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(54) Title: IN VITRO METABOLIC ENGINEERING ON MICROSCALE DEVICES

(57) Abstract: Disclosed herein is a microfluidics device that can be used to prepare natural products and their analogs. The device comprises the enzymes of a biosynthetic pathway immobilized thereon and a means for sequentially directing a starting material and each ensuing reaction product to the enzymes of the biosynthetic pathway in the order corresponding to the steps of the biosynthetic pathway. The device can thus be used to prepare the natural product using the natural starting material of the biosynthetic pathway or analogs of the natural product using an unnatural starting material. Alternatively, artificial pathways can be created by immobilizing an appropriate selection of enzymes on the device in an order whereby each subsequent enzyme can catalyze a reaction with the product of the prior enzyme. Novel chemical entities can be prepared from these artificial pathways.

IN VITRO METABOLIC ENGINEERING ON MICROSCALE DEVICES

10 BACKGROUND OF THE INVENTION

Nature produces a huge number of structurally diverse chemical substances with varying and potent biological activities. By exploiting these biological activities, researchers have discovered many utilities for natural products, including, but not limited to, their use as therapeutic agents, pesticides and
15 antibiotic agents.

After discovering that a natural product has a particular biological activity, it is often desirable to prepare analogs of the natural product in order to optimize its properties. Generally, this is accomplished by preparing the analogs from the natural product itself or by synthesizing the analogs directly from readily
20 available starting materials. Unfortunately, natural products and their analogs are typically complex molecules requiring multi-step syntheses to prepare even small quantities of the compound. To develop such syntheses is usually laborious, costly, and time consuming.

25 SUMMARY OF THE INVENTION

Disclosed herein is a novel microscale, microfluidics device that can be used to prepare natural products and their analogs. The device comprises a solid support with the enzymes of a biosynthetic pathway immobilized thereon and a micro-directing element (e.g., channels or conduits) for sequentially directing a
30 starting material, and each ensuing reaction product, to the enzymes of the biosynthetic pathway in the order corresponding to the steps of the biosynthetic pathway. The device can thus be used to prepare a natural product using the natural starting material of the biosynthetic pathway, or analogs of the natural product using an unnatural starting material. Alternatively, artificial pathways
35 can be created by immobilizing an appropriate selection of enzymes on the device in an order whereby each subsequent enzyme can catalyze a reaction

with the product of the prior enzyme. New chemical entities can be prepared from these artificial pathways. The invention is described in greater detail below.

One embodiment of the invention is an apparatus for conducting a plurality
5 of microscale reactions. The apparatus includes a solid support comprising a first and a second reaction site. Each site comprises a distinct immobilized biocatalyst, and a micro-directing element to direct an intermediate composition from the first site to the second site.

Another embodiment of the invention is a method for conducting reactions
10 at a plurality of reaction sites using the apparatus disclosed herein. The method includes the step of directing a substrate composition to the first reaction site under conditions suitable for reacting the substrate with the immobilized catalyst of the first site, thereby producing a first intermediate composition. The first intermediate composition is then directed to the second reaction site, and
15 exposed to conditions suitable for reacting the first intermediate with the immobilized catalyst at the second site, thereby producing a second intermediate composition.

The advantages of the invention disclosed herein are numerous and significant. The invention provides a means of optimizing biosynthetic
20 pathways in a modular fashion. Furthermore, it allows the intrinsic limits of a pathway to be determined free from the restrictions of cellular processes. A further advantage is that the complexity of a pathway can be reduced compared to cellular systems. Yet another advantage is that the sequence and number of steps in a pathway can be varied, leading to synthesis of novel products. Still
25 another advantage is that catalysts can be combined in ways that would be difficult or impossible in a cellular pathway. Yet another advantage is that components not found in biological systems can be used, such as chemical catalysts, synthetic starting materials, and organic solvents. Another advantage is that products can be produced or substrates used that would be toxic in kind
30 or amount to a cell, if produced or used in a cellular pathway.

