



(51) International Patent Classification:

C12N 1/15 (2006.01) C12N 15/31 (2006.01)
C12N 5/00 (2006.01) C07K 1/00 (2006.01)
C12N 9/00 (2006.01) C07K 19/00 (2006.01)

(21) International Application Number:

PCT/US2014/015343

(22) International Filing Date:

7 February 2014 (07.02.2014)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

61/762,125 7 February 2013 (07.02.2013) US

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

[Continued on next page]

(54) Title: TALE TRANSCRIPTIONAL ACTIVATORS

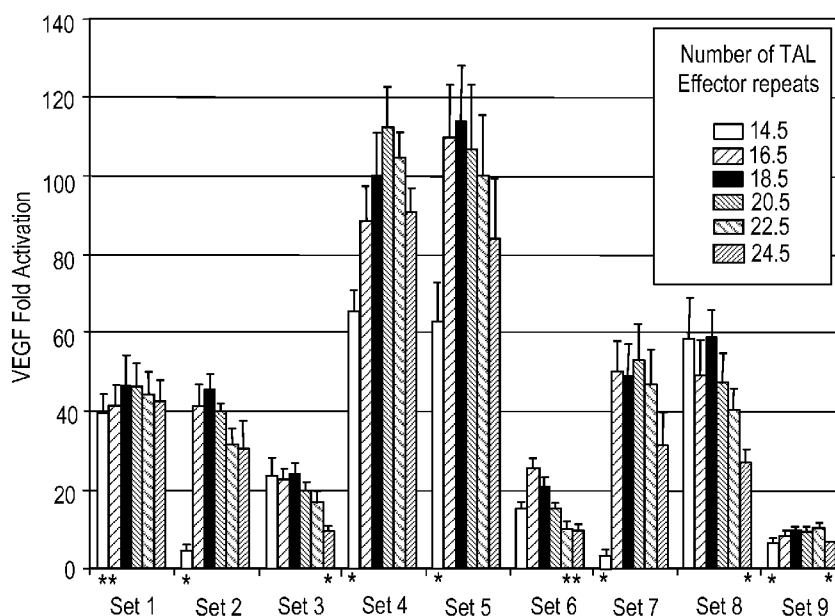


FIG. 1B

(57) Abstract: Computer programs, algorithms, and methods for identifying TALE-activator binding sites, and methods for generation and use of TALE-activators that bind to said sites.



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- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

TALE TRANSCRIPTIONAL ACTIVATORS

CLAIM OF PRIORITY

This application claims the benefit of U.S. Provisional Patent Application Serial No. 61/762,125, filed on February 7, 2013. The entire contents of the foregoing are hereby incorporated by reference.

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with Government support under Grant Nos. DP1 OD006862, P50 HG005550, R01 NS073124, and T32 CA009216 awarded by the National Institutes of Health. The Government has certain rights in the invention.

TECHNICAL FIELD

This invention relates to methods, e.g., computer-implemented methods, for designing and engineering artificial TAL effector activators (TALE-activators).

BACKGROUND

Rapid advances in *Xanthomonas*-derived transcription activator-like (TAL) effector technology have enabled any researcher to construct tools for targeted alteration of gene sequence or expression. Highly conserved 33-35 amino acid TAL effector repeat domains each bind to one nucleotide of DNA with specificity dictated by the identities of two hypervariable residues.¹ To construct a protein capable of recognizing a specific DNA sequence, repeats with different specificities are simply joined together into a multimerized array. Much recent effort has focused on engineered TAL effector nucleases (TALENs), fusions consisting of TAL effector repeat arrays and a nuclease domain that enable routine targeted modification of endogenous genes in a variety of different organisms and cell types.¹ TAL effector repeat arrays have also been fused to transcriptional activation domains to construct artificial TAL effector activators (TALE-activators) that can increase endogenous gene expression in plant and human cells.²⁻¹⁰ Artificial transcription factors that can be custom-made for target genes of interest have already shown promise as broadly useful research tools and may have potential for therapeutic applications.¹¹

SUMMARY

At least in part, the present invention is based on the discovery that TALE-activators composed of 16.5 to 22.5 repeats have optimal activity, and that the level of gene expression induced by TALE-activators can be fine-tuned, by altering the specific activation domain used and/or by exploiting the ability of TALE-activators, like naturally occurring transcription factors, to function synergistically.

Thus in a first aspect the invention provides computer-implemented methods performed by one or more processing devices. The methods comprise providing information to cause a user device to display a user interface that includes a user input mechanism for receiving information related to a target gene; receiving, from the user device, a selected target gene; identifying, by one or more computers, one or more subsequences of the target gene sequence, wherein: the subsequence is within a regulatory region of the target gene, e.g., within a promoter region; the subsequence is within a DNase I hypersensitive region of the regulatory region of the target gene, the subsequence is 18-24 nucleotides long; and optionally, the first nucleotide (5' to the first canonical TALE-repeat domain binding nucleotide) in the subsequence is a thymine; and selecting the one or more subsequences; and providing information to cause the user device to display at least some of the selected one or more subsequences.

In another aspect the invention provides methods for identifying a candidate *Xanthomonas*-derived transcription activator-like effector (TALE) activator binding site. The methods comprise: selecting a target gene; identifying one or more subsequences of the target gene sequence, wherein: the subsequence is within a regulatory region of the target gene, e.g., within a promoter region; the subsequence is within a DNase I hypersensitive region of the regulatory region of the target gene, the subsequence is 18-24 nucleotides long; and optionally, the first nucleotide (i.e., 5' to the first canonical TALE-repeat domain binding nucleotide) in the subsequence is a thymine; and selecting the one or more subsequences as candidate TALE-activator binding sites.

The selection of a subsequence is made based on the presence of the subsequence within a regulatory region of the target gene, e.g., within a promoter region; based on the presence of the subsequence within a DNase I hypersensitive region of the regulatory region of the target gene; selecting a subsequence that is 18-

24 nucleotides long; and optionally, selecting a sequence that has a thymine as the nucleotide just 5' to the first nucleotide in the subsequence.

In some embodiments, the methods can include identifying a subsequence wherein one or more of the following is true, or is not true: the second nucleotide of the subsequence is an adenosine; the 3' most nucleotide of subsequence is not a thymine; and/or the base composition of the TAL effector repeat array binding site varies from an observed percent composition of naturally occurring binding sites by more than 2 standard deviations, i.e., is other than A = 0-63%, C = 11-63%, G = 0-25%, T = 2-42%.

In an additional aspect, the invention provides methods for making a TALE-activator that increases transcription of a target gene, e.g., a coding or non-coding gene, e.g., a miRNA. The methods comprise: selecting a target gene; identifying one or more subsequences of the target gene sequence, wherein: the subsequence is within a regulatory region of the target gene, e.g., within a promoter region; the subsequence is within a DNase I hypersensitive region of the regulatory region of the target gene; the subsequence is 18-24 nucleotides long, preferably 18 nucleotides long; and optionally the first nucleotide (5' to the first canonical TALE-repeat domain binding nucleotide) in the subsequence is a thymine; selecting a subsequence; and generating a fusion protein comprising: an engineered DNA-binding domain that comprises an engineered transcription activator-like effector (TALE) repeat array and that binds specifically to the selected subsequence, and a transactivation domain comprising a sequence that increases transcription of a target gene; thereby making a TALE-activator that increases transcription of the target gene.

In some embodiments, the TALE repeat array is 16.5 to 22.5 repeats (the C-terminal repeat is typically shorter and is referred to as a "half repeat").

In some embodiments, the transactivation domain comprises a VP16, VP64 or NF-KB p65 domain, preferably VP64.

In an additional aspect, the invention provides methods for increasing transcription of a target sequence in a cell, the method comprising contacting the cell with a TALE-activator made by a method described herein.

In an additional aspect, the invention provides methods for increasing transcription of a target sequence in a cell, by contacting the cell with two or more TALE-activators made by a method described herein.

In some embodiments, at least one of the two or more TALE-activators comprises VP64, and at least one of the two or more TALE-activators comprises NF-KB p65 domain.

The subsequences identified by the methods described herein are also referred to as TALE-activator binding sites.

In some embodiments of the methods describe herein wherein the first (5') nucleotide in the subsequence is a thymine, the subsequence includes the DNA bases (e.g., 17-23 bases) that are each specified by a single canonical TALE-repeat domain, and an additional T base that is located just 5' to the first base contacted by the amino-terminal-most canonical TALE-repeat domain; this T base is part of the subsequence (i.e., the subsequence includes the 5' T), but in preferred embodiments is not bound by one of the canonical TALE repeat domains (the 5' T is believed to contact the N terminus of the TALE that precedes the first canonical TALE-repeat domains; there is a pseudo-repeat-like domain there that is believed to make the contact to this T). See, e.g., Joung and Sander, *Nature Reviews Molecular Cell Biology* 14, 49-55 (2013). In some embodiments where the 5' nucleotide is other than thymine, the subsequence can be 17-23 nucleotides long, and in some embodiments is 17-18 nucleotides long, and therefore consists entirely of nucleotides that contact the TALE repeat domains.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Methods and materials are described herein for use in the present invention; other, suitable methods and materials known in the art can also be used. The materials, methods, and examples are illustrative only and not intended to be limiting. All publications, patent applications, patents, sequences, database entries, and other references mentioned herein are incorporated by reference in their entirety. In case of conflict, the present specification, including definitions, will control.

Other features and advantages of the invention will be apparent from the following detailed description and figures, and from the claims.

DESCRIPTION OF DRAWINGS

Figures 1A-B Activities of 54 variable length TALE-activators targeted to the endogenous human *VEGF-A* gene. **(a)** Schematic depicting the human *VEGF-A* promoter region. The transcription startpoint is indicated with a black arrow and

previously published DNase I hypersensitive regions¹⁹ are shown as grey bars. The DNase I hypersensitive region located between positions +400 to +650 relative to the transcription start site has been expanded, with red arrows indicating the locations and orientations of the 26 bp sites bound by the longest length TALE-activator (harboring 24.5 TAL effector repeats) in each set. (b) Activation of VEGF-A protein expression in 293 cells by 54 variable-length TALE-activators. Fold-activation values were calculated as described in Methods. Each TALE-activator was assayed in triplicate and error bars represent standard errors of the mean. Asterisks indicate fold-activation values that are outliers (assuming a normal distribution) relative to other values in the same set. All activators tested (except the 14.5-repeat activator from set 7) induced fold-activation of VEGF-A expression to a value significantly greater than 1, as determined by a one-sided, paired t-test.

Figure 1C Schematic of TALE-activator architecture used in this study.

The TALE-activator architecture we used for our experiments is similar to one described by Rebar and colleagues (Miller, J.C. et al. Nat Biotechnol 29, 143-148 (2011)). These proteins contain the Δ 152 N-terminal domain and the +95 C-terminal domain that flank the TAL effector repeat array as well as an N-terminal nuclear localization signal (NLS) and a C-terminal activation domain (either VP64 or p65).

Figures 2A-C Activities of 16 TALE-activators targeted to the endogenous human *VEGF-A*, *miR-302/367* cluster, and *NTF3* genes. For all three gene targets, experiments were performed in triplicate with TALE-activators harboring either the VP64 (green bars) or NF-KB p65 (blue bars) activation domain. Error bars represent standard errors of the mean. (a) *VEGF-A*-targeted TALE-activators. Fold-activation values of VEGF-A protein were determined as described in Methods. Asterisks indicate activators that induced fold-activation of VEGF-A significantly greater than 1, as determined by a one-sided, paired t-test. (b) *miR-302/367*-targeted TALE-activators. Fold-activation values of *miR-302a* transcript were determined as described in Methods. Asterisks indicate activators that induced fold-activation of *miR-302a* transcript levels to a level significantly greater than 1 as determined by a one-sided, paired t-test. (c) *NTF3*-targeted TALE activators. Expression levels of *NTF3* mRNA relative to *GAPDH* mRNA are shown. Asterisks indicate activators that induced significant elevation of *NTF3* transcript levels relative to a control as determined by a one-sided, paired t-test.

Figures 2D-E Correlation between activity of TALE-activators and violations of previously described computationally-derived target site guidelines. **(d)** Guideline violations and activities of 54 TALE-activators targeted to the human *VEGF-A* gene. Correlation p-value is shown. **(e)** Same data as in **(d)** but broken down into nine sets each consisting of six TALE-activators composed of 14.5, 16.5, 18.6, 20.5, 22.5 or 24.5 TAL effector repeat arrays targeted to overlapping sites.

Figures 3A-B Schematic overview of TALE-activator binding sites within the (a) *VEGF-A*, (b) *miR-302/367*, and (c) *NTF3* gene promoter regions. Thick black lines indicate exons, thin black lines indicate introns or promoter regions, and black arrows indicate the start site of transcription. Thick blue lines represent miRNAs. Grey bars indicate digital DNase I hypersensitive regions. DNase I hypersensitive regions we targeted are expanded and red arrows depict precise locations of TALE-activator binding sites and orientations of the activators when bound on the DNA (the arrow indicates the direction of the protein from amino- to carboxy-terminus when bound to its target DNA site).

Figure 4. A flowchart of an exemplary process for identifying potential TALE-activator binding sites.

Figure 5. An example of a computing device for use in the present methods.

DETAILED DESCRIPTION

Although TALE-activators have a broad range of potential applications, the low activities and restricted targeting range of these proteins as described in the literature to date raise concerns about the robustness of this technology. Published TALE-activators made for endogenous genes have generally shown very modest activities^{3-6, 8, 9} – 13 of the 26 previously described proteins (for which quantitative information is available) induced target gene expression by three-fold or more and only 4 out of 26 activated by five-fold or more (**Table 1**).

