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(54) **NUCLEIC ACID BASED FLUORESCENT  
SENSOR FOR COPPER DETECTION**

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(56) **References Cited**

#### **U.S. PATENT DOCUMENTS**

4,362,603 A 12/1982 Presson et al.  
4,703,017 A 10/1987 Campbell et al.  
4,746,631 A 5/1988 Clagett  
4,855,240 A 8/1989 Rosenstein et al.  
4,857,319 A 8/1989 Crowe et al.  
5,008,109 A 4/1991 Tin  
5,459,040 A 10/1995 Hammock et al.  
5,472,881 A 12/1995 Beebe et al.  
5,580,967 A 12/1996 Joyce  
5,593,835 A 1/1997 Rando et al.  
5,631,148 A 5/1997 Urdea  
5,663,064 A 9/1997 Burke et al.  
5,807,718 A 9/1998 Joyce et al.  
5,807,967 A 9/1998 Snow et al.  
5,910,408 A 6/1999 Szostak et al.  
5,989,813 A 11/1999 Gerdes  
6,040,138 A 3/2000 Lockhart et al.  
6,110,462 A 8/2000 Barbas et al.  
6,159,347 A 12/2000 Sumner, Jr. et al.  
6,287,765 B1 9/2001 Cubicciotti  
6,316,194 B1 11/2001 Karn et al.  
6,326,508 B1 12/2001 Godbole et al.  
6,361,944 B1 3/2002 Mirkin et al.  
6,387,617 B1 5/2002 Asher et al.  
6,426,335 B1 7/2002 Janjic et al.

6,451,535 B1 9/2002 Jenne et al.  
6,485,982 B1 11/2002 Charlton  
6,541,617 B1 4/2003 Bamdad et al.  
6,630,306 B1 10/2003 Breaker  
6,706,474 B1 3/2004 Lu et al.  
6,818,455 B2 11/2004 May et al.  
6,843,890 B1 1/2005 Godbole  
6,849,414 B2 2/2005 Guan et al.  
6,890,719 B2 5/2005 Lu et al.  
7,109,165 B2 9/2006 Matulic-Adamic et al.  
7,192,708 B2 3/2007 Lu et al.  
7,332,283 B2 2/2008 Lu et al.  
7,459,145 B2 12/2008 Bao et al.  
7,485,419 B2 2/2009 Lu et al.  
7,534,560 B2 5/2009 Lu et al.  
7,612,185 B2 11/2009 Lu et al.  
7,799,554 B2 9/2010 Mazumdar et al.  
7,829,350 B2 11/2010 Josephson et al.  
7,892,734 B2 2/2011 Lu et al.  
7,902,353 B2 3/2011 Lu et al.  
7,906,320 B2 3/2011 Lu et al.  
2003/0149257 A1 8/2003 Sorge et al.  
2003/0215810 A1 11/2003 Lu et al.  
2003/0235611 A1 12/2003 Ehringer et al.  
2004/0018515 A1 1/2004 Diener et al.  
2004/0110167 A1 6/2004 Gerdes et al.  
2004/0126882 A1 7/2004 Ellington et al.  
2004/0158051 A1 8/2004 Ozkan et al.  
2004/0175693 A1 9/2004 Lu et al.  
2005/0037075 A1 2/2005 Farokhzad et al.  
2005/0136500 A1 6/2005 Yang et al.  
2005/0282186 A1 12/2005 Lu et al.  
2006/0019406 A1 1/2006 Wei et al.  
2006/0040408 A1 2/2006 Jones et al.

(Continued)

#### **FOREIGN PATENT DOCUMENTS**

EP 121970 10/1984  
EP 1219708 7/2002

(Continued)

#### **OTHER PUBLICATIONS**

Abstract of Joyce, G., "Design and catalytic activity of enzymic  
DNA molecules", (1998).

Aggarwal, S.K., et al., "Determination of lead in urine and whole  
blood by stable isotope dilution gas chromatography-mass spectrom-  
etry", Clinical Chemistry, vol. 40, No. 8, pp. 1494-1502, (1994).

Alivisatos, A.P., et al., "Organization of "nanocrystal molecules"  
using DNA", Nature, vol. 382, pp. 609-611, (1996).