DETAILED DESCRIPTION OF THE INVENTION

The invention generally is related to an apparatus and method for conducting stepwise microscale chemical syntheses of natural products and related compounds. The apparatus includes the enzymes of a natural biosynthetic pathway, arranged so that a starting material can be directed to each enzyme on the apparatus in the order that they occur in nature. Thus, using the starting material of the natural biosynthetic pathway, the natural product of the pathway can be produced using the apparatus (See Examples 1 and 2 in the Exemplification). The apparatus can also be used to prepare related products through a number of variations. For example, the enzymes on the apparatus can use starting materials that are not used in nature. Alternatively, micro-directing elements of the apparatus can be arranged to conduct the steps of the synthesis in a different order than the natural pathway, or to combine enzymes from different pathways or enzymes that are not associated with specific pathways, or even enzymes from different organisms. The apparatus can mix biosynthetic enzymes from other pathways, and can also include catalysts, such as chemical catalysts that are not part of any natural biosynthetic pathway. In a preferred embodiment, the apparatus uses microfluidics techniques to direct substrates, intermediates, products, reagents, solvents and the like among the reaction sites. "Microfluidics" means directing fluids on the microscale, typically using micro-directing elements incorporated into a solid support in combination with a motive force, typically generated by electroosmotic flow.

"Microscale" means that dimensions of significant features such as the micro-directing elements or the reaction sites are submillimeter. For example, the width and height of a channel or conduit are typically between 1-1000 micrometers, typically between 10 and 500 micrometers and more typically between 10 and 250 micrometers. A microscale apparatus can also be defined in terms of the combined volume of the reaction sites and micro-directing elements. Typically, this combined volume is less than 500 nanoliters, more commonly less than 250 nanoliters and often less than 100 nanoliters. Typically,

the combined volume is greater than a nanoliter and more commonly greater than 10 nanoliters.

A solid support is a piece of solid material that incorporates reaction sites and other features of the apparatus. For example, a solid support can be a
5 microscope slide with reaction sites and connecting channels etched into its surface. A solid support can be made of many different materials, including glass, plastic, quartz, silicon, metal, and the like.

A reaction site is a location on the solid support where a chemical reaction can take place. A reaction site can be located at a conduit or channel used to
10 transport fluid compositions including substrates, intermediates, and reagents. Alternatively, a reaction site is located in a reservoir, i.e., an enlarged volume relative to a channel or conduit to which a channel or conduit is connected.

Chemical reactions that can be carried out on the disclosed apparatus include reactions that chemically transform a substrate compound, or starting
15 material, into an intermediate compound, or reaction product. An intermediate from one reaction can serve as a substrate for the next enzyme in the sequence. A substrate is a starting material for a catalyzed reaction, and is the molecule or molecules that are chemically transformed into the intermediate or product. Specific kinds of chemical reaction include, among others, condensation,
20 acylation, dimerization, alkylation, rearrangement, transposition, decarbonylation, coupling, aromatization, epoxidation, disproportionation, hydrogenation, oxidation, reduction, substitution, isomerization, stereoisomerization, functional group conversion, functional group addition, elimination, bond cleavage, photolysis, photodimerization, cyclization,
25 hydrolysis, polymerization, and the like.

A biocatalyst is a catalyst that has a biological origin. A catalyst is an agent that causes a chemical reaction to proceed more quickly, without being chemically modified itself. Thus, a single catalyst can speed up the chemical transformation of many substrate molecules. Biocatalysts include catalytic
30 antibodies, enzymes, catalytic peptides and catalytic RNA molecules. As used herein, biocatalysts can also be selections from natural biocatalysts, for

example, the smallest functional catalytic portion of a multi-enzyme complex can be used, instead of the entire complex. A biocatalyst, as used herein, includes intact cells, cell organs, and cell extracts that can catalyze reactions.

An immobilized biocatalyst is attached to a reaction site so that is fixed, i.e.,
5 it is generally not washed away by the fluids used by the invention.

Furthermore, an immobilized biocatalyst is attached in a way that allows it to retain most of the function of its non-immobilized state, and is stabilized against loss of catalytic activity that could occur due to reaction conditions. For example, immobilized enzymes can often be used with organic solvents that
10 would cause denaturation of non-immobilized enzymes.

Biocatalysts can be immobilized by encapsulation in or covalent attachment to a number of different materials. Suitable materials can be substituted or unsubstituted, and include, for example, a solgel, a hydrogel, collagen gel, a polysaccharide gel, or other polymers. A solgel, for example, is a
15 tetramethoxyorthosilicate, a methyl-trimethoxyorthosilicate, a tetraalkoxyorthosilicate, or a trialkoxyorthosilicate. A hydrogel is, for example, a polyacrylamide, a polyacrylate, a sugar-substituted polyacrylate, or a polyvinyl alcohol. A polysaccharide gel is, for example, is an alginate, a dextran, a starch, a cellulose, a carrageenan, a poly(hyaluronic acid), a heparin,
20 a guar, or an inulin. Other polymers include a polyvinylene, a poly(vinyl acetate), a poly(ethyl vinyl ether), a polyacrylate such as a polymethyl methacrylate, a polystyrene, a polyvinyl silicate, a polyurethane, a polyalkanoate, a poly(lactic acid), a poly(3-hydroxybutyrate), or substituted variations thereof.

