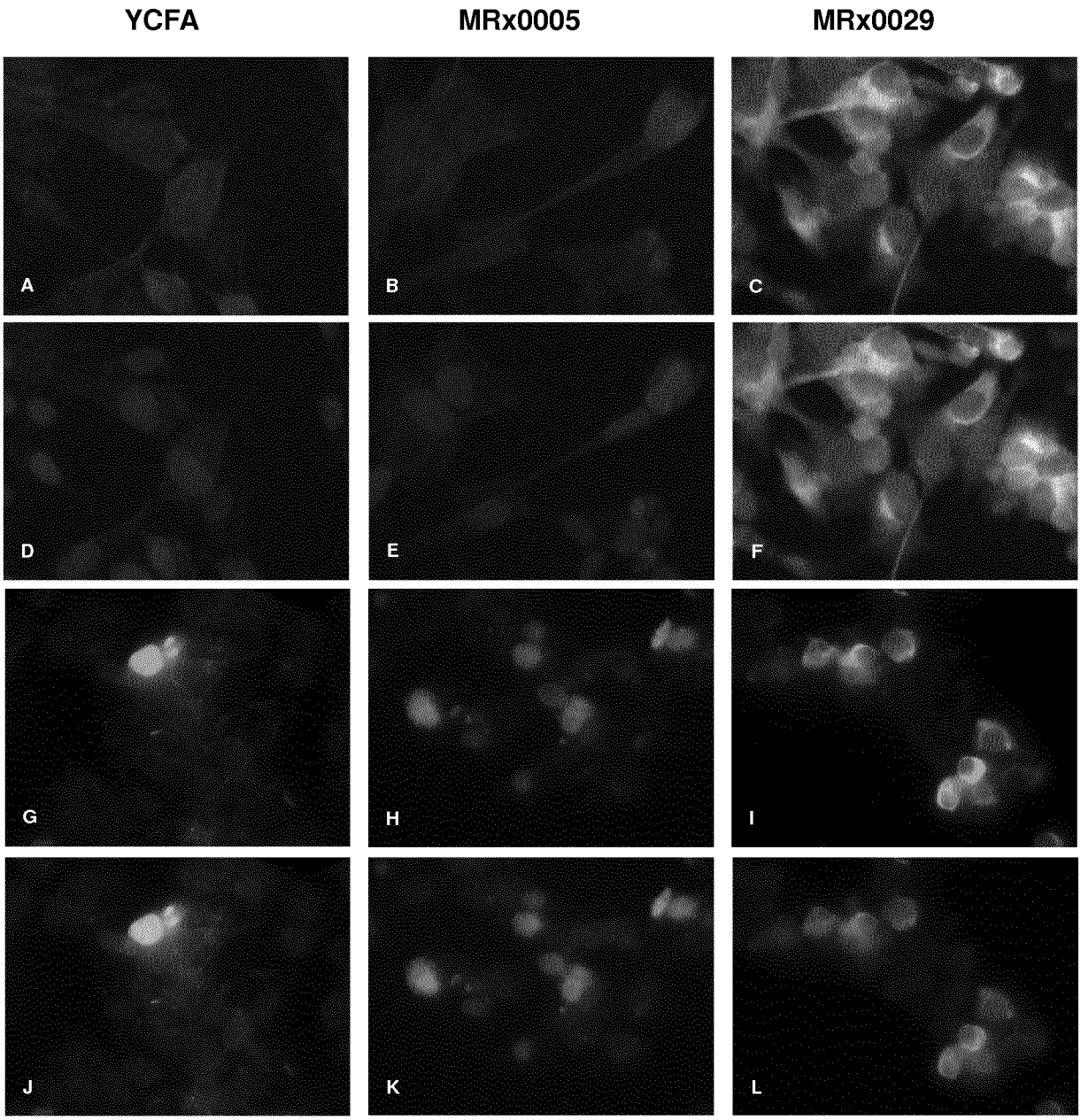


FIG 50 continued