Allara, D. et al., "Spontaneously organized molecular assemblies.  
1. Formation, dynamics and physical properties of n-alkanoic acids  
adsorbed from solution on an oxidized aluminum surface",  
Langmuir, vol. 1, No. 1, pp. 45-52, (1985).

Andreola, M-L., et al., "DNA aptamers selected against the HIV-1  
RNase H display in vitro antiviral activity", Biochemistry, vol. 40,  
No. 34, pp. 10087-10094, (2001).

Bain, C. D., et al., "Modeling organic surfaces with self-assembled  
monolayers", Angew. Chem. Int. Ed. Engl., vol. 28, No. 4, pp.  
506-512, (1989).

(Continued)

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(57) **ABSTRACT**

A nucleic acid enzyme responsive to copper, comprising an  
oligonucleotide comprising a nucleotide sequence of SEQ ID  
NO:1, wherein the nucleic acid enzyme is not self-cleaving.

**20 Claims, 13 Drawing Sheets**

## U.S. PATENT DOCUMENTS

2006/0045910	A1	3/2006	Ehringer
2006/0094026	A1	5/2006	Lu et al.
2006/0166222	A1	7/2006	Lu et al.
2007/0037171	A1	2/2007	Lu et al.
2007/0269821	A1	11/2007	Mazumdar et al.
2008/0176228	A1	7/2008	Lu et al.
2009/0011402	A1	1/2009	Lu et al.
2009/0029874	A1	1/2009	Lu et al.
2009/0197261	A1	8/2009	Lu et al.
2010/0105039	A1	4/2010	Lu et al.
2010/0151579	A1	6/2010	Wang et al.
2010/0166842	A1	7/2010	Lu et al.
2011/0123982	A1	5/2011	Lu et al.
2011/0171635	A1	7/2011	Lu et al.

## FOREIGN PATENT DOCUMENTS

EP	1 312 674	5/2003
GB	2339280	1/2000
WO	WO 91/14696	10/1991
WO	WO 96/17086	6/1996
WO	WO 97/09342	3/1997
WO	WO 98/04740	2/1998
WO	WO 98/27104	6/1998
WO	WO 98/39484	9/1998
WO	WO 98/49346	11/1998
WO	WO 99/13338	3/1999
WO	WO 99/27351	6/1999
WO	WO 99/47704	9/1999
WO	WO 00/26226	5/2000
WO	WO 00/58505	10/2000
WO	WO 01/00876	1/2001
WO	WO 01/23548	4/2001
WO	WO 01/24696	4/2001
WO	WO 01/27612 A2	4/2001
WO	WO 01/27612 A3	4/2001
WO	WO 01/51665	7/2001
WO	WO 01/73123	10/2001
WO	WO 02/00006	1/2002
WO	WO 02/22882	3/2002
WO	WO 02/098364	12/2002
WO	WO 03/062422	7/2003
WO	WO 03/068963	8/2003
WO	WO 03/094838	11/2003
WO	WO 03/095648	11/2003
WO	WO 2004/046687	6/2004
WO	WO 2004/081235	9/2004
WO	WO 2005/082922	9/2005
WO	WO 2005/095967	10/2005
WO	WO 2005/100602	10/2005
WO	WO 2006/020768	2/2006
WO	WO 2006/048164	5/2006
WO	WO 2006/052419	5/2006
WO	WO 2006/078660	7/2006
WO	WO 2007/106118	9/2007
WO	WO 2007/109500	9/2007
WO	WO 2008/089248	7/2008
WO	WO 2009/012309	1/2009
WO	WO 2009/045632	4/2009

## OTHER PUBLICATIONS

Bannon, D.I., et al., "Graphite furnace atomic absorption spectroscopic measurement of blood lead in matrix-matched standards", *Clinical Chemistry*, vol. 40, No. 9, pp. 1730-1734, (1994).

Been, M.D., et al., "Self-cleaving ribozymes of hepatitis delta virus RNA", *Eur. J. Biochem.*, vol. 247, pp. 741-753, (1997).

Berens, C., et al., "A tetracycline-binding RNA aptamer", *Bioorganic & Medicinal Chemistry*, vol. 9, pp. 2549-2556, (2001).

Biroccio, A., et al., "Selection of RNA aptamers that are specific and high-affinity ligands of the hepatitis C virus RNA-dependent RNA polymerase", *Journal of Virology*, vol. 76, No. 8, pp. 3688-3696, (2002).