25 In the case of covalent attachment, for example, an enzyme is first chemically modified by attaching it via a chemical bond to an immobilizing polymer. For example, an enzyme can be reacted with acrylamide, which contains an ethylenically unsaturated group. The enzyme can then be combined with a polymerization precursor that also contain ethylene groups, such as
30 acrylate. By co-polymerizing the ethyleneic groups on the enzyme with the acrylate precursor, an acrylate polymer is formed wherein the enzyme is

attached by one or more chemical bonds to the polymer. Also, by attaching it directly to the polymer, the enzyme can be located within the polymer as well as on the surface of the polymer, increasing the amount of enzyme that can be immobilized at a reaction site.

5 In the case of non-covalent encapsulation, for example, an enzyme can be combined with one of the immobilizing materials noted above. Alternatively, the enzyme is combined with a precursor of a material, such as glucose acrylate or a solgel precursor, and the mixture is reacted to form the material so that the enzyme is encapsulated as the precursor is polymerized. Alternatively, an
10 additional step includes crosslinking the material to further restrict the enzyme to the material.

The details of immobilizing enzymes in sol-gels, hydrogels, and other materials are fully described in previously published work, including: Kim, Y; Park, C.; Clark, D. 2001 Biotechnol Bioeng., **73**, 331-337; Wang, P., Sergeeva,
15 M.V., Lim, L., and Dordick, J.S. 1997, Nat. Biotechnol. **15**: 789-793; Novick, S.J. and Dordick, J.S. 2000, Biotechnol. Bioeng. **68**: 665-671; Sergeeva, M.V., Paradkar, V.M., and Dordick, J.S. 1997, Enzyme Microb. Technol. **20**: 623-628; Novick, S.J. and Dordick, J.S. 1998, Chem. Mat. **10**: 955-958; Kim, J., Delio, R. and Dordick, J.S. 2002; Biotechnol. Prog. The entire teaching of the preceding
20 works are incorporated herein by reference.

When the immobilizing polymer is a polyacrylate, for example its precursor monomer can be advantageously substituted with a sugar such as sucrose, lactose, mannose, an alkylmannoside, glucose, an alkylglucoside, galactose, an alkylgalactoside, fructose, an alkylfructoside, or trehalose. Immobilizing
25 enzymes in combination with sugar molecules helps to maintain their normal catalytic activity. Referencing the above example, the polymerization precursor could be, for example, acrylate substituted with glucose.

As used herein, distinct catalysts are catalysts, including biocatalysts, which have different structures, different formulas or catalyze different reactions. For
30 example, two enzymes that vary by a single amino acid in sequence are distinct.

Also, enzymes that produce different products from the same substrate are distinct.

A "micro-directing element" is a physical feature such as a channel, a conduit, a chamber, and the like that can be used to transport substrates, intermediates, products, reagents, solvents, and the like from one reaction site to another. A micro-directing element can also introduce substrates or reagents to the apparatus from a source, or direct an intermediate or a product to a detector or to a location off the apparatus.

The apparatus can employ active or passive transport mechanisms to move intermediates, products, reagents, solvents, and the like from one site to another. In one embodiment, the micro-directing element is a channel, and a passive transport mechanism employs diffusion, thermal convection, capillary action, and the like. In another embodiment, an active transport mechanism is a device that employs a motive force including pressure, electroosmotic force, piezoelectric force, electrostatic force, centrifugal force, or force generated by centripetal acceleration. In a preferred embodiment, the force used is electroosmotic force.

Optionally, the disclosed apparatus includes a micro-directing element to direct a composition from a source to at least one reaction site. A source can be, for example, a chamber or reservoir containing a substrate composition or another consumable composition needed at a reaction site, such as a solvent, buffer, reagent, etc. The disclosed apparatus can comprise more than one source, each directed to the same reaction site, to different reaction sites or to other useful locations on the apparatus.

The disclosed apparatus often comprises more than two reaction sites, e.g., typically comprising n additional reaction sites, wherein n is an integer from 1 to 50. Typically, each additional reaction site comprises a distinct immobilized biocatalyst. The apparatus additionally comprises micro-directing elements to sequentially direct a composition from the second reaction site to each of the n additional reaction sites. "Sequentially" means that a composition can be directed in a particular and pre-designated order from a first reaction site to the

last reaction site through each of the other reaction sites in the pre-designated order. For example, that when there are four distinct reaction sites (i.e., n is 2), a composition can be directed to the first reaction site, then to the second reaction site, then to third reaction site and finally to the fourth reaction site.