TABLE 1								
Gene Targeted	Organism/Cell line	TALE length (# of repeats)	Activation Domain	Approximate Fold Activation	Ref.	Architecture	Target Site	SEQ ID NO:
NTF3	Human HEK293 cells	17.5	VP16	30	1	A	TGGAGCCATCTGGCCGGGT*	1.
	mouse	12.5	VP16	5.5	2		TTTATTCCCTGACA	2.
	mouse	12.5	VP16	2.2			TTCTTACTTATAAC	3.
	mouse	12.5	VP16	no activation			TTCTCCCACCCCCA	4.
	mouse	12.5	VP16	no activation			TCCCGAGTCCCCAA	5.
PUMA	Human HEK293T-Rex cells	17.5	VP16	1.5	3		TACTTGGAGGCAGTCAAGT*	6.
IFN α 1	Human HEK293T-Rex cells	19.5	VP16	3.1			TGGAAGTGGCCCCAGAACAT	7.
IFN β 1	Human HEK293T-Rex cells	17.5	VP16	3.5			TCTCATATAAATAGGCCAT	8.
FXN	Human 293FT cells	13.5	VP64	0.9 to 1.7	4		TCCCTTGGGTCAGG*	9.
				1.1 to 1.6			TGGTTGCACTCCGT*	10.
				1.0 to 1.6			TGCTTTGCACAAAG*	11.
				1.1 to 2.0			TGCACGAATAGTGC*	12.
				1.1 to 1.4			TAGTGCTAAGCTGG*	13.
				1.7 to 3.1			TCCTGAGGTCTAAC*	14.
				1.1 to 1.5			TGAGGTCTAACCTC*	15.
OSGIN2	Human U-2OS cells	18.5	VP64	4.8	5	B	TCCTCCCCACCTTTAATTT*	16.
ZC3H10	Human U-2OS cells	18.5	VP64	1.3	TACCATATCCCATCCAACTC		17.	
ROCK1	Human HeLa	16.5	VP64	n.d.	TCTCCTCGTCAGGAAGTCT		18.	

TABLE 1							
Gene Targeted	Organism/Cell line	TALE length (# of repeats)	Activation Domain	Approximate Fold Activation	Ref.	Architecture	Target Site
	cells						
CACNA1C	Human 293FT cells	16.5	VP64	5.5	7		TCGGCCCCCTGCCGGCCCCA
				2.75			TCGGCCCCCTGCCGGCCCCA
				4.5			TCGGCCCCCTGCCGGCCCCA
				6			TCGGCCCCCTGCCGGCCCCA
				3			TGGTAGACCTTAGGGCTA
				1.5			TGGTAGACCTTAGGGCTA
				4			TGGTAGACCTTAGGGCTA
				3.5			TGGTAGACCTTAGGGCTA
OCT4	Mouse ES cells	17.5	VP16	4	8		TCCCACCCCCACAGCTCTG
	Mouse neural stem cells			30**			
Bs3	pepper plants	13.5	native AvrHah1 activation domain	n.d.	9	G	TGTAACCTTGACCCT

* - sequence within a DNaseI hypersensitive site

** Activation observed in the presence of VPA and/or 5-azadC

Architecture Key:

A = originally referenced in Miller et al., Nature Biotech 2011

B = originally referenced in Zhang et al., Nature Biotech 2011

C = originally referenced in Geissler et al., PLoS ONE 2011

D = originally described in Garg et al., NAR 2012

E = originally described in Huang et al., Nature Biotech 2011

F = originally described in Morbitzer et al., NAR 2011

G = originally described in Cernak et al., NAR 2011

One potential explanation for these observed low activities is that certain DNA sequences may be suboptimal for targeting by TALE-activators, a concept recently codified by Bogdanove and colleagues in five computationally-derived guidelines for choosing target sites (Doyle, E.L. et al., *Nucleic Acids Res* 40, W117-122 (2012); discussed further below). Consistent with this, 19 of the 20 target sites for the 26 published TALE-activators described above fail to meet one or more of these five guidelines (**Table 2**). Another potential cause for the low fold-activation values observed could be that some of the various TALE-activator architectures used in previous studies may not be optimal, as discussed further below. However, the seven different architectures used to date to construct TALE-activators tested on endogenous gene targets^{2, 4, 5, 7, 9, 10} have been evaluated on only relatively small numbers of sites, making it difficult to evaluate their individual efficiencies (**Tables 1 and 2**). Thus, a robust, well-validated TALE-activator platform with a broad targeting range has yet to be identified for investigators interested in using these proteins.

Described herein are TALE-activators constructed on a single common architecture in which parameters that do and do not affect the activities of these proteins in human cells are systematically defined. As shown herein, TALE-activators of certain critical defined lengths can robustly activate transcription of not only protein-coding, but also non-coding microRNA (miRNA), genes in human cells. In addition, TALE-activators made on the present platform are not constrained by four of five previously described computationally-derived guidelines that restrict target site choice (Doyle, E.L. et al., *Nucleic Acids Res* 40, W117-122 (2012)), thereby greatly expanding the targeting range for these proteins. Finally, levels of target gene expression can be variably tuned by altering the specific activation domain used and/or by exploiting the ability of TALE-activators, like naturally occurring transcription factors, to function synergistically. Taken together, the present data provide clear and large-scale evidence that, contrary to the published literature, TALE-activators are indeed a robust platform for controlling expression of essentially any endogenous gene of interest over a wide dynamic range in human cells.

Guidelines for choosing monomeric TALE-activator binding sites and effects on targeting range

Cermak et al. originally proposed five guidelines for identifying optimal TALE-activator binding sites of engineered dimeric TALENs (Cermak, T. et al. *Nucleic Acids Res* 39, e82 (2011)). These guidelines were computationally derived from data on the binding preferences of naturally occurring TAL effectors but were not prospectively tested experimentally. As summarized previously (Doyle, E.L. et al. *Nucleic Acids Res* 40, W117-122 (2012)), the Cermak guidelines can be stated as follows:

1. The nucleotide just 5' to the first nucleotide in the TALE-activator binding site should be a thymine.
2. The first nucleotide of the TALE-activator binding site should not be a thymine.
3. The second nucleotide of the TALE-activator binding site should not be an adenosine.
4. The 3' most nucleotide of the TALE-activator binding site should be a thymine.
5. The base composition of the TALE-activator binding site should not vary from the observed percent composition of naturally occurring binding sites by more than 2 standard deviations. The percent composition of naturally occurring TAL effector repeat array binding sites was determined to be: A = 31±16%, C = 37±13%, G = 9±8%, T = 22±10%. Therefore, the base composition of TALE-activator binding sites should be: A = 0-63%, C = 11-63%, G = 0-25%, T = 2-42%.

In a previous large-scale study, it was demonstrated that highly active dimeric TALENs can be made for target binding sites that violate one or more of guidelines 2 through 5 (none of the sites targeted violated guideline 1) (Reyon, D. et al. *Nat Biotechnol* 30, 460-465 (2012)). As demonstrated herein, no significant correlation exists between the number of guideline violations and the activities of the engineered dimeric TALENs (Reyon, D. et al. (2012)). These results strongly suggested that guidelines 2 through 5 do not need to be followed when choosing target sites for dimeric TALENs.

More recently, Doyle et al. suggested that target binding site selection for monomeric TAL effector-based proteins should be limited by these same five

guidelines (Doyle, E.L. et al. Nucleic Acids Res 40, W117-122 (2012)). The TALE-NT 2.0 web-based software tool (boglab.plp.iastate.edu) recently developed by Bogdanove and colleagues (Doyle, E.L. et al. Nucleic Acids Res 40, W117-122 (2012)) also applies these five guidelines in its default settings when choosing target sites for monomeric TAL effector repeat arrays used in TALE-activators.

TABLE 2

Reference	Gene Targeted	TALE length (# of RVDs)	Binding site	Cermak Guidelines					Total Guideline Violations	SEQ ID NO:
				1	2	3	4	5		
2	<i>NTF3</i>	17.5	CGGAGCCATCTGGCCGGGT	X				X	2	30.
	<i>SOX2</i>	12.5	TTTATTCCTGACA		X		X		2	31.
3	<i>KLF4</i>	12.5	TTCTTACTTATAAC		X		X	X	3	32.
	<i>OCT4</i>	12.5	TCCCGAGTCCCCAA				X		1	33.
	<i>C-MYC</i>	12.5	TTCTCCACCCCCCA		X		X	X	3	34.
	<i>PUMA</i>	17.5	TACTTGGAGGCAGTCAAGT					X	1	35.
4	<i>IFNa1</i>	19.5	TGGAAGTGGCCAGAGCAT					X	1	36.
	<i>IFNb1</i>	17.5	TCTCATATAAATAGGCCAT						0	37.
			CTCCCTTGGGTCAGG	X			X	X	3	38.
6	frataxin	13.5	CTGGTTGCACTCCGT	X				X	2	39.
			GTGCTTTGCACAAAG	X			X		2	40.
			ATGCACGAATAGTGC	X			X	X	3	41.
			ATAGTGCTAAGCTGG	X			X	X	3	42.
			TTCTGAGGCTTAAC				X		1	43.
			CTGAGGCTTAACCTC	X		X	X		3	44.
			TCCTCCCCACCTTTAATTT					X	1	45.
			TACCATATCCCATCCAATC				X		1	46.
5	<i>OSGIN2</i>	18.5								
7	<i>ZC3H10</i>	18.5								
	<i>ROCK1</i>	16.5	TCTCCTCGTCAGAACTCT						0	47.
8	<i>CACNA1C</i>	16.5	TGGGCCCCCTGCCGGCCCA				X	X	2	48.
10	<i>OCT4</i>	17.5	TGGTAGACCTTAGGGCTA				X	X	2	49.
18	<i>Bs3</i>	17.5	TCCCACCCCCACAGCTCTG				X		1	50.
		13.5	TGTAAACCTGACCCCT						0	51.

* Exact site targeted is not present in the human genome

** Able to activate only when used in combination with VPA and 5-aza

The implementation of these prior art guidelines has the effect of substantially limiting the targeting range of engineered monomeric TALE-activators. For example, application of the five guidelines restricts the identification of a targetable 18 bp site (bound by a 16.5 TAL effector repeat array) to once in every 27 bps of random DNA sequence. By contrast, relaxing guidelines 2 through 5, enables a targetable 18 bp site to be found once in every two bps of random DNA, a more than 13-fold improvement in targeting range.

Thus, in some embodiments, the present methods include selecting a TALE-activator binding site wherein the binding site is within a DNaseI hypersensitive site; wherein the nucleotide just 5' to the first nucleotide in the canonical TALE-repeat domain binding site is a thymine; and wherein the binding site is 18 to 24 bps in length (including the 5' T).

In some embodiments, one or more of the following is also true:

- A. The first nucleotide of the TALE-activator binding site is a thymine;
- B. The second nucleotide of the TALE-activator binding site is an adenosine;
- C. The 3' most nucleotide of the TALE-activator binding site is not a thymine; and/or
- D. The base composition of the TALE-activator binding site varies from the observed percent composition of naturally occurring binding sites by more than 2 standard deviations, i.e., is other than A = 0-63%, C = 11-63%, G = 0-25%, T = 2-42%.

In some embodiments, one or more, e.g., all, of B-D are not true.

Methods for Engineering TALE-Activators

Described herein is large-scale validation and optimization of a TALE-activator architecture that can be used to robustly activate expression of endogenous genes in human cells. Systematic testing of the effect of TAL effector repeat number on this architecture demonstrated that TALE-activators composed of 16.5 to 22.5 repeats (targeting sites 18 to 24 bps in length, with a T at the 5' end of the binding site) possess optimal activities. The data also provide clear-cut experimental evidence showing that TALE-activators made on this architecture do not need to adhere to four of five published computationally-derived guidelines (Doyle, E.L. et al., *Nucleic Acids Res* 40, W117-122 (2012)), thereby greatly expanding the targeting range of

this platform to one 18 bp site in every two bps of random DNA sequence. These parameters were validated by prospectively making TALE-activators targeted to sites within known or predicted DNase I hypersensitive sites and demonstrating high activities and high success rates on protein-coding and miRNA cluster genes, a result that stands in contrast to previously published studies that described less robust activation (Table 1).

Thus, the methods described herein include selecting a target sequence of interest, preferably a target sequence that is part of or comprises a regulatory region, e.g., a promoter, of a target gene. In some embodiments, the methods include selecting a target sequence that is in a known DNase I hypersensitive region, e.g., based on comparison to one or more databases. In some embodiments, the methods include performing a DNase I hypersensitivity assay as known in the art to identify a target sequence that is within a DNase I hypersensitivity region.

The methods further include identifying potential (or candidate) TALE-activator binding sites based on the guidelines set forth herein, i.e., TALE-activator binding sites 18 – 24 bp in length preferably including the 5' T. In some embodiments, users can change this length constraint, e.g., by entering a new value in a length input box. The studies described herein suggest that TAL effector repeat arrays composed of 16.5 to 22.5 repeats (that bind to sites 18 – 24 bps in length preferably including a 5' T) should be made to ensure robust activity of TALE-activators.