Blake, D.A., et al., "Antibody-based sensors for heavy metal ions", *Biosensors & Bioelectronics*, vol. 16, pp. 799-809, (2001).

Blank, M., et al., "Systematic evolution of a DNA aptamer binding to rat brain tumor microvessels. Selective targeting of endothelial regulatory protein pigpen", *Journal of Biological Chemistry*, vol. 276, No. 19, pp. 16464-16468, (2001).

Bock, L.C., et al., "Selection of single-stranded DNA molecules that bind and inhibit human thrombin", *Nature*, vol. 355, pp. 564-566, (1992).

Bogden, J.D., et al., "Soil contamination from lead in paint chips", *Bulletin of Environmental Contamination & Toxicology*, vol. 14, No. 3, pp. 289-294, (1975).

Boiziau, C., et al., "DNA aptamers selected against the HIV-1 trans-activation-responsive RNA element form RNA-DNA kissing complexes", *Journal of Biological Chemistry*, vol. 274, No. 18, pp. 12730-12737, (1999).

Bowins, R.J., et al., "Electrothermal isotope dilution inductively coupled plasma mass spectrometry method for the determination of sub-ng ml<sup>-1</sup> levels of lead in human plasma", *Journal of Analytical Atomic Spectrometry*, vol. 9, pp. 1233-1236, (1994).

Breaker, R.R., "Catalytic DNA: in training and seeking employment", *Nature Biotechnology*, vol. 17, pp. 422-423, (1999).

Breaker, R.R., "DNA aptamers and DNA enzymes" *Current Opinion in Chemical Biology*, vol. 1, pp. 26-31, (1997).

Breaker, R.R., "DNA enzymes", *Nature Biotechnology*, vol. 15, pp. 427-431, (1997).

Breaker, R.R., "Molecular Biology: Making Catalytic DNAs", *Science*, vol. 290, issue 5499, pp. 2095-2096, (2000).

Breaker, R.R., et al., "A DNA enzyme that cleaves RNA", *Chemistry & Biology*, vol. 1, No. 4, pp. 223-229, (1994).

Breaker, R.R., et al., "A DNA enzyme with Mg<sup>2+</sup>-dependent RNA phosphoesterase activity", *Chemistry & Biology*, vol. 2, No. 10, pp. 655-660, (1995).

Breaker, R.R., et al., "Engineered allosteric ribozymes as biosensor components", *Current Opinion in Biotechnology*, vol. 13, pp. 31-39, (2002).

Brody, E.N., et al., "Aptamers as therapeutic and diagnostic agents", *Reviews in Molecular Biotechnology*, vol. 74, pp. 5-13, (2000).

Broude, N.E., "Stem-loop oligonucleotides: a robust tool for molecular biology and biotechnology", *Trends in Biotechnology*, vol. 20, No. 6, pp. 249-256, (2002).

Brown, A.K., et al., "A lead-dependent DNzyme with a two-step mechanism", *Biochemistry*, vol. 42, No. 23, pp. 7152-7161, (2003).

Brueschoff, P.J., et al., "Improving metal ion specificity during In Vitro selection of catalytic DNA", *Combinatorial Chemistry & High Throughput Screening*, vol. 5, pp. 327-335, (2002).

Bruno, J.G., et al., "In vitro selection of DNA aptamers to anthrax spores with electrochemiluminescence detection", *Biosensors & Bioelectronics*, vol. 14, pp. 457-464, (1999).

Bruno, J.G., et al., "Use of magnetic beads in selection and detection of biotoxin aptamers by electrochemiluminescence and enzymatic methods", *BioTechniques*, vol. 32, No. 1, pp. 178-180, pp. 182-183, (2002).

Brust, M., et al., "Novel gold-dithiol nano-networks with non-metallic electronic properties", *Advanced Materials*, vol. 7, No. 9, pp. 795-797, (1995).

Burdette, S.C., et al., "Fluorescent Sensors for Zn<sup>2+</sup> Based on a Fluorescein Platform: Synthesis, Properties and Intracellular Distribution", *J. Am. Chem. Soc.*, vol. 123, No. 32, pp. 7831-7841, (2001).

Burgstaller, P., et al., "Isolation of RNA aptamers for biological cofactors by in vitro selection", *Angew. Chem. Int. Ed. Engl.*, vol. 33, No. 10, pp. 1084-1087, (1994).