5 In another option, the apparatus additionally comprises at least one reaction site that comprises a catalyst of non-biological origin. For example, a catalyst normally used in a non-biological context, such as a metal oxidation catalyst, can be incorporated into a reaction site.

10 In still another embodiment, the biocatalyst at the first reaction and the biocatalyst at the second reaction site are each a functional catalytic unit from sequential steps in a natural biosynthetic pathway. A natural biosynthetic pathway is a sequence of reaction steps that a living cell performs to transform a substrate compound into a natural product compound. A functional catalytic unit comprises the biocatalytic components that conduct a reaction step. A
15 functional catalytic unit can be a single enzyme, or an enzyme and its cofactor, or a multi-enzyme complex, and the like. For example, in a simple two-step biosynthetic pathway, a substrate S can be acted on by an enzyme A to produce a first intermediate I . A multi-enzyme complex B can then act upon first
20 intermediate I to produce a second intermediate, or product P . To produce this pathway in the apparatus, enzyme A is immobilized at the first reaction site, and multi-enzyme complex B is immobilized at the second reaction site.

25 In another embodiment of the apparatus, the biocatalyst at the first reaction site, the second reaction site and each of the n additional reaction sites are a functional catalytic unit from the steps of a natural biosynthetic pathway, and the apparatus additionally comprises micro-directing elements to direct a
30 composition sequentially to each of the reaction sites in the order of the sequence of the catalytic units in the biosynthetic pathway. In this embodiment, the apparatus reproduces an entire biosynthetic pathway. Examples of natural biosynthetic pathways that can be reproduced in the disclosed apparatus include the picromycin polyketide synthase pathway, the erythromycin polyketide

synthase pathway, the nonribosomal peptide synthetase pathway, or the β -lactam nonribosomal peptide synthetase pathway.

Optionally, the apparatus includes a device to control the temperature of at least a portion of the apparatus. Such devices can include a heat exchanger, a heating element, a chilled water loop, a refrigeration loop, a heat sink, a thermal gradient maintained between two heat sinks of different temperature, a spot heating method such as an individual heating element, a focused infrared light source, and the like. Temperature affects reaction rates and the stability of substrates, catalysts, biocatalysts, and intermediates. Certain operations on the apparatus can raise the temperature, for example, in some circumstances, employing electroosmotic force can lead to increased temperature. This can be undesirable in some situations so it can be necessary to cool the apparatus. By contrast, it can be advantageous to change the temperature of a reaction site to change a reaction rate. Thus, the same apparatus could optionally include location specific temperature control as well as apparatus-wide temperature control.

Other optional features of the apparatus include a detector and micro-directing elements to direct at a composition from one reaction site to a detector. A detector is a component or series of components that detect properties of a reaction or a reaction product. For example, a mass spectrometer can measure the molecular weight of a chemical compound or a spectrometer could measure the concentration of a compound via absorption. The detector can include an aspiration probe, a laser desorption probe, an ion beam desorption probe, a gas desorption probe, a liquid desorption probe, a contact probe, an optical spectrometer, a microscope, an imager, a mass spectrometer, a chromatography apparatus, an electrochemical detector, a particle detector, a radiation detector, a magnetic resonance spectrometer, or a chemical indicator.

A preferred embodiment of the invention is a microfluidics chip, comprising a solid support comprising a first and second reaction site, wherein the first and second reaction sites each comprise a distinct biocatalyst. Each biocatalyst is a functional catalytic unit of a natural biosynthetic pathway; and each said

biocatalyst is immobilized by a polyacrylate substituted with sucrose, lactose, mannose, an alkylmannoside, glucose, an alkylglucoside, galactose, an alkylgalactoside, fructose, an alkylfructoside, or trehalose. The chip uses microfluidics to direct a substrate composition from a source to the first reactive composition, and microfluidics elements to direct an intermediate composition from the first reaction site to the second reaction site, wherein the biocatalysts at the first and second sites are from sequential steps in the natural biosynthetic pathway.

The apparatus can be used in a number of different ways, e.g., to conduct sequential reactions, to mimic portions of a natural biosynthetic pathway, to conduct variations on a natural pathway, to create hybrid elements of natural and unnatural pathways, and to conduct novel pathways.