Once a binding site has been identified using the methods described herein, the methods can further include generating a TALE-activator that binds to an identified binding site. The TALE activators include a TAL effector repeat array assembly (which binds to the identified binding site) fused to a transcription activator. Transcription activators that can be used in the TALE activators are known in the art, e.g., one or more, preferably four, VP16 peptides (i.e., VP64), or an NF-KB p65 transactivation domain. See, e.g., Tremblay et al., *Hum Gene Ther.* 2012 Aug;23(8):883-90; Li et al., *Scientific Reports* 2:897 (2012) DOI: 10.1038/srep00897; and US 20110301073.

TAL effector repeat arrays include tandem repeats, typically 33-35 amino acids in length. Each repeat is largely identical except for two variable amino acids at positions 12 and 13, the repeat variable di-residues (RVDs). The C-terminal repeat is generally shorter and referred to as a “half repeat”. Each repeat binds to a single base

pair based on a simple code; the four most common RVDs each preferentially bind to one of the four bases (HD to C, NI to A, NG to T, NN to G) (see, e.g., Li et al., Scientific Reports 2:897 (2012); Boch et al., Review of Phytopathology 48: 419–36; US 20110301073). Thus, an engineered TALE-activator protein with N.5 domains will contact a site that is $N.5 + 1.5$ bps long (which includes the 5' T). For example, a TALE-activator protein as described herein that is 12.5 domains long will contact a 14 bp site including the 5' T if present, or a 13 bp site if the 5' T is absent.

A number of methods for TAL effector repeat array assembly are known in the art (e.g., REAL (Sander, J.D. et al. Nat Biotechnol 29, 697-698 (2011); Reyon, D. et al. Curr Protoc Mol Biol., 2012 Oct;Chapter 12:Unit12.15); REAL-Fast (Reyon, D. et al. Curr Protoc Mol Biol., 2012 Oct;Chapter 12:Unit12.15); or FLASH (Reyon, D. et al. Nat Biotechnol 30, 460-465 (2012) and PCT/US2012/046451)) and can be used to construct TALE-activators on the architecture used in this report. All plasmids required to practice REAL are available through the non-profit plasmid distribution service Addgene (addgene.org/talengineering/). The archive of 376 plasmids required to practice FLASH and REAL-Fast are also available (TALengineering.org). Molecular biological techniques known in the art can be used to construct the TALE activators. See, e.g., Tremblay et al., Hum Gene Ther. 2012 Aug;23(8):883-90; Li et al., Scientific Reports 2:897 (2012) DOI: 10.1038/srep00897; and US 20110301073.

DNase I Hypersensitive Sites

As used herein, a “DNase I hypersensitive site” is a short region of chromatin identified by its super sensitivity to cleavage by DNase I. DNase I hypersensitive sites can be identified using methods known in the art, e.g., empirically, or can be identified based on published data or databases of DNase I hypersensitive sites. For example, DNaseI fingerprinting can be performed by a method that includes DNaseI digestion of intact nuclei, isolating DNaseI 'double-hit' fragments as described in Sabo et al. (Nat Methods. 2006 Jul;3(7):511-8.), and direct sequencing of fragment ends (which correspond to in vivo DNaseI cleavage sites) using the Illumina Ilx (and Illumina HiSeq by early 2011) platform (36 bp reads). Uniquely-mapping high-quality reads can be mapped to the genome using Bowtie. DNaseI sensitivity is directly reflected in raw tag density, which is shown in the track as density of tags mapping within a 150 bp sliding window (at a 20 bp step across the genome). DNaseI sensitive zones (HotSpots) can then be identified using the HotSpot algorithm

described in Sabo et al. (Proc Natl Acad Sci U S A. 2004 Nov 30;101(48):16837-42). In some embodiments, false discovery rate thresholds of 1.0% (FDR 1.0%) are computed for each cell type by applying the HotSpot algorithm to an equivalent number of random uniquely-mapping 36mers. DNaseI hypersensitive sites (DHSs or Peaks) are then identified as signal peaks within FDR 1.0% hypersensitive zones using a peak-finding algorithm (I-max).

Other methods of identifying DNaseI hypersensitive sites can also be used. See, e.g., Madrigal and Krajewski, Front Genet. 2012; 3:230; Wu, Nature. 1980 Aug 28; 286(5776):854-60; Gross and Garrard, Annu Rev Biochem. 1988; 57:159-97; Boyle et al., Cell. 2008 Jan 25; 132(2):311-22; McDaniell et al., Databases of DNaseI hypersensitive sites can also be used to identify and select candidate subsites, e.g., the DNase I hypersensitive regions identified in the University of Washington ENCODE data. Such sites can be identified using the UCSC genome browser (genome.ucsc.edu; Rosenbloom et al. Nucleic Acids Res 40, D912-917 (2012)).

In some embodiments, empirical DNase I sensitivity data obtained from a specific cell type of interest is used, i.e., the same cell type in which an increase in transcription is desired (i.e., the target cell type). In some embodiments, DNase I hypersensitive sites are selected that have been identified as DNase I hypersensitive sites in multiple different cell types, based on the reasoning that these areas have a high probability of being in open chromatin in the target cell type.

Computer- and Software-Based Embodiments

In some embodiments, various implementations of the systems and methods described here can be realized in digital electronic circuitry, integrated circuitry, specially designed ASICs (application specific integrated circuits), computer hardware, firmware, software, and/or combinations thereof. These various implementations can include implementation in one or more computer programs that are executable and/or interpretable on a programmable system including at least one programmable processor, which may be special or general purpose, coupled to receive data and instructions from, and to transmit data and instructions to, a storage system, at least one input device, and at least one output device.

These computer programs (also known as programs, software, software applications or code) include machine instructions for a programmable processor, and can be implemented in a high-level procedural and/or object-oriented programming

language, and/or in assembly/machine language. As used herein, the terms “machine-readable medium” and “computer-readable medium” refer to any computer program product, apparatus and/or device (e.g., magnetic discs, optical disks, memory, Programmable Logic Devices (PLDs)) used to provide machine instructions and/or data to a programmable processor, including a machine-readable medium that receives machine instructions as a machine-readable signal. The term “machine-readable signal” refers to any signal used to provide machine instructions and/or data to a programmable processor.

To provide for interaction with a user, the systems and techniques described here can be implemented on a computer having a display device (e.g., a CRT (cathode ray tube) or LCD (liquid crystal display) monitor) for displaying information to the user and a keyboard and a pointing device (e.g., a mouse or a trackball) by which the user can provide input to the computer. Other kinds of devices can be used to provide for interaction with a user as well; for example, feedback provided to the user can be any form of sensory feedback (e.g., visual feedback, auditory feedback, or tactile feedback); and input from the user can be received in any form, including acoustic, speech, or tactile input.

The systems and techniques described here can be implemented in a computing system that includes a back end component (e.g., as a data server), or that includes a middleware component (e.g., an application server), or that includes a front end component (e.g., a client computer having a graphical user interface or a Web browser through which a user can interact with an implementation of the systems and techniques described here), or any combination of such back end, middleware, or front end components. The components of the system can be interconnected by any form or medium of digital data communication (e.g., a communication network). Examples of communication networks include a local area network (“LAN”), a wide area network (“WAN”), and the Internet.

The computing system can include clients and servers. A client and server are generally remote from each other and typically interact through a communication network. The relationship of client and server arises by virtue of computer programs running on the respective computers and having a client-server relationship to each other.

In some embodiments, computer based identification of potential TALE-activator binding sites is performed as shown in Figure 4. In some embodiments, the

identification includes a comparison of a user-inputted query that includes a target sequence with records related to hypersensitive regions stored in a database. A computer system causes a user device to display a user interface that includes a user input mechanism for receiving information related to a target gene (101). A target sequence of interest, preferably a target sequence that is part of or comprises a regulatory region, e.g., a promoter, of a target gene, is provided by a user, e.g., by entry into a query box, to a computer processor programmed to perform the present methods. Regulatory regions can be identified using methods known in the art, e.g., from a database, or from empirical studies. The system receives the user-input query (102) (and optionally formats the query) and uses the query to select one or more records from a database. In some embodiments, the processor will identify DNase I hypersensitive regions within the target sequence based on comparison to records stored in one or more databases accessible by the computer system. In some alternative embodiments, the user will provide a target sequence already known to be in a DNase I hypersensitive region. In some embodiments, DNase I hypersensitive regions can be identified empirically, and the sequences entered into the computer.

Once a DNase I hypersensitive region has been identified, the processor will then identify potential TALE-activator binding sites within that region based on the guidelines set forth herein, i.e., TALE-activator binding sites composed of 16.5 to 22.5 repeats that bind to sites 18 – 24 bp in length (103). In some embodiments, users can change this length constraint, e.g., by entering a new value in a length input box. The modification of the length constraint input by the user can be received by the computer system as part of the original query definition or as a method to further filter a set of results provided based on a prior search. The studies of this report suggest that only TAL effector repeat arrays composed of 16.5 to 22.5 repeats (that bind to sites 18 – 24 bps in length) should be made to ensure robust activity of TALE-activators. The processor will then select one or more sequence of potential TALE-activator binding sites (104) and provide sequences of the identified potential TALE-activator binding sites to the user, e.g., by display on a screen, storage on a computer readable medium, or by inclusion in a message such as an email (105).

In some embodiments, the computer system is associated with a database that includes information required to generate a TALE-activator. Upon identification of a TALE-activator binding site, the software may access the additional stored information and provide users with access to the further information required to

generate a TALE-activator, e.g., using FLASH or REAL/REAL-Fast. For example, in some embodiments, depending on the mode of assembly chosen (FLASH or REAL/REAL-Fast), the computer system will provide users with information about the names of plasmids required for assembly, and optionally a printable graphical guide. All plasmids required to practice REAL are available through the non-profit plasmid distribution service Addgene (addgene.org/talengineering/). The archive of 376 plasmids required to practice FLASH and REAL-Fast are also available (TALengineering.org).

FIG. 5 shows an example of a generic computer device 900 and a generic mobile computing device 950, which may be used with techniques described here. Computing device 900 is intended to represent various forms of digital computers, such as laptops, desktops, workstations, personal digital assistants, servers, blade servers, mainframes, and other appropriate computers. Computing device 950 is intended to represent various forms of mobile devices, such as personal digital assistants, cellular telephones, smartphones, and other similar computing devices. The components shown here, their connections and relationships, and their functions, are meant to be exemplary only, and are not meant to limit described and/or claimed implementations.

Computing device 900 includes a processor 902, memory 904, a storage device 906, a high-speed interface 908 connecting to memory 904 and high-speed expansion ports 910, and a low speed interface 912 connecting to low speed bus 914 and storage device 906. Each of the components 902, 904, 906, 908, 910, and 912, are interconnected using various busses, and may be mounted on a common motherboard or in other manners as appropriate. The processor 902 can process instructions for execution within the computing device 900, including instructions stored in the memory 904 or on the storage device 906 to display graphical information for a GUI on an external input/output device, such as display 916 coupled to high speed interface 908. In other implementations, multiple processors and/or multiple buses may be used, as appropriate, along with multiple memories and types of memory. Also, multiple computing devices 900 may be connected, with each device providing portions of the necessary operations (e.g., as a server bank, a group of blade servers, or a multi-processor system).

The memory 904 stores information within the computing device 900. In one implementation, the memory 904 is a volatile memory unit or units. In another

implementation, the memory 904 is a non-volatile memory unit or units. The memory 904 may also be another form of computer-readable medium, such as a magnetic or optical disk.

The storage device 906 is capable of providing mass storage for the computing device 900. In one implementation, the storage device 906 may be or contain a computer-readable medium, such as a floppy disk device, a hard disk device, an optical disk device, or a tape device, a flash memory or other similar solid state memory device, or an array of devices, including devices in a storage area network or other configurations. A computer program product can be tangibly embodied in an information carrier. The computer program product may also contain instructions that, when executed, perform one or more methods, such as those described above. The information carrier is a computer- or machine-readable medium, such as the memory 904, the storage device 906, memory on processor 902, or a propagated signal.

The high speed controller 908 manages bandwidth-intensive operations for the computing device 900, while the low speed controller 912 manages lower bandwidth-intensive operations. Such allocation of functions is exemplary only. In one implementation, the high-speed controller 908 is coupled to memory 904, display 916 (e.g., through a graphics processor or accelerator), and to high-speed expansion ports 910, which may accept various expansion cards (not shown). In the implementation, low-speed controller 912 is coupled to storage device 906 and low-speed expansion port 914. The low-speed expansion port, which may include various communication ports (e.g., USB, Bluetooth, Ethernet, wireless Ethernet) may be coupled to one or more input/output devices, such as a keyboard, a pointing device, a scanner, or a networking device such as a switch or router, e.g., through a network adapter.

The computing device 900 may be implemented in a number of different forms, as shown in the figure. For example, it may be implemented as a standard server 920, or multiple times in a group of such servers. It may also be implemented as part of a rack server system 924. In addition, it may be implemented in a personal computer such as a laptop computer 922. Alternatively, components from computing device 900 may be combined with other components in a mobile device (not shown), such as device 950. Each of such devices may contain one or more of computing device 900, 950, and an entire system may be made up of multiple computing devices 900, 950 communicating with each other.

Computing device 950 includes a processor 952, memory 964, an input/output device such as a display 954, a communication interface 966, and a transceiver 968, among other components. The device 950 may also be provided with a storage device, such as a microdrive or other device, to provide additional storage. Each of the components 950, 952, 964, 954, 966, and 968, are interconnected using various buses, and several of the components may be mounted on a common motherboard or in other manners as appropriate.