Burgstaller, P., et al., "Structural probing and damage selection of citrulline- and arginine-specific RNA aptamers identify base positions required for binding", *Nucleic Acids Research*, vol. 23, No. 23, pp. 4769-4776, (1995).

Burke, D.H., et al., "A Novel Acidophilic RNA Motif That Recognizes Coenzyme A", *Biochemistry*, vol. 37, No. 13, pp. 4653-4663, (1998).

Burke, D.H., et al., "RNA aptamers to the adenosine moiety of S-adenosyl methionine: structural inferences from variations on a theme and the reproducibility of SELEX", *Nucleic Acids Research*, vol. 25, No. 10, pp. 2020-2024, (1997).

Burke, D.H., et al., "RNA aptamers to the peptidyl transferase inhibitor chloramphenicol", *Chemistry & Biology*, vol. 4, No. 11, pp. 833-843, (1997).

Burmeister, J., et al., "Cofactor-assisted self-cleavage in DNA libraries with a 3'-5'-phosphoramidate bond", *Angew. Chem. Int. Ed. Engl.*, vol. 36, No. 12, pp. 1321-1324, (1997).

- Burwell Jr., R.L., "Modified silica gels as adsorbents and catalysts", *Chemical Technology*, 4, pp. 370-377, (1974).
- Cadwell, R.C., et al., "Mutagenic PCR", *PCR Methods and Applications*, vol. 3, pp. S136-S140, (1994).
- Cadwell, R.C., et al., "Randomization of genes by PCR mutagenesis", *PCR Methods and Applications*, vol. 2, pp. 28-33, (1992).
- Cake, K.M., et al., "In vivo x-ray fluorescence of bone lead in the study of human lead metabolism: serum lead, whole blood lead, bone lead, and cumulative exposure", *Advances in X-Ray Analysis*, vol. 38, pp. 601-606, (1995).
- Camara Rica, C., et al., "Determination of trace concentrations of lead and nickel in human milk by electrothermal atomisation atomic absorption spectrophotometry and inductively coupled plasma emission spectroscopy", *The Science of the Total Environment*, vol. 22, pp. 193-201, (1982).
- Cao, Y.W., et al., "DNA-modified core-shell Ag/Au nanoparticles", *J. Am. Chem. Soc.*, vol. 123, No. 32, pp. 7961-7962, (2001).
- Carmi, N., et al., "Cleaving DNA with DNA", *Proc. Natl. Acad. Sci. USA*, vol. 95, pp. 2233-2237, (1998).
- Carmi, N., et al., "In vitro selection of self-cleaving DNAs", *Chemistry & Biology*, vol. 3, No. 12, pp. 1039-1046, (1996).
- Cech, T.R., "Structure and mechanism of the large catalytic RNAs: group I and group II introns and ribonuclease P", *The RNA World*, pp. 239-269, Cold Spring Harbor Laboratory Press, Cold Spring Harbor, New York, (1993).
- Cech, T.R., et al., "Group I ribozymes: substrate recognition, catalytic strategies, and comparative mechanistic analysis", *Nucleic Acids and Molecular Biology*, vol. 10, pp. 1-17, (1996).
- Chaloin, L., et al., "Endogenous expression of a high-affinity pseudoknot RNA aptamer suppresses replication of HIV-1", *Nucleic Acids Research*, vol. 30, No. 18, pp. 4001-4008, (2002).
- Chapman, K.B., et al., "In vitro selection of catalytic RNAs", *Current Opinion in Structural Biology*, vol. 4, pp. 618-622, (1994).
- Chartrand, P., et al., "Effect of structural modifications on the activity of the leadzyme", *Biochemistry*, vol. 36, No. 11, pp. 3145-3150, (1997).
- Chen, J., et al., "Synthesis from DNA of a molecule with the connectivity of a cube", *Nature*, vol. 350, pp. 631-633, (1991).
- Chen, C-T., et al., "A highly selective fluorescent chemosensor for lead ions", *J. Am. Chem. Soc.*, vol. 124, pp. 6246-6247, (2002).
- Chen, J-H., et al., "A specific quadrilateral synthesized from DNA branched junctions", *J. Am. Chem. Soc.*, vol. 111, No. 16, pp. 6402-6407, (1989).
- Chen, L., et al., "Crystal structure of a four-stranded intercalated DNA: d(C<sub>4</sub>)", *Biochemistry*, vol. 33, No. 46, pp. 13540-13546, (1994).
- Chinnappen, D.J.F., et al., "Hemin-stimulated docking of cytochrome c to a hemin-DNA aptamer complex", *Biochemistry*, vol. 41, No. 16, pp. 5202-5212, (2002).
- Ciesiolka, J., et al., "Selection of an RNA domain that binds Zn<sup>2+</sup>", *RNA*, vol. 1, pp. 538-550, (1995).
- Ciesiolka, J., et al., "Small RNA-divalent domains", *RNA*, vol. 2, pp. 785-793, (1996).
- Conaty, J., et al., "Selected classes of minimised hammerhead ribozyme have very high cleavage rates at low Mg<sup>2+</sup> concentration", *Nucleic Acids Research*, vol. 27, No. 11, pp. 2400-2407, (1999).
- Conn, M.M., et al., "Porphyrin Metalation Catalyzed by a Small RNA Molecule", *J. Am. Chem. Soc.*, vol. 118, No. 29, pp. 7012-7013, (1996).
- Connell, G.J., et al., "RNAs with dual specificity and dual RNAs with similar specificity", *Science, New Series*, vol. 264, issue 5162, pp. 1137-1141, (1994).