To conduct the disclosed method using the disclosed apparatus, a substrate is directed to the first reaction site and exposed to conditions suitable for reacting said substrate with said immobilized catalyst, thereby producing a first intermediate composition.

The method further includes directing the first intermediate to the second reaction site, again exposing the second reaction site to conditions suitable for reacting the first intermediate with the immobilized catalyst, thereby producing a second intermediate composition. This process can be repeated for each subsequent reaction site, i.e., the intermediate produced by a reaction site becomes the substrate for a subsequent reaction site. The intermediate produced by the final reaction site in the sequence can then be termed the product of the sequence.

Suitable conditions for reaction include chemical, physical, and biological elements that allow, facilitate, or are necessary for a reaction to take place between a substrate and a catalyst. A chemical element can be a solvent, a buffer, a co-substrate, a consumable chemical reagent, and the like. A physical element can be the temperature, pressure, reaction time, and the like. A physical element can be also be, for example, application of a light source for an enzyme-catalyzed photochemical reaction, or application of an electric potential

to assist an oxidation or reduction reaction. A biological element can be, for example, an enzyme cofactor, or a supply of a consumable reagent such as adenosine triphosphate (ATP) or nicotinamide adenine dinucleotide phosphate (NADPH).

5 By combining the apparatus and methods disclosed herein a variety of different reaction scenarios can be realized. For natural biosynthetic pathways, portions or entire pathways can be reproduced. The elements of natural pathways can be rearranged to produce unnatural sequences. Additional steps can be incorporated, whether duplicated steps form the original pathway, steps
10 from other biosynthetic pathways, or artificial reaction steps that are not part of any natural pathway. In addition, natural pathways can be altered by using unnatural substrates, whether by adding them to the apparatus from a source or by creating unnatural intermediates that result from preceding reactions. Also, an apparatus can consist of biocatalysts where no two biocatalysts originate
15 from the same natural pathway. With every possibility, a substrate is directed to a reaction site, exposed to conditions suitable for reaction with the biocatalyst immobilized at that site, and the resulting intermediate is directed to the next site, where the reaction cycle repeats. Thus, using the same apparatus, numerous different synthetic pathways can be produced. In this manner, large
20 numbers of natural products, variations on natural products, and completely novel products can be synthesized.

Another option in the method of the invention is detecting a constituent of a composition, e.g., an end product, an intermediate, an unwanted intermediate, unreacted substrate, byproducts, consumable reagents, and the like. The step of
25 detecting employs an aspiration probe, a laser desorption probe, an ion beam desorption probe, a gas desorption probe, a liquid desorption probe, a contact probe, an optical spectrometer, a microscope, an imager, a mass spectrometer, a chromatography apparatus, an electrochemical detector, a particle detector, a radiation detector or a magnetic resonance spectrometer.

30 Another embodiment of the invention is a method for conducting sequential reactions, comprising the steps of providing a microfluidics chip, where the chip

comprises a first reaction site and a second reaction site. Each reaction site comprises an immobilized biocatalyst, wherein each catalyst is a catalytic antibody, an enzyme, an enzyme domain, a multi-enzyme complex, a catalytic peptide or a catalytic RNA molecule. Each said immobilized catalyst is

5 immobilized by a material comprising a polyacrylate substituted with sucrose, lactose, mannose, an alkylmannoside, glucose, an alkylglucoside, galactose, an alkylgalactoside, fructose, an alkylfructoside, or trehalose. Using this apparatus, the method comprises the steps of directing (preferably by

10 microfluidics) a substrate composition to the first reaction site under conditions suitable for reacting said substrate with said biocatalyst, thereby producing a first intermediate composition. Another step includes directing said first intermediate to the second reaction site under conditions suitable for reacting said intermediate with said biocatalyst, thereby producing a second intermediate composition.

15

EXEMPLIFICATION

The present invention is illustrated by the following examples, which are not intended to be limiting in any way.

Example 1: Enzymatic polyphenol synthesis on a microfluidics chip

20 A simple T-shaped microfluidic biochip was fabricated using standard photolithographic techniques and wet etching. The reservoirs had a volume of 3 μL and the main channel length was 30 mm with a width of 176 micrometers and a depth of 15 micrometers to give a channel volume of 80 nanoliters. Stable bonding of the cover slide, which is necessary to allow flow to occur in

25 channels and avoid leakage, was done at 595°C with optimized heating and cooling rates. Fluid transport in the channels was carried out electroosmotically after hydrolyzing the silanol groups on the channel wall using 1N NaOH.