The processor 952 can execute instructions within the computing device 950, including instructions stored in the memory 964. The processor may be implemented as a chipset of chips that include separate and multiple analog and digital processors. The processor may provide, for example, for coordination of the other components of the device 950, such as control of user interfaces, applications run by device 950, and wireless communication by device 950.

Processor 952 may communicate with a user through control interface 958 and display interface 956 coupled to a display 954. The display 954 may be, for example, a TFT LCD (Thin-Film-Transistor Liquid Crystal Display) or an OLED (Organic Light Emitting Diode) display, or other appropriate display technology. The display interface 956 may comprise appropriate circuitry for driving the display 954 to present graphical and other information to a user. The control interface 958 may receive commands from a user and convert them for submission to the processor 952. In addition, an external interface 962 may be provided in communication with processor 952, so as to enable near area communication of device 950 with other devices. External interface 962 may provide, for example, for wired communication in some implementations, or for wireless communication in other implementations, and multiple interfaces may also be used.

The memory 964 stores information within the computing device 950. The memory 964 can be implemented as one or more of a computer-readable medium or media, a volatile memory unit or units, or a non-volatile memory unit or units. Expansion memory 974 may also be provided and connected to device 950 through expansion interface 972, which may include, for example, a SIMM (Single In Line Memory Module) card interface. Such expansion memory 974 may provide extra storage space for device 950, or may also store applications or other information for device 950. Specifically, expansion memory 974 may include instructions to carry out or supplement the processes described above, and may include secure information

also. Thus, for example, expansion memory 974 may be provided as a security module for device 950, and may be programmed with instructions that permit secure use of device 950. In addition, secure applications may be provided via the SIMM cards, along with additional information, such as placing identifying information on the SIMM card in a non-hackable manner.

The memory may include, for example, flash memory and/or NVRAM memory, as discussed below. In one implementation, a computer program product is tangibly embodied in an information carrier. The computer program product contains instructions that, when executed, perform one or more methods, such as those described above. The information carrier is a computer- or machine-readable medium, such as the memory 964, expansion memory 974, memory on processor 952, or a propagated signal that may be received, for example, over transceiver 968 or external interface 962.

Device 950 may communicate wirelessly through communication interface 966, which may include digital signal processing circuitry where necessary. Communication interface 966 may provide for communications under various modes or protocols, such as GSM voice calls, SMS, EMS, or MMS messaging, CDMA, TDMA, PDC, WCDMA, CDMA2000, or GPRS, among others. Such communication may occur, for example, through radio-frequency transceiver 968. In addition, short-range communication may occur, such as using a Bluetooth, WiFi, or other such transceiver (not shown). In addition, GPS (Global Positioning System) receiver module 970 may provide additional navigation- and location-related wireless data to device 950, which may be used as appropriate by applications running on device 950.

Device 950 may also communicate audibly using audio codec 960, which may receive spoken information from a user and convert it to usable digital information. Audio codec 960 may likewise generate audible sound for a user, such as through a speaker, e.g., in a handset of device 950. Such sound may include sound from voice telephone calls, may include recorded sound (e.g., voice messages, music files, etc.) and may also include sound generated by applications operating on device 950.

The computing device 950 may be implemented in a number of different forms, as shown in the figure. For example, it may be implemented as a cellular telephone 980. It may also be implemented as part of a smartphone 982, personal digital assistant, or other similar mobile device.

In addition to the steps described herein and shown in the figures, other steps may be provided, or steps may be eliminated, from the described flows, and other components may be added to, or removed from, the described systems. Accordingly, other embodiments are within the scope of the present invention.

Methods for Optimizing Expression Levels of Target Genes

At least three sources of variation exist in the various TALE-activator architectures described to date: (1) variability within TAL effector repeats of amino acids present at positions other than the hypervariable residues, (2) differences in the length and composition of the TAL effector-derived sequences that flank the TAL effector repeat array, and (3) the choice of activation domain used (e.g., VP16 or VP64). Boch and colleagues have recently presented data suggesting that variation in the amino acids at non-hypervariable repeat positions can affect binding activity (Streubel, J., et al. *Nat Biotechnol* 30, 593-595 (2012)). Various reports have also shown that differences in the length of TAL effector-derived sequences flanking the TAL effector repeat array can influence activities of TALE-activators (Miller, J.C. et al. *Nat Biotechnol* 29, 143-148 (2011); Zhang, F. et al. *Nat Biotechnol* 29, 149-153 (2011); Mussolino, C. et al. *Nucleic Acids Res* 39, 9283-9293 (2011)).

Described herein are a number of different approaches that can be used to fine-tune the level of gene expression induced by TALE-activators, an important capability that will broaden the range of applications for this technology.

First, varying the position of TALE-activator binding (even within a single DNase I hypersensitive site) can lead to differences in the level of activation observed. Although it is currently not possible to predict the level of activation induced from any given site, the high success rate and ease with which TALE-activators can be constructed using the present methods make it straightforward for one of skill in the art to produce a panel of TALE-activators of differing activities, and empirically identify activators that induce desired levels of expression.

Second, choosing DNA-binding domains composed of 16.5 to 22.5 TALE repeats as described herein is predicted to result in more highly active TALE activators.

Third, varying the activation domain can affect the level of gene expression induced by a TALE-activator. For example, in the two cell lines examined herein,

VP64 TALE-activators generally induced higher levels of gene expression than matched counterparts bearing a p65 activation domain.

Finally, using combinations of TALE-activators can function synergistically to activate a target gene. Thus different combinations of TALE-activators can be tested to find the desired level of gene expression; in addition, these combinations can be used to make target genes responsive to multiple inputs, enabling synthetic biology applications in which artificial circuits interface with endogenous genes. In some embodiments, pairs (or more) of TALE activators that all target the same gene, but bind to different places in the regulatory region of the gene, are used. In some embodiments, all of the TALE activators have different transactivation domains, e.g., combinations of VP64 and p65 TALE-activators; in some embodiments, all of the TALE activators have the same transactivation domain, e.g., all either VP64 or p65 domains.

Methods for Regulating Expression of Non-Coding Genes

The present data demonstrate that TALE-activators can be used to regulate expression of a miRNA cluster, and thus might also be used to increase expression of other classes of non-coding genes such as lincRNAs, snoRNAs or piRNAs. Therefore in some embodiments the methods include selecting TALE-activator binding sites that are within regulatory regions of non-coding genes.

EXAMPLES

The invention is further described in the following examples, which do not limit the scope of the invention described in the claims.

Methods

The following methods were used in the experiments described in the Examples below.

Selection of TALE-activator binding sites. For the human *VEGF-A* gene, target sites were chosen that fall within DNase I hypersensitive sites previously described for 293 cells (Liu, P.Q. et al. J Biol Chem 276, 11323-11334 (2001)). For the *NTF3* and *miR-302/367* cluster genes, target sites were chosen within DNase I hypersensitive regions identified from University of Washington ENCODE data using the UCSC genome browser (genome.ucsc.edu; Rosenbloom, K.R. et al. Nucleic Acids Res 40, D912-917 (2012)); these regions were targeted because they have been

identified as DNase I hypersensitive sites in multiple different cell types and therefore it was reasoned that these areas had a high probability of being in open chromatin.

Construction of TALE Activators. DNA fragments encoding TAL effector repeat arrays were generated using the Fast Ligation-based Automatable High-throughput Assembly (FLASH) method as previously described (Reyon et al., 2012, and PCT/US2012/046451). These fragments were cloned using overhangs generated by digestion with BsmBI restriction enzyme into expression vectors containing an EF1 α promoter and the Δ 152 N-terminal and +95 C-terminal TALE-derived domains from the previously described TALE-activator NT-L+95.² NF-KB p65 and VP64 activation domains were fused directly to the C-terminal end of the +95 domain and all fusion proteins harbor a nuclear localization signal.

Cell Culture and Transfection. Human Flp-In T-REx 293 cells and primary human BJ fibroblasts were maintained in Advanced DMEM supplemented with 10% FBS, 1% penicillin-streptomycin and 1% Glutamax (Life Technologies). Cells were transfected using either Lipofectamine LTX (Life Technologies) or Nucleofection (Lonza) according to manufacturer's instructions. Briefly, for experiments targeting *VEGF-A* and *NTF3* expression, 160,000 Flp-In T-REx 293 cells were seeded in 24-well plates and transfected the following day with 300 ng of plasmid encoding TALE-activator, 30 ng of pmaxGFP plasmid (Lonza), 0.5 μ l Plus Reagent and 1.65 μ l Lipofectamine LTX. For experiments targeting *miR-302/367* cluster expression, 5×10^5 BJ fibroblasts were Nucleofected with 10 μ g of plasmid encoding TALE-activator and 500 ng of pmaxGFP plasmid using the NHDF kit (Lonza) and program U-023 on the Nucleofector 2b device.

ELISA Assays. Flp-In TREx 293 cells were transfected with plasmids encoding TALE-activators targeted to the human *VEGF-A* gene. All transfections were performed in triplicate. Cell media was harvested 40 hours after transfection and secreted VEGF-A protein levels in the media were assayed using a Human VEGF-A ELISA kit (R&D Systems). All samples were measured according to the manufacturer's instructions. Fold-activation values were calculated by dividing mean VEGF-A levels from media harvested from cells transfected with plasmids expressing TALE-activators by mean VEGF-A levels from cells transfected with plasmid expressing only the VP64 or p65 activation domain.

Quantitative RT-PCR assays. To measure *NTF3* mRNA levels, cells were harvested 2 days post-transfection and total RNA was isolated using the TRIzol Plus

RNA purification system (Ambion). RNA was reverse transcribed using SuperScript III First-Strand Synthesis SuperMix and oligo-dT primer (Life Technologies). qPCR was then performed using the following Taqman primer/probe sets, as previously described² except with the modification that the GAPDH probe was labeled with HEX to allow for multiplexing - NTF3 forward primer: 5'-GATAAACACTGGAAGCTCTCAGTGCAA-3' (SEQ ID NO:52); NTF3 reverse primer: 5'-GCCAGCCCACGAGTTTATTGT-3' (SEQ ID NO:53); NTF3 taqman probe: 5'-/56-FAM/CAAACCTAC/ZEN/GTCCGAGCACTGACTTCAGA/3IABkFQ/-3' (SEQ ID NO:54); GAPDH forward primer: 5'-CCATGTTTCGTCATGGGTGTGA-3' (SEQ ID NO:55); GAPDH reverse primer: 5'-CATGGACTGTGGTCATGAGT-3' (SEQ ID NO:56); GAPDH taqman probe: 5'-/5HEX/TCCTGCACC/ZEN/ACCAACTGCTTAGCA/ 3IABkFQ/-3' (SEQ ID NO:57). All TALE-activator-encoding plasmids and control plasmids were introduced into cells by Nucleofection in triplicate and qRT-PCR was performed in triplicate on each sample.

To measure *miR-302a* transcript levels, cells were harvested 3 days post-transfection and GFP-positive cells were isolated by flow cytometry. Total miRNA was isolated using the mirVana miRNA Isolation Kit (Ambion). Reverse transcription and qPCR were performed according to manufacturer's instructions using Applied Biosystems Taqman microRNA Assays (cat. #000529 for has-miR-302a and cat. #001006 for RNU48 control). Fold-activation of *miR-302a* RNA transcripts was calculated by comparing transcript levels from BJ fibroblasts transfected with plasmids encoding TALE-activators to transcript levels from BJ fibroblasts transfected with control plasmids expressing only the VP64 or p65 activation domains and using the comparative C_T ($\Delta\Delta C_T$) method. All TALE-activators and controls were introduced into cells by Nucleofection in triplicate and qRT-PCR for *miR302a* transcript and small RNA control *RNU48* were performed in triplicate on each sample.

Example 1

In initial experiments, a systematic and large-scale study aimed at defining the number of TAL effector repeats needed for optimal TALE-activator function was performed. A single consistent architecture based on one previously used by Rebar

and colleagues to build a highly active TALE-activator (Miller, J.C. et al. Nat Biotechnol 29, 143-148 (2011)) (**Figure 1C**), but that harbors a VP64 activation domain, was utilized. Using the recently described Fast Ligation-based Automatable Solid-phase High-throughput (FLASH) assembly method (Reyon, D. et al. Nat Biotechnol 30, 460-465 (2012) and PCT/US2012/046451), sets of six variable-length TALE-activators (harboring arrays of 14.5, 16.5, 18.5, 20.5, 22.5, or 24.5 TAL effector repeats) were constructed for nine different target regions within the human *VEGF-A* gene (a total of 54 TALE-activators). To minimize the effects of potentially obstructive chromatin on our experiment, the nine regions chosen all lie within a single DNase I hypersensitive region located ~500 bp downstream of the *VEGF-A* transcription startpoint (**Figure 1a**). Strikingly, 53 out of the 54 TALE-activators tested induced significant increases in VEGF-A protein expression in cultured human cells ranging from 5.3- to 114-fold (average of 44.3-fold activation) (**Figure 1b**). Interestingly, for each of the nine target regions, either the 14.5 repeat and/or 24.5 repeat TALE-activators showed significantly lower fold-activation of VEGF-A than the other proteins harboring 16.5 to 22.5 repeats (**Figure 1b**). These data suggest that the DNA-binding activities of monomeric TALE-activators can be optimized by ensuring that they contain at least 16.5, but no more than 22.5, repeats.