- Connell, G.J., et al., "Three small ribooligonucleotides with specific arginine sites", *Biochemistry*, vol. 32, No. 21, pp. 5497-5502, (1993).
- Cuenoud, B., et al., "A DNA metalloenzyme with DNA ligase activity", *Nature*, vol. 375, pp. 611-614, (1995).
- Czarnik, A.W., "Desperately seeking sensors", *Chemistry & Biology*, vol. 2, No. 7, pp. 423-428, (1995).
- Dai, X., et al., "Cleavage of an amide bond by a ribozyme", *Science, New Series*, vol. 267, issue 5195, pp. 237-240, (1995).
- Davis, J.H., et al., "Isolation of high-affinity GTP aptamers from partially structured RNA libraries", *Proc. Natl. Acad. Sci. USA*, vol. 99, No. 18, pp. 11616-11621, (2002).
- Davis, K.A., et al., "Staining of cell surface human CD4 with 2'-F-pyrimidine-containing RNA aptamers for flow cytometry", *Nucleic Acids Research*, vol. 26, No. 17, pp. 3915-3924, (1998).
- Definition of the word "ion" printed from Merriam-Webster online dictionary ([www.m-w.com](http://www.m-w.com)) on Jun. 30, 2004.
- Definition of the word "particle" printed from Merriam-Webster online dictionary ([www.m-w.com](http://www.m-w.com)) on Jun. 29, 2004.
- Deo, S., et al., "A Selective, Ratiometric Fluorescent Sensor for Pb<sup>2+</sup>", *J. Am. Chem. Soc.*, vol. 122, No. 1, pp. 174-175, (2000).
- Deroose, V.J., "Two Decades of RNA Catalysis", *Chemistry & Biology*, vol. 9, pp. 961-969, (2002).
- Didenko, V.V., "DNA probes using fluorescence resonance energy transfer (FRET): Designs and applications", *BioTechniques*, vol. 31, pp. 1106-1121, (2001). We have reference, but we are missing pp. 1119-1121.
- Doudna, J.A., et al., "The Chemical Repertoire of Natural Ribozymes", *Nature*, vol. 418, pp. 222-228, (2002).
- Dubois, L.H., et al., "Synthesis, structure, and properties of model organic surfaces", *Annu. Rev. Phys. Chem.*, vol. 43, pp. 437-463, (1992).
- Earnshaw, D.J., et al., "Modified oligoribonucleotides as site-specific probes of RNA structure and function", *Biopolymers (Nucleic Acid Sciences)*, vol. 48, pp. 39-55, (1998).
- Ekland, E.H., et al., "RNA-catalysed RNA polymerization using nucleoside triphosphates", *Nature*, vol. 382, pp. 373-376, (1996).
- Ekland, E.H., et al., "Structurally complex and highly active RNA ligases derived from random RNA sequences", *Science*, vol. 269, issue 5222, pp. 364-370, (1995).
- Elghanian, R., et al., "Selective colorimetric detection of polynucleotides based on the distance-dependent optical properties of gold nanoparticles", *Science*, vol. 277, pp. 1078-1081, (1997).
- Ellington, A.D., et al., "Aptamers as potential nucleic acid pharmaceuticals", *Biotechnology Annual Review*, vol. 1, pp. 185-214, (1995).
- Ellington, A.D., et al., "In vitro selection of RNA molecules that bind specific ligands", *Nature*, vol. 346, pp. 818-822, (1990).
- Ellington, A.D., et al., "Selection in vitro of single-stranded DNA molecules that fold into specific ligand-binding structures", *Nature*, vol. 355, pp. 850-852, (1992).
- Famulok, M., "Molecular Recognition of Amino Acids by RNA-Aptamers: An L-Citrulline Binding RNA Motif and Its Evolution into an L-Arginine Binder", *J. Am. Chem. Soc.*, vol. 116, No. 5, pp. 1698-1706, (1994).
- Famulok, M., "Oligonucleotide aptamers that recognize small molecules", *Current Opinion in Structural Biology*, vol. 9, pp. 324-329, (1999).
- Famulok, M., et al., "In Vitro Selection Analysis of Neomycin Binding RNAs with a Mutagenized Pool of Variants of the 16S rRNA Decoding Region", *Biochemistry*, vol. 35, No. 14, pp. 4265-4270, (1996).
- Famulok, M., et al., "Stereospecific recognition of tryptophan agarose by in vitro selected RNA", *J. Am. Chem. Soc.*, vol. 114, No. 10, pp. 3990-3991, (1992).
- Faulhammer, D., et al., "Characterization and Divalent Metal-ion Dependence of in Vitro Selected Deoxyribozymes which Cleave DNA/RNA Chimeric Oligonucleotides", *J. Mol. Biol.*, vol. 269, pp. 188-202, (1997).
- Faulhammer, D., et al., "The Ca<sup>2+</sup> ion as a cofactor for a novel RNA-cleaving deoxyribozyme", *Angew. Chem., Int. Ed. Engl.*, vol. 35, No. 23/24, pp. 2837-2841, (1996).
- Feldman, B.J., et al., "Determination of lead in blood by square wave anodic stripping voltammetry at a carbon disk ultramicroelectrode", *Analytical Chemistry*, vol. 66, No. 13, pp. 1983-1987, (1994).
- Ferguson, A., et al., "A novel strategy for selection of allosteric ribozymes yields riboreporter™ sensors for caffeine and aspartame", *Nucleic Acids Research*, vol. 32, No. 5, pp. 1756-1766, (2004).
- Fodor, S.P.A., et al., "Light-directed, spatially addressable parallel chemical synthesis", *Science, New Series*, vol. 251, issue 4995, pp. 767-773, (1991).