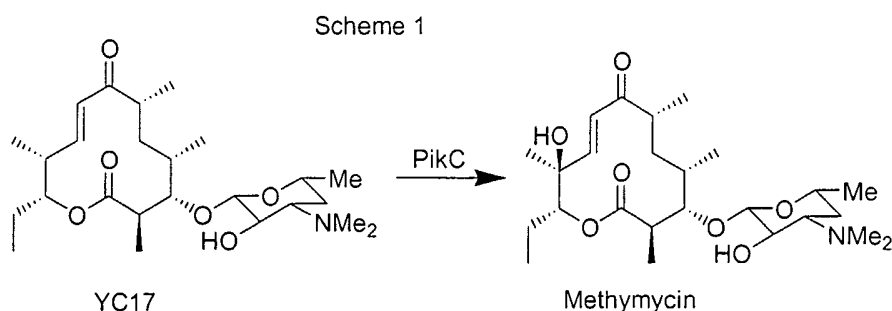
Calcein blue was used as a fluorescent dye to visualize fluid flow using a CCD camera. A similar microfluidic system was used to demonstrate enzyme-catalyzed polymer synthesis. Specifically, soybean peroxidase and *p*-cresol

30 (from one reservoir) were mixed with H_2O_2 (from a second reservoir) and the

mixture was directed through the channel using voltages ranging from 500-2000 V. Other conditions include 100 $\mu\text{g/ml}$ SBP (enzyme reservoir); 10 mM *p*-cresol (substrate reservoir), 0.4 mM H_2O_2 (consumable reagent reservoir), pH 5 aqueous buffer containing 30% (v/v) DMF. The T-junction aided in the mixing of the reactant streams. The increase in product is constant and enables us to calculate a conversion of $\sim 50\%$ (within the microchannel) based on the limiting substrate, H_2O_2 . Analysis was performed by removing a 2 μL aliquot from the receiving well, diluting 10x, and measuring fluorescence in a plate reader in 384-well plates. In addition to *p*-cresol, we used other *para* substituted phenols in this microfluidic bioreactor, including methoxyphenol, phenylphenol, and hydroxyphenyl acetic acid.

Example 2: Methymycin synthesis on a microfluidics chip

The microfluidic chip design in Example 1 was used to perform the PikC-catalyzed hydroxylation of YC-17 to methymycin (Scheme 1). The macrolide substrate (YC-17) and PikC (from one reservoir) was mixed with spinach-ferredoxin NADP⁺-reductase, ferredoxin, and NADPH (from the second reservoir) and the hydroxylation reaction was allowed to take place down the microchannel using electroosmotic flow conditions as described for polyphenol synthesis in Example 1. Conversions of ca. 75% (using conditions summarized in Fig. 2) were achieved, thereby demonstrating that one of the key enzymatic steps of the polyketide synthesis pathway can be performed on the microscale.



Scheme 1. The enzyme catalyzed reaction described in Example 2. Hydroxylation of YC-17 (0.5 mM) to methymycin catalyzed by PikC hydroxylase (1 μM) in the presence of spinach ferredoxin-NADP⁺ reductase (0.1 U), ferredoxin (3.5 μM), and NADPH (1 mM)

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein
5 without departing from the scope of the invention encompassed by the appended claims.

CLAIMS

What is claimed is:

- 5 1. An apparatus for conducting a plurality of microscale reactions,
comprising
- a. a solid support comprising a first and a second reaction site,
wherein each site comprises a distinct immobilized biocatalyst;
- 10 b. a micro-directing element to direct an intermediate composition
from the first site to the second site.
2. The apparatus of Claim 1, further comprising a micro-directing element
to direct a composition from a source to at least one said reaction site.
- 15 3. The apparatus of Claim 2, wherein each said biocatalyst is a catalytic
antibody, an enzyme, an enzyme domain, a multi-enzyme complex, a
catalytic peptide or a catalytic RNA molecule.
4. The apparatus of Claim 2, wherein
- 20 a. the apparatus comprises n additional reaction sites;
- b. n is an integer from 1 to 50;
- c. each reaction site comprises a distinct immobilized biocatalyst; and
- d. the apparatus additionally comprises one or more micro-directing
25 elements to sequentially direct a composition from the second
reaction site to each of the n additional reaction sites.
5. The apparatus of Claim 3, wherein the apparatus additionally comprises
at least one reaction site which comprises a catalyst of non-biological
origin.