The data on the activities of the 54 *VEGF-A*-targeted TALE-activators was used to test the importance of following five computationally-derived guidelines for target site choice (Doyle, E.L. et al. Nucleic Acids Res 40, W117-122 (2012)). All 54 sites targeted failed to meet one or more of these five guidelines with 49 of the 54 sites actually violating two or more guidelines (note that all of the sites did meet the guideline requiring a 5' T) (**Table 3**). The ability of 53 of the 54 activators tested to increase VEGF-A expression by five-fold or more clearly demonstrates that there is no absolute requirement to follow at least four of the five design guidelines. Whether a relationship might exist between the total number of guideline violations and the level of TALE-activator activity observed was examined, but no significant correlation was found ($p = 0.5428$; **Figure 2D**). Instead, the level of fold-activation induced appeared to be largely locus-associated — that is, TALE-activators of variable lengths targeted to one of the nine loci, regardless of the number of guideline violations, tend to show similar levels of fold-activation (**Figure 2E**). Thus highly active monomeric TALE-activators can be made without meeting four of the five design guidelines. The ability to relax these restrictions improved the targeting range

of TALE-activators by more than ten-fold – for example, enabling proteins consisting of 16.5 TAL effector repeats to be made for a site once in every two bps of random DNA sequence.

TABLE 3								
TALE Name	Target site	SEQ ID NO:	Guidelines					Total Guideline Violations
			1	2	3	4	5	
VEGF1	TCGGGAGGCGCAGCGGTT	58.					X	1
VEGF2	TTGGGGCAGCCGGGTAGC	59.		X		X	X	3
VEGF3	TGGAGGGGGTCGGGGCTC	60.				X	X	2
VEGF4	TGAGTGACCTGCTTTTGGG	61.			X	X	X	3
VEGF5	TGAGTGAGTGTGTGCGTGT	62.			X		X	2
VEGF6	TCACTCCAGGATTCCAATA	63.			X	X		2
Ntf3-1	TTCTGTTACAGGGACTCA	64.		X		X		2
Ntf3-2	TCCGAACAGCTCCGCGCA	65.				X		1
Ntf3-3	TTCCCCTGCTGGGTAGTG	66.		X		X	X	3
Ntf3-4	TACGCCTCAGACCTGATC	67.				X		1
Ntf3-5	TCCCTCAATCTGGGAAAG	68.				X		1
miR1	TGGAAGCAATCTATTTAT	69.						0
miR2	TACATTTAACATGTAGAT	70.						0
miR3	TAGAAACACAATGCCTTT	71.						0
miR4	TGGGAGCACTCATTGTTA	72.				X	X	2
miR5	TAATCTATGCCATCAAAC	73.			X	X		2
VEGF1-1	TTGGGGGTGACCGCCG	74.		X		X	X	3
VEGF1-2	TTGGGGGTGACCGCCGGA	75.		X		X	X	3
VEGF1-3	TTGGGGGTGACCGCCGGAGC	76.		X		X	X	3
VEGF1-4	TTGGGGGTGACCGCCGGAGCGC	77.		X		X	X	3
VEGF1-5	TTGGGGGTGACCGCCGGAGCGCGG	78.		X		X	X	3
VEGF1-6	TTGGGGGTGACCGCCGGAGCGCGGC G	79.		X		X	X	3
VEGF2-1	TCCCGCAGCTGACCAG	80.				X	X	2
VEGF2-2	TCCCGCAGCTGACCAGTC	81.				X		1
VEGF2-3	TCCCGCAGCTGACCAGTCGC	82.				X	X	2
VEGF2-4	TCCCGCAGCTGACCAGTCGCGC	83.				X	X	2
VEGF2-5	TCCCGCAGCTGACCAGTCGCGCTG	84.				X	X	2
VEGF2-6	TCCCGCAGCTGACCAGTCGCGCTGAC	85.				X	X	2
VEGF3-1	TACCACCTCCTCCCCG	86.				X	X	2
VEGF3-2	TACCACCTCCTCCCCGGC	87.				X	X	2
VEGF3-3	TACCACCTCCTCCCCGGCCG	88.				X	X	2
VEGF3-4	TACCACCTCCTCCCCGGCCGGC	89.				X		1
VEGF3-5	TACCACCTCCTCCCCGGCCGGCGG	90.				X	X	2
VEGF3-6	TACCACCTCCTCCCCGGCCGGCGGC G	91.				X	X	2
VEGF4-1	TCCCCGGCCGGCGGGCG	92.				X	X	2
VEGF4-2	TCCCCGGCCGGCGGGCGGA	93.				X	X	2
VEGF4-3	TCCCCGGCCGGCGGGCGGACA	94.				X	X	2

TABLE 3							
TALE Name	Target site	SEQ ID NO:	Guidelines				Total Guideline Violations
VEGF4-4	TCCCCGGCCGGCGGCGGACAGT	95.				X	1
VEGF4-5	TCCCCGGCCGGCGGCGGACAGTGG	96.			X	X	2
VEGF4-6	TCCCCGGCCGGCGGCGGACAGTGGAC	97.			X	X	2
VEGF5-1	TGGACGCGGCGGCGGAG	98.			X	X	2
VEGF5-2	TGGACGCGGCGGCGGAGCC	99.			X	X	2
VEGF5-3	TGGACGCGGCGGCGGAGCCGCG	100.			X	X	2
VEGF5-4	TGGACGCGGCGGCGGAGCCGCGG	101.			X	X	2
VEGF5-5	TGGACGCGGCGGCGGAGCCGCGGGC	102.			X	X	2
VEGF5-6	TGGACGCGGCGGCGGAGCCGCGGGCA	103.			X	X	2
VEGF6-1	TCCCAAGGGGGAGGGC	104.			X	X	2
VEGF6-2	TCCCAAGGGGGAGGGGCTC	105.			X	X	2
VEGF6-3	TCCCAAGGGGGAGGGGCTCAC	106.			X	X	2
VEGF6-4	TCCCAAGGGGGAGGGGCTCACGC	107.			X	X	2
VEGF6-5	TCCCAAGGGGGAGGGGCTCACGCCG	108.			X	X	2
VEGF6-6	TCCCAAGGGGGAGGGGCTCACGCCGC	109.			X	X	2
VEGF7-1	TCCGTCAGCGCGACTG	110.			X	X	2
VEGF7-2	TCCGTCAGCGCGACTGGT	111.				X	1
VEGF7-3	TCCGTCAGCGCGACTGGTCA	112.			X	X	2
VEGF7-4	TCCGTCAGCGCGACTGGTCAGC	113.			X	X	2
VEGF7-5	TCCGTCAGCGCGACTGGTCAGCTG	114.			X	X	2
VEGF7-6	TCCGTCAGCGCGACTGGTCAGCTGCG	115.			X	X	2
VEGF8-1	TCCACTGTCCGCCGCCG	116.			X		1
VEGF8-2	TCCACTGTCCGCCGCCGG	117.			X	X	2
VEGF8-3	TCCACTGTCCGCCGCCGGCC	118.			X	X	2
VEGF8-4	TCCACTGTCCGCCGCCGGCCGG	119.			X	X	2
VEGF8-5	TCCACTGTCCGCCGCCGGCCGGGG	120.			X	X	2
VEGF8-6	TCCACTGTCCGCCGCCGGCCGGGGA	121.			X	X	2
VEGF9-1	TCCACCCCGCCTCCGG	122.			X	X	2
VEGF9-2	TCCACCCCGCCTCCGGGC	123.			X	X	2
VEGF9-3	TCCACCCCGCCTCCGGGCGC	124.			X	X	2
VEGF9-4	TCCACCCCGCCTCCGGGCGCGG	125.			X	X	2
VEGF9-5	TCCACCCCGCCTCCGGGCGCGGGC	126.			X	X	2
VEGF9-6	TCCACCCCGCCTCCGGGCGCGGGCT	127.			X	X	2

Having defined optimum repeat array lengths and relaxed criteria for choosing target sequences, whether TALE-activators made using these parameters would efficiently regulate expression of both protein-coding and miRNA genes in human cells was tested. For these experiments, FLASH was used to construct VP64 TALE-activators composed of 16.5 or 17.5 TAL effector repeats to six additional sites in the human *VEGF-A* gene promoter, to five sites in the human *NTF3* gene promoter, and

to five sites in the *miR-302/367* cluster promoter. To minimize the potential confounding effects of obstructive chromatin, all 16 sites targeted were again chosen based on their position within cell-type-specific or database-predicted DNase I hypersensitivity regions (**Figures 3A-B and Methods**). Testing of these VP64 TALE-activators in human cells revealed that 15 of the 16 proteins induced significant increases in expression of their endogenous gene targets, an overall success rate of ~94% (**Figures 2A-C, lighter grey bars**). Notably, five of six TALE-activators targeted to *VEGF-A* and four of five activators targeted to the *miR-302/367* cluster increased expression of their target genes by five-fold or more in human transformed 293 and primary BJ fibroblasts, respectively (**Figure 2a and 2b**). Because *NTF3* mRNA is expressed at an essentially undetectable level in the 293 cells used for our experiments, it was not possible to reliably quantify fold-activation values for proteins targeted to this gene, but even the weakest activator induced an approximately 1000-fold increase in expression (**Figure 2c**). Interestingly, replacement of VP64 with the NF-KB p65 activation domain led to decreased activation for all 15 functional activators (**Figure 2A-C, darker grey bars**). These results demonstrate that VP64 TALE-activators composed of 16.5 to 17.5 repeats can robustly activate expression of endogenous human genes (including non-coding miRNA genes) without the need to follow restrictive targeting guidelines and that VP64 TALE-activators generally have stronger stimulatory effects than NF-KB p65 TALE-activators.

Because the present platform provides the capability to robustly generate multiple highly active TALE-activators for essentially any gene, the next experiments were performed to determine whether these proteins could also function synergistically. Activators are said to function synergistically if the fold-activation observed in the presence of multiple proteins is higher than the additive effects of the individual proteins. Naturally occurring activators in eukaryotes function synergistically (Carey, M. et al. Nature 345, 361-364 (1990)) and exploit this property to enable both combinatorial and graded control of transcription. To test whether TALE-activators might also behave synergistically, combinations of five VP64 or five p65 TALE-activators were tested on activation of the *miR-302/267* cluster and the *NTF3* gene. For all combinations tested, the expression of multiple activators led to substantially elevated transcription of the *miR-302/367* and *NTF3* genes (**Figure 2b and 2c**). Synergistic activation was observed with VP64 and p65 activators on the

miR-302/367 cluster (**Figure 2b**) and with p65 activators on the *NTF3* gene (**Figure 2c**). Thus, both VP64 and p65 TALE-activators can function synergistically to increase expression of endogenous human genes and this mechanism can be used to induce even greater levels of activation than can be achieved with individual activators.

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OTHER EMBODIMENTS

It is to be understood that while the invention has been described in conjunction with the detailed description thereof, the foregoing description is intended to illustrate and not limit the scope of the invention, which is defined by the scope of the appended claims. Other aspects, advantages, and modifications are within the scope of the following claims.

WHAT IS CLAIMED IS:

1. A method of identifying a candidate *Xanthomonas*-derived transcription activator-like effector (TALE) activator binding site, the method comprising:
selecting a target gene;
identifying one or more subsequences of the target gene sequence, wherein:
the subsequence is within a regulatory region of the target gene;
the subsequence is within a DNase I hypersensitive region of the regulatory region of the target gene,
the subsequence is 18-24 nucleotides long; and
optionally, the first (5') nucleotide in the subsequence is a thymine; and
selecting the one or more subsequences as candidate TALE-activator binding sites.
2. A method of making a TALE-activator that increases transcription of a target gene, the method comprising:
selecting a target gene;
identifying one or more subsequences of the target gene sequence, wherein:
the subsequence is within a regulatory region of the target gene;
the subsequence is within a DNase I hypersensitive region of the regulatory region of the target gene;
the subsequence is 18-24 nucleotides long, preferably 18 nucleotides long; and
optionally, the first (5') nucleotide in the subsequence is a thymine;
selecting a subsequence; and
generating a fusion protein comprising:
an engineered DNA-binding domain that comprises an engineered transcription activator-like effector (TALE) repeat array and that binds specifically to the selected subsequence, and
a transactivation domain comprising a sequence that increases transcription of a target gene;
thereby making a TALE-activator that increases transcription of the target gene.
3. The method of claim 2, wherein the TALE repeat array is 16.5 to 22.5 repeats.

4. The method of claim 2, wherein the transactivation domain comprises a VP16, VP64 or NF-KB p65 domain, preferably VP64.
5. A computer-implemented method performed by one or more processing devices, the method comprising:
 - providing information to cause a user device to display a user interface that includes a user input mechanism for receiving information related to a target gene;
 - receiving, from the user device, a selected target gene;
 - identifying, by one or more computers, one or more subsequences of the target gene sequence, wherein:
 - the subsequence is within a regulatory region of the target gene;
 - the subsequence is within a DNase I hypersensitive region of the regulatory region of the target gene,
 - the subsequence is 18-24 nucleotides long; and
 - optionally, the first (5') nucleotide in the subsequence is a thymine; and
 - selecting the one or more subsequences; and
 - providing information to cause the user device to display at least some of the selected one or more subsequences.
6. A method of increasing transcription of a target sequence in a cell, the method comprising contacting the cell with a TALE-activator made by the method of any of claims 3-5.
7. A method of increasing transcription of a target sequence in a cell, the method comprising contacting the cell with two or more TALE-activators made by the method of any of claims 3-5.
8. The method of claim 7, wherein at least one of the two or more TALE-activators comprises VP64, and at least one of the two or more TALE-activators comprises NF-KB p65 domain.
9. The method of any of claims 1-5, wherein the target gene is a coding or non-coding gene.
10. The method of claim 9, wherein the non-coding gene is a miRNA.