- Frank, D.N., et al., "In vitro selection for altered divalent metal specificity in the RNase P RNA", *Proc. Natl. Acad. Sci. USA*, vol. 94, pp. 14355-14360, (1997).
- Frens, G., et al., "Controlled Nucleation for the regulation of the particle size in monodisperse gold suspensions", *Nature Physical Science*, vol. 241, pp. 20-22, (1973).
- Fukusaki, E.-I., et al., "DNA aptamers that bind to chitin", *Bioorganic & Medicinal Chemistry letters*, vol. 10, pp. 423-425, (2000).
- Geiger, A., et al., "RNA aptamers that bind L-arginine with sub-micromolar dissociation constants and high enantioselectivity", *Nucleic Acids Research*, vol. 24, No. 6, pp. 1029-1036, (1996).
- Geyer, C.R., et al., "Evidence for the metal-cofactor independence of an RNA phosphodiester-cleaving DNA enzyme", *Chemistry & Biology*, vol. 4, No. 8, pp. 579-593, (1997).
- Geyer, C.R., et al., "Lanthanide Probes for a Phosphodiester-cleaving, Lead-dependent, DNzyme", *J. Mol. Biol.*, vol. 275, pp. 483-489, (1998).
- Giver, L., et al., "Selection and design of high-affinity RNA ligands for HIV-1 Rev", *Gene*, vol. 137, pp. 19-24, (1993).
- Giver, L., et al., "Selective optimization of the Rev-binding element of HIV-1", *Nucleic Acids Research*, vol. 21, No. 23, pp. 