6. The apparatus of Claim 3, wherein the biocatalyst at the first reaction and the biocatalyst at the second reaction site are each a functional catalytic unit from sequential steps in a natural biosynthetic pathway.
- 5 7. The apparatus of Claim 4, wherein:
- a. the biocatalyst at the first reaction site, the second reaction site and each of the n additional reaction sites are a functional catalytic unit from the steps of a natural biosynthetic pathway;
- b. the apparatus additionally comprises one or more micro-directing
10 elements to direct a composition sequentially to each of the reaction sites in the order of the sequence of the catalytic units in the biosynthetic pathway.
8. The apparatus of Claim 7, wherein said biosynthetic pathway is the
15 picromycin polyketide synthase pathway, the erythromycin polyketide synthase pathway, the nonribosomal peptide synthetase pathway, or the β -lactam nonribosomal peptide synthetase pathway.
9. The apparatus of Claim 4, wherein each biocatalyst is immobilized by a
20 material comprising, a polyacrylamide, a polyacrylate, a sugar-substituted polyacrylate, a polyvinyl alcohol, a polyvinylene, or a polyvinyl silicate.
10. The apparatus of Claim 9, wherein each said material comprises a
25 polyacrylate substituted with sucrose, lactose, mannose, an alkylmannoside, glucose, an alkylglucoside, galactose, an alkylgalactoside, fructose, an alkylfructoside, or trehalose.
11. The apparatus of Claim 10, wherein said micro-directing elements
30 comprise a channel or a conduit between each reaction site in the sequence.

12. The apparatus of Claim 11, wherein said apparatus additionally comprising a device to propel a fluid between the reaction sites using electroosmotic force.
- 5
13. The apparatus of Claim 12, further comprising a device to control the temperature of at least a portion of the apparatus.
14. The apparatus of Claim 13, further comprising a micro-directing element to direct at least one said intermediate composition from one said reaction site to a detector.
- 10
15. The apparatus of Claim 14, further comprising a detector, wherein said detector comprises an aspiration probe, a laser desorption probe, an ion beam desorption probe, a gas desorption probe, a liquid desorption probe, a contact probe, an optical spectrometer, a microscope, an imager, a mass spectrometer, a chromatography apparatus, an electrochemical detector, a particle detector, a radiation detector or a magnetic resonance spectrometer.
- 15
- 20
16. A microfluidics chip, comprising
- a. a solid support comprising a first and second reaction site, wherein
- i. the first and second reaction sites each comprise a distinct biocatalyst that is a functional catalytic unit of a natural biosynthetic pathway;
- 25
- ii. each said biocatalyst is immobilized by a polyacrylate substituted with sucrose, lactose, mannose, an alkylmannoside, glucose, an alkylglucoside, galactose, an alkylgalactoside, fructose, an alkylfructoside, or trehalose;
- 30
- b. directing a substrate composition by microfluidics from a source to the first reactive composition, and directing an intermediate

composition by microfluidics from the first reaction site to the second reaction site, wherein the biocatalysts at the first and second sites are from sequential steps in the natural biosynthetic pathway

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17. A method for conducting reactions at a plurality of reaction sites, comprising the steps of:
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- a. providing an apparatus, wherein
 - i. said apparatus is a solid support comprising a first reaction site and a second reaction site;
 - ii. each reaction site comprises a distinct immobilized biocatalyst; and
 - b. directing a substrate composition to said first reaction site and exposing the first reaction site to conditions suitable for reacting said substrate with said immobilized catalyst, thereby producing a first intermediate composition; and
 - c. directing said first intermediate composition to said second reaction site and exposing the second reaction site to conditions suitable for reacting said first intermediate with said immobilized catalyst, thereby producing a second intermediate composition.
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18. The method of Claim 17, further comprising the step of directing a composition from a source to at least one said reaction site.
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19. The method of Claim 17, wherein
- a. the apparatus additionally comprises n additional reaction sites;
 - b. n is an integer from 1 to 50;
 - c. each reaction site comprises a distinct immobilized biocatalyst; and
 - d. the apparatus additionally comprises one or more micro-directing elements to sequentially direct a composition from the second
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reaction site to each of the n additional reaction sites, wherein the method further comprises the steps of:

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- i. directing the second intermediate to the next reaction site in the sequence and exposing the next reaction site to conditions suitable for reacting the second intermediate with the biocatalyst at the next site, thereby producing a third intermediate;
 - ii. repeating step (i) with the third intermediate and each subsequent intermediate.

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20. The method of Claim 19, wherein each said biocatalyst is a catalytic antibody, an enzyme, an enzyme domain, a multi-enzyme complex, a catalytic peptide or a catalytic RNA molecule.