11. The method of any of claims 1-5, wherein the regulatory region of the target gene,
is a promoter region.

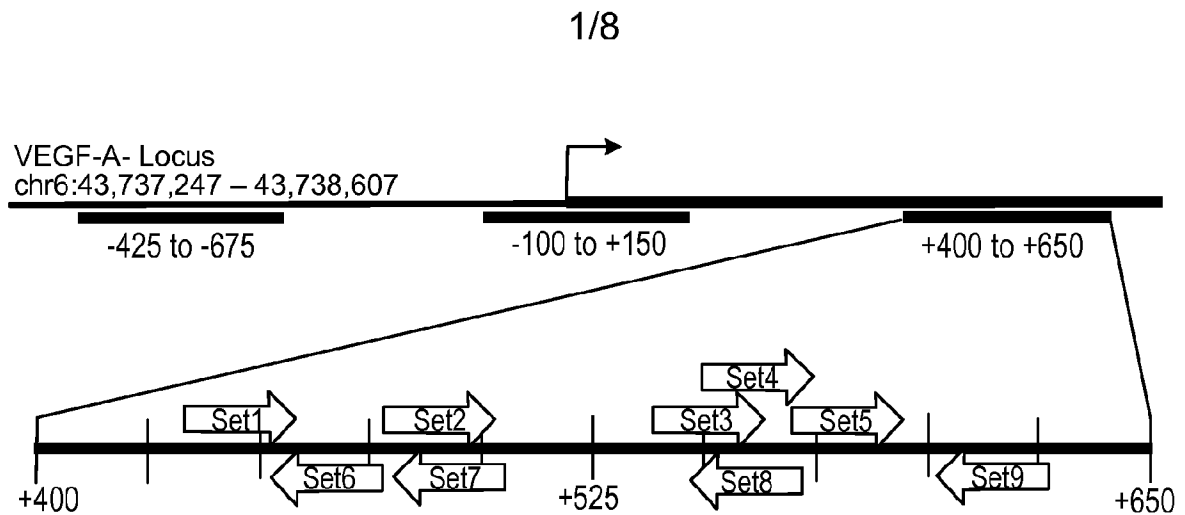


FIG. 1A

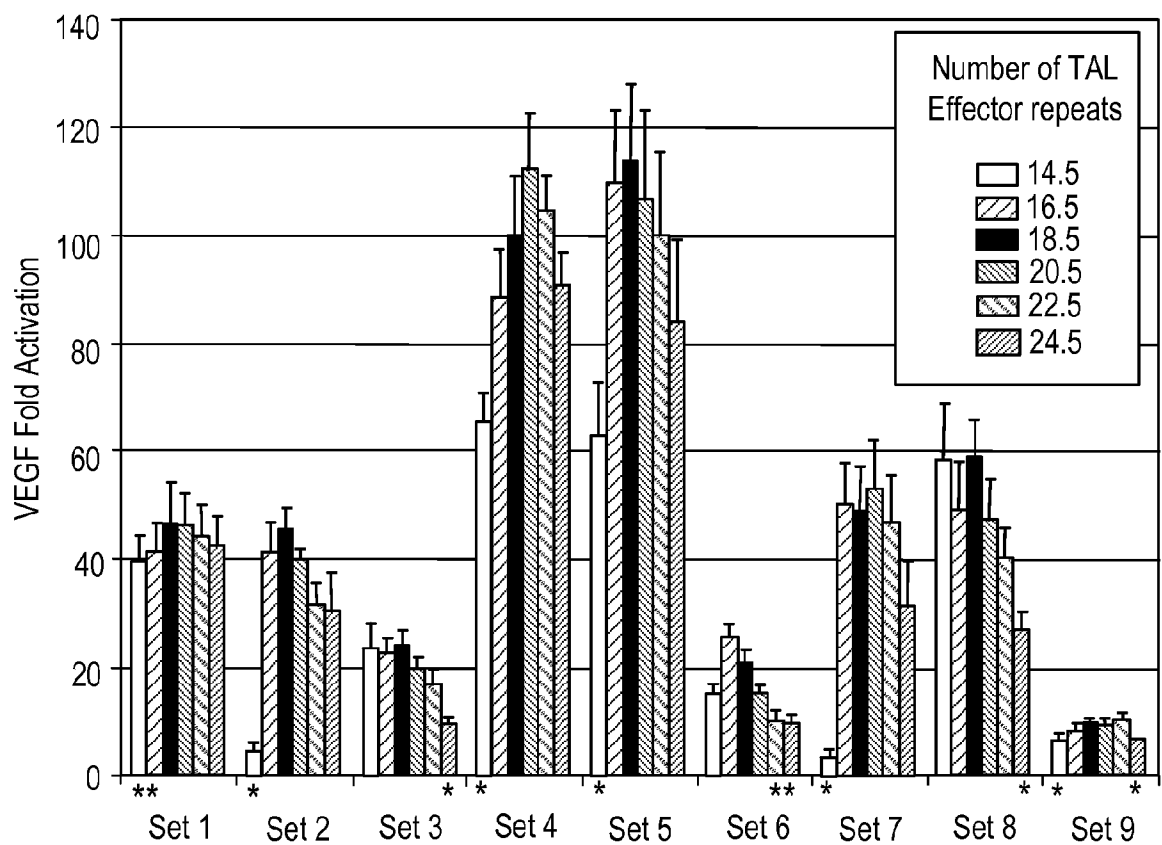


FIG. 1B

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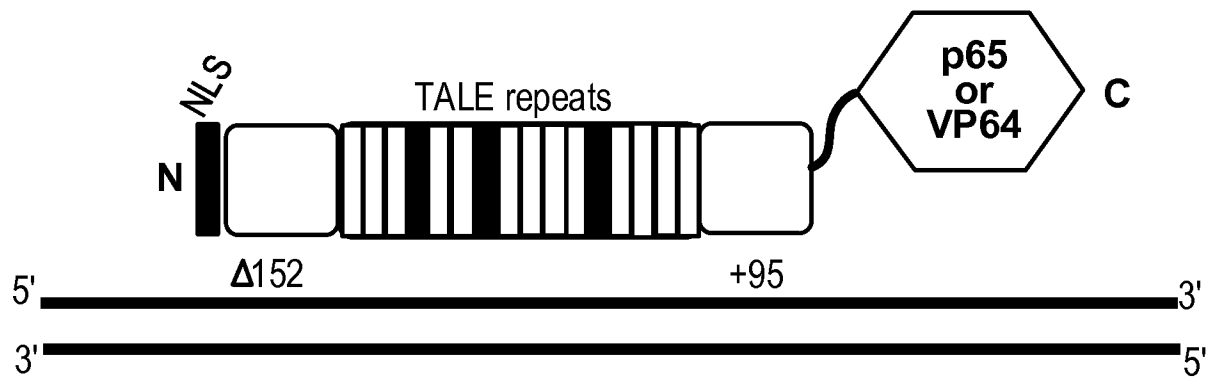


FIG. 1C

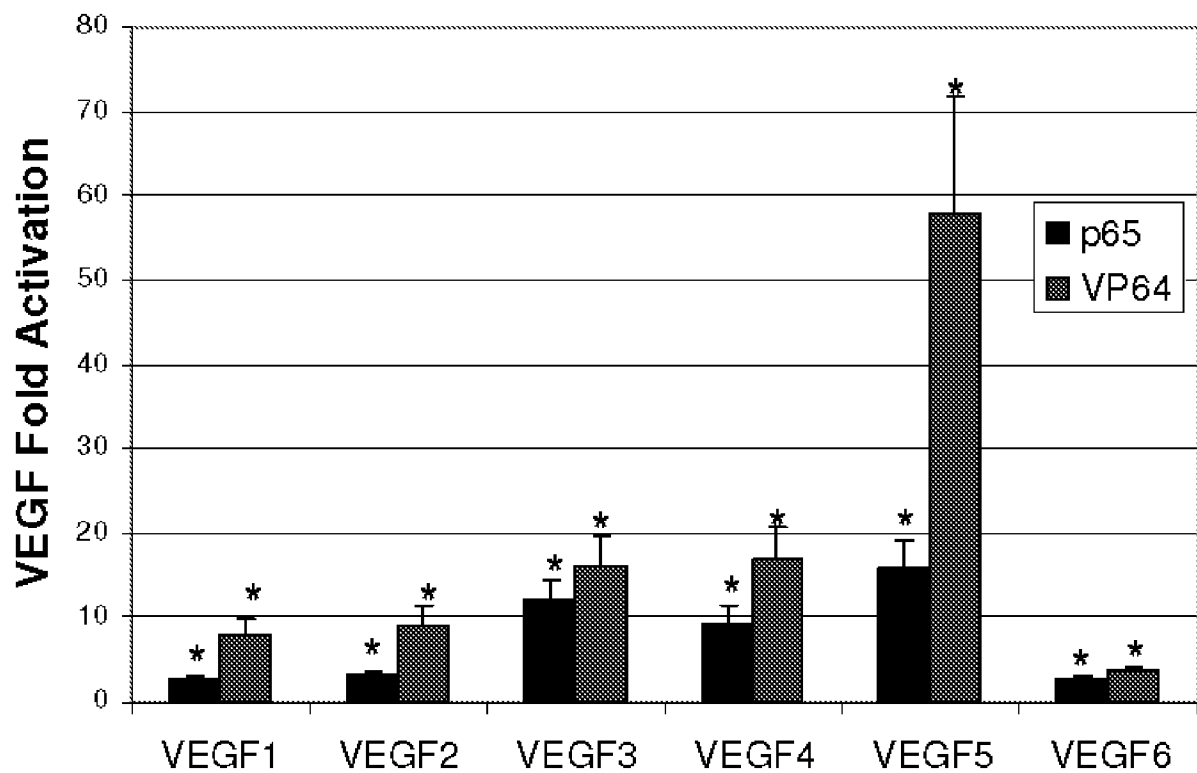


FIG. 2A

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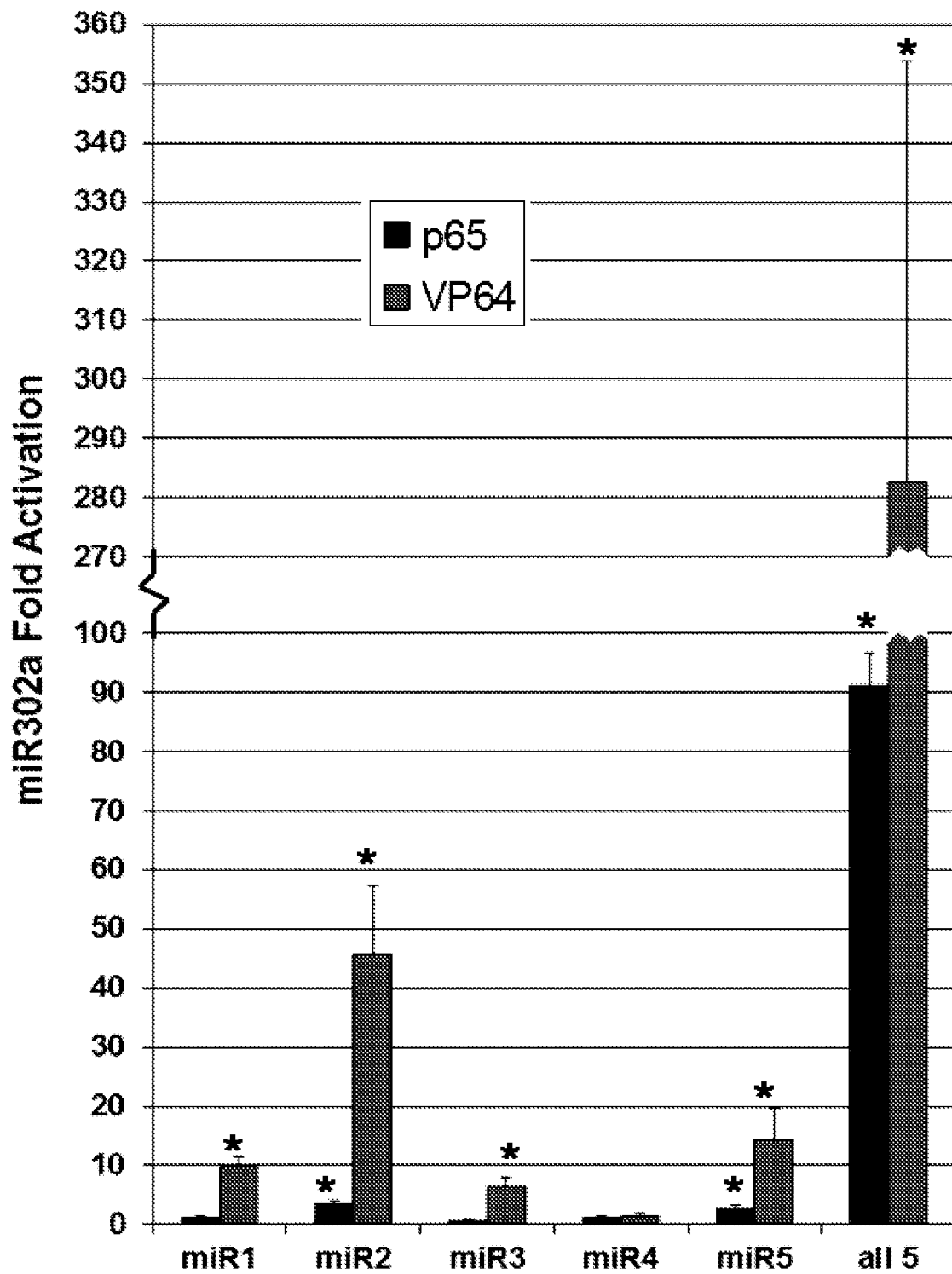