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21. The method of Claim 17, wherein the substrate is an unnatural substrate for the biocatalyst at the first reaction site, or one of the intermediates is an unnatural substrate for the biocatalyst at the next reaction site in the sequence.

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22. The method of Claim 17, wherein the apparatus additionally comprises a catalyst of non-biological origin.

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23. The method of Claim 17, wherein the biocatalyst at the first reaction site and at the second reaction site are each a distinct functional catalytic unit from sequential steps in a natural biosynthetic pathway.

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24. The method of Claim 23, wherein said biosynthetic pathway is the picromycin polyketide synthase pathway, the erythromycin polyketide synthase pathway, the nonribosomal peptide synthetase pathway, or the β -lactam nonribosomal peptide synthetase pathway.

25. The method of Claim 19, wherein:
- a. the biocatalyst at the first reaction site, the second reaction site and each of the n additional reaction sites are a functional catalytic unit from the steps of a natural biosynthetic pathway;
 - 5 b. wherein the reaction sequence of the apparatus and the reaction sequence of the biosynthetic pathway are the same.
26. The method of Claim 17, wherein each said immobilized catalyst is immobilized by a material comprising a polyacrylamide, a polyacrylate, 10 a sugar-substituted polyacrylate, a polyvinyl alcohol, a polyvinylene, or a polyvinyl silicate.
27. The method of Claim 26, wherein each said material comprises a polyacrylate substituted with a sugar comprising sucrose, lactose, 15 mannose, an alkylmannoside, glucose, an alkylglucoside, galactose, an alkylgalactoside, fructose, an alkylfructoside, or trehalose.
28. The method of Claim 27, wherein the micro-directing element is a channel or a conduit between each reaction site in the sequence; and 20 the compositions are directed by pressure, electroosmotic force, piezoelectric force, electrostatic force, centrifugal force, or a force generated by centripetal acceleration.
29. The method of Claim 28, further comprising the step of directing said 25 compositions by electroosmotic force.
30. The method of Claim 29, further comprising the step of detecting a constituent of a composition.
- 30 31. The method of Claim 30, wherein the step of detecting employs an aspiration probe, a laser desorption probe, an ion beam desorption probe,

a gas desorption probe, a liquid desorption probe, a contact probe, an optical spectrometer, a microscope, an imager, a mass spectrometer, a chromatography apparatus, an electrochemical detector, a particle detector, a radiation detector or a magnetic resonance spectrometer.

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32. The method of Claim 31, further comprising the step of controlling the temperature.
33. A method for conducting sequential reactions, comprising the steps of:
- 10 a. providing a microfluidics chip, wherein:
- i. said chip comprises a first reaction site and a second reaction site; and
- ii. each said reaction site comprises an immobilized biocatalyst, wherein each said catalyst is a catalytic antibody, an enzyme, an enzyme domain, a multi-enzyme complex, a catalytic peptide or a catalytic RNA molecule; and
- 15 b. directing a substrate composition to the first reaction site under conditions suitable for reacting said substrate with said biocatalyst, thereby producing a first intermediate composition; and
- 20 c. directing said first intermediate to the second reaction site under conditions suitable for reacting said intermediate with said biocatalyst, thereby producing a second intermediate composition.
34. The method of Claim 33 wherein the biocatalysts in step (ii) combined with step (b) and step (c) collectively constitute the sequence of a portion of a natural biosynthetic pathway.
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35. The method of Claim 33 wherein the biocatalysts in step (ii) combined with step (b) and step (c) collectively constitute an unnatural sequence.

36. The apparatus of Claim 1, wherein each biocatalyst is immobilized by a material, wherein said material comprises a solgel, a collagen gel, a hydrogel, or a polysaccharide gel
- 5 37. The apparatus of Claim 36, wherein a solgel is substituted or unsubstituted and is a tetramethoxyorthosilicate, a methyl-trimethoxyorthosilicate, a tetraalkoxyorthosilicate, or a trialkoxyorthosilicate.
- 10 38. The apparatus of Claim 37, wherein a hydrogel is substituted or unsubstituted and is a polyacrylamide, a polyacrylate, a sugar-substituted polyacrylate, or a polyvinyl alcohol.
- 15 39. The apparatus of Claim 38, wherein a polysaccharide gel is substituted or unsubstituted and is an alginate, a dextran, a starch, a cellulose, a carrageenan, a poly(hyaluronic acid), a heparin, a guar, or an inulin.