FIG. 2B

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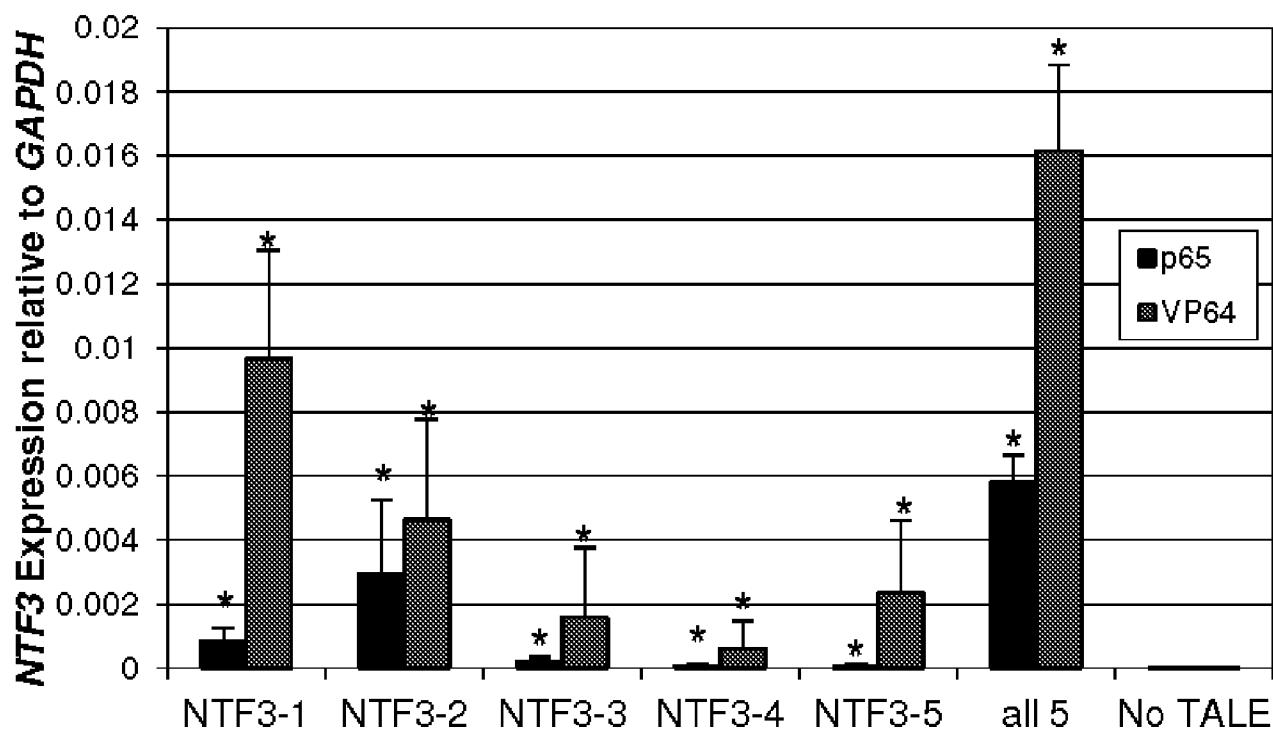


FIG. 2C

All 54 VEGF Activators

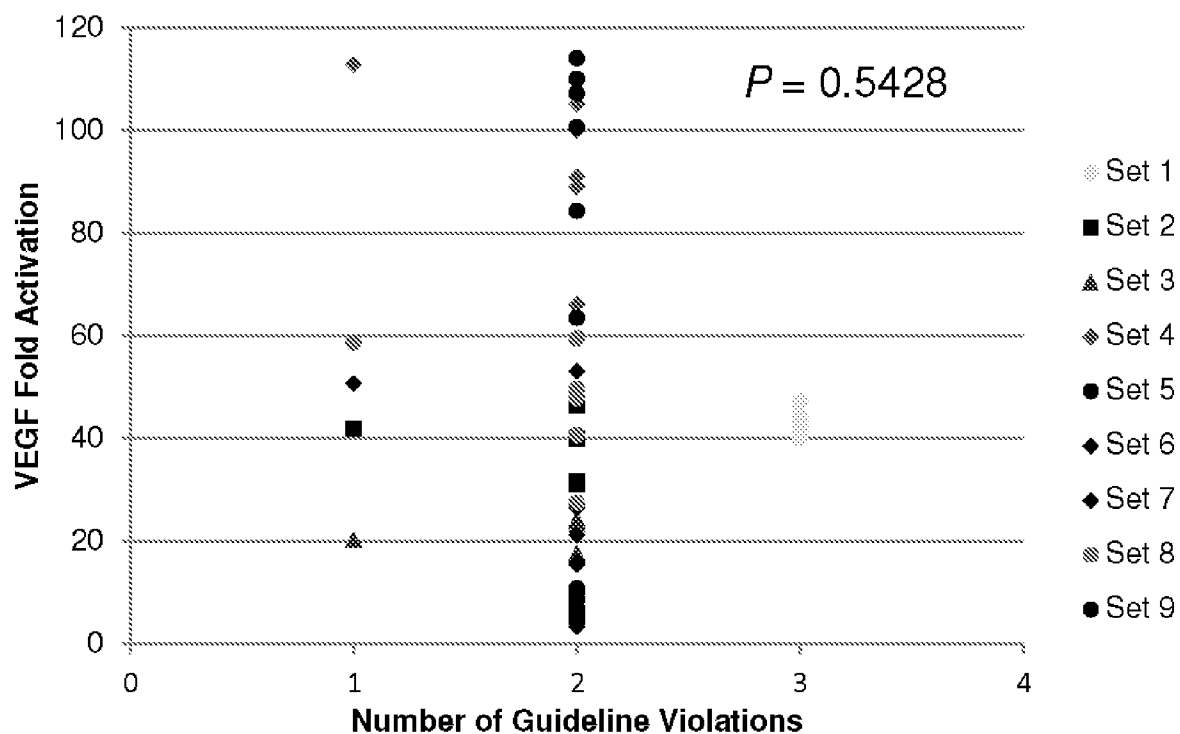


FIG. 2D

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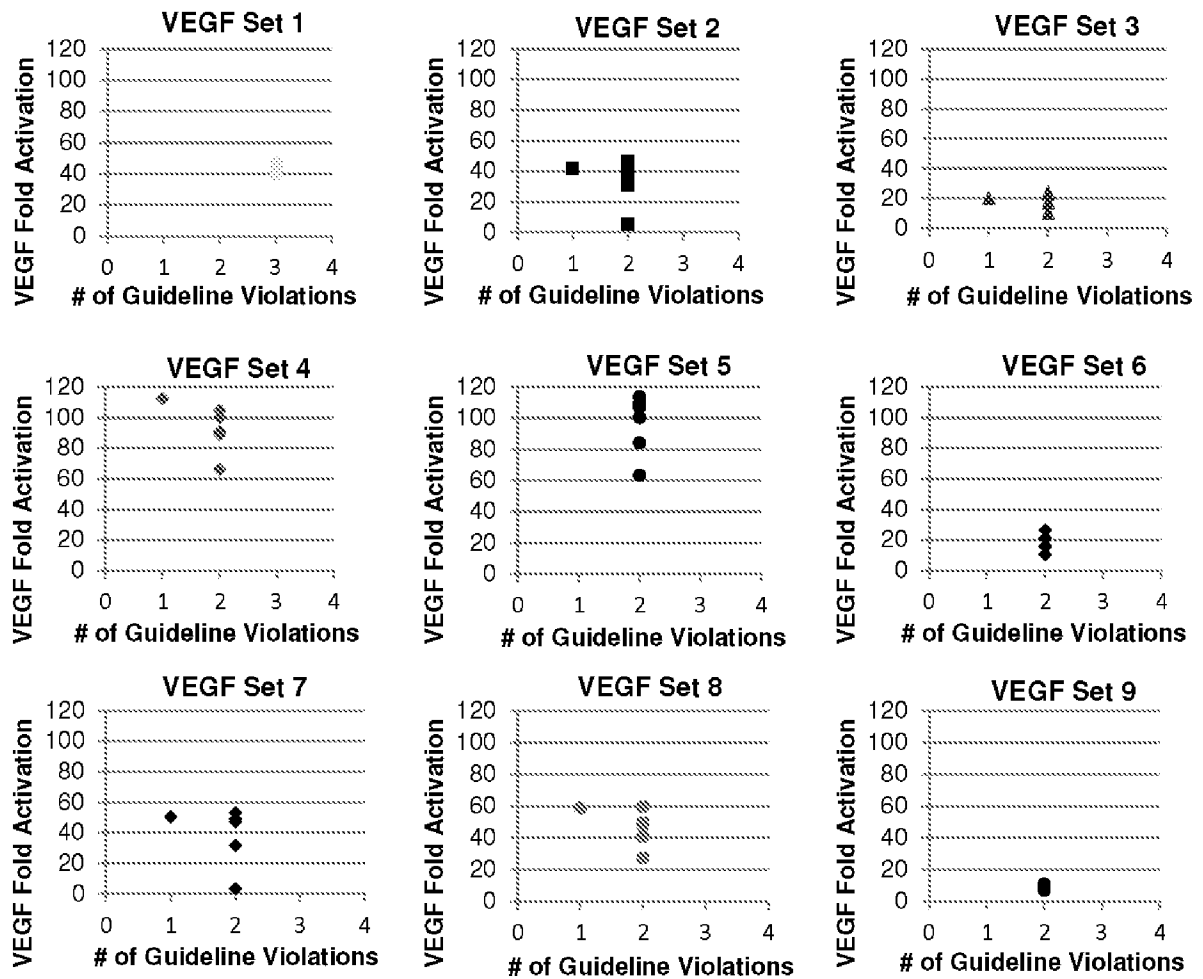


FIG. 2E

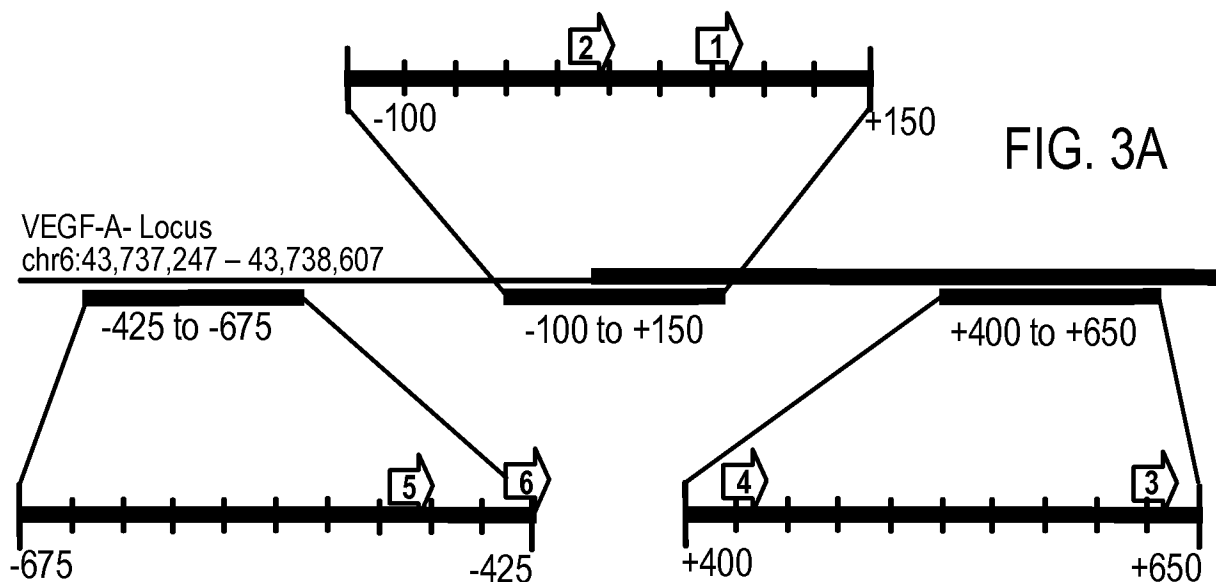


FIG. 3A

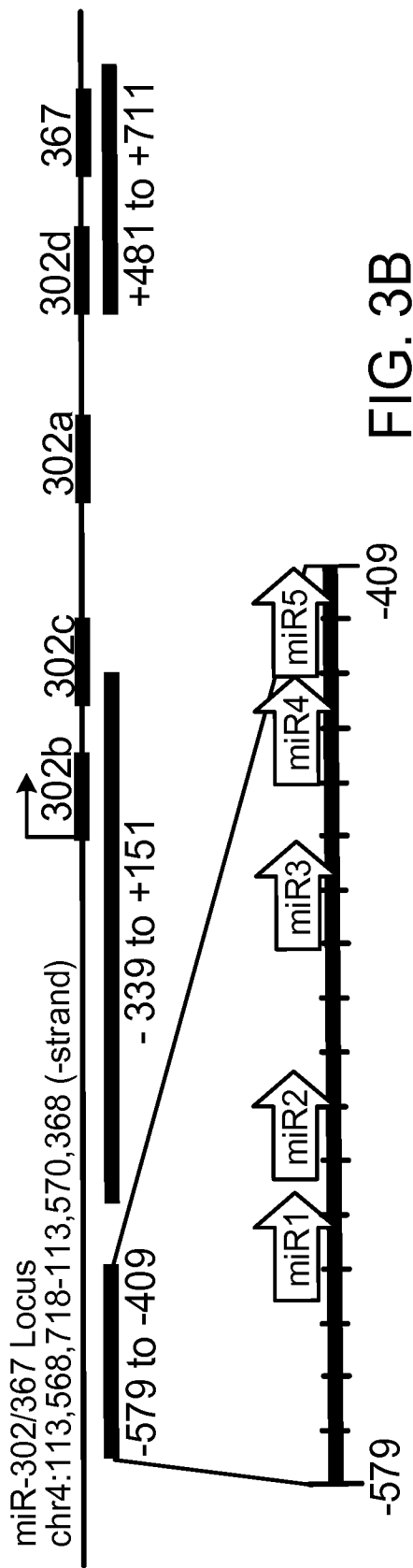


FIG. 3B

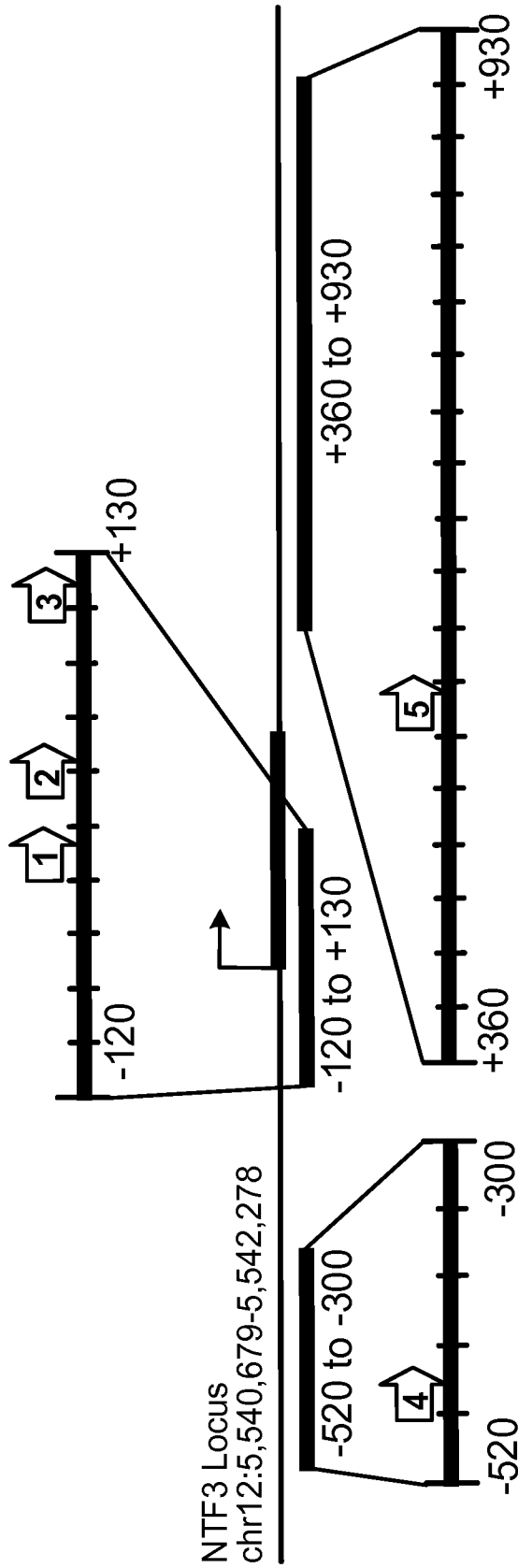


FIG. 3C

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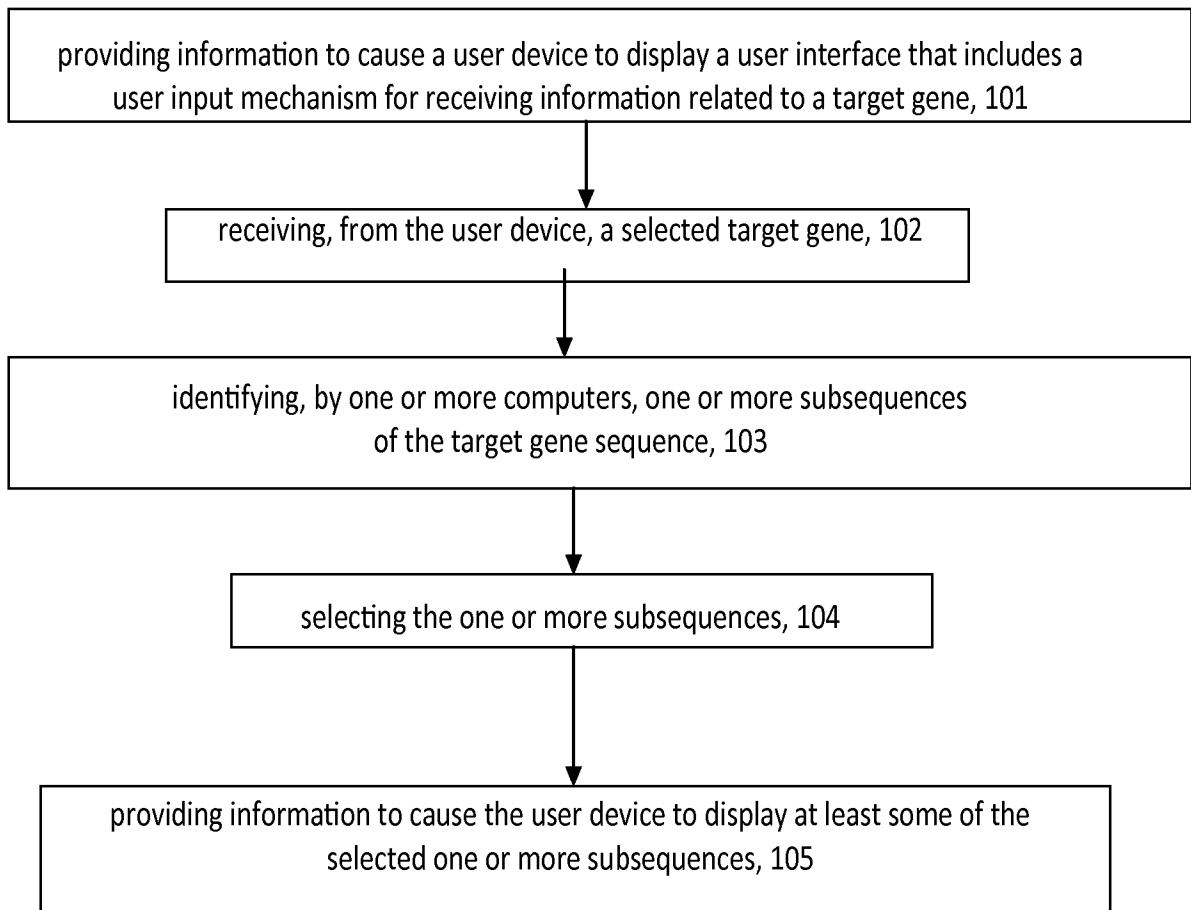


FIG. 4

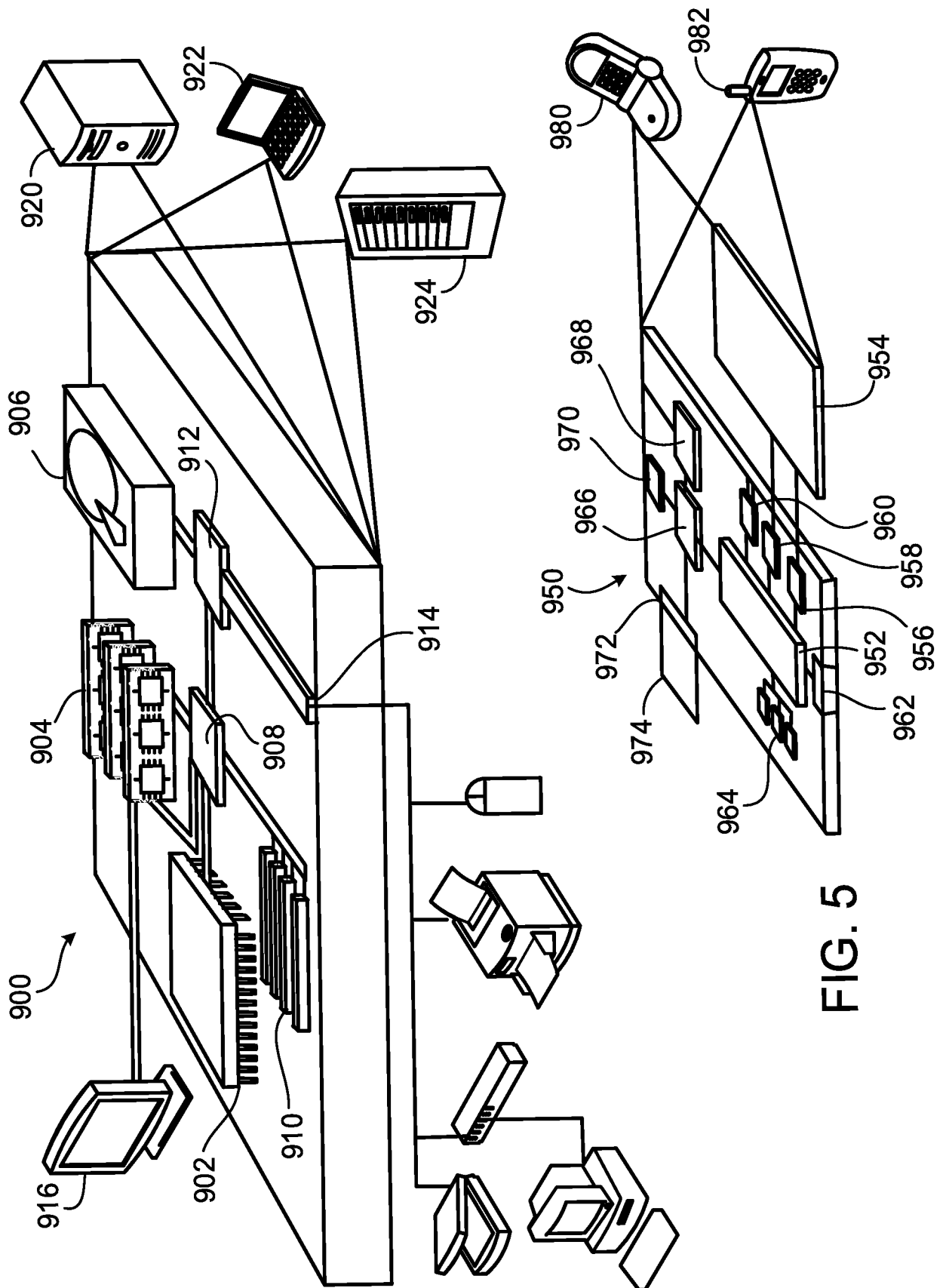


FIG. 5

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US14/15343

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - C12N 1/15, 5/00, 9/00, 15/31; C07K 1/00, 19/00 (2014.01)

USPC - 435/4, 325, 252.3, 320.1; 530/333; 536/23.1, 24.1

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(8): C12N 1/00, 1/15, 1/21, 5/00, 5/10, 9/00, 15/31, 15/62, 15/63, 15/66; C12P 19/34; C07H 21/04; C07K 1/00, 14/24 (2014.01);

USPC: 435/4, 6.1, 41, 72, 84, 85, 89, 91, 188, 325, 419, 252.3, 254.11, 320.1; 530/333; 536/23.1, 24.1

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

MicroPatent (US-G, US-A, EP-A, EP-B, WO, JP-bib, DE-C.B, DE-A, DE-T, DE-U, GB-A, FR-A); Google; Google Scholar; PubMed; xanthomonas, 'transcription activator like effector (TALE or TAL effector)', 'subsequence', 'DNase hypersensitivity', 'non-coding', 'miRNA', 'promoter', 'fusion protein', 'repeat array', 'VP16', 'NF-kB p65', 'VP64'

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2013/012674 A1 (JOUNG, JK et al.) January 24, 2013; page 5, lines 13-18; page 5, lines 22-25; page 9, lines 18-20; page 10, line 2; page 22, lines 11-14; page 22, lines 19-20; page 23, lines 21-26; page 25, lines 29-30; page 26, lines 29-30; page 27, lines 3-6; page 45, lines 6-9; page 46, lines 15-20; page 51, lines 4-6; page 51, lines 9-13; page 93, line 15 to page 94, line 11; page 94, line 26; Tables 3, 6, 7.	1-5, 6/3-6/5, 7/3-7/5, 8/7/3-8/7/5, 9/1-9/5, 10/9/1-10/9/5, 11/1-11/5
Y	THURMAN, RE et al. The Accessible Chromatin Landscape Of The Human Genome. Nature. 06 September 2012, Vol. 489, No. 7414: pages 75-82; abstract; page 75, column 1, paragraph 1.	1-5, 6/3-6/5, 7/3-7/5, 9/1-9/5, 10/9/1-10/9/5, 11/1-11/5
Y	BLANCAFORT, P et al. Designing Transcription Factor Architectures For Drug Discovery. Mol. Pharmacol. December 2004, Vol. 66, No. 6: pages 1361-1371; page 1362, paragraph 3.	4, 6/4, 7/4, 8/7/3-8/7/5, 9/4, 10/9/4, 11/4

☐ Further documents are listed in the continuation of Box C.

* Special categories of cited documents:

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

23 May 2014 (23.05.2014)

Date of mailing of the international search report

03 JUN 2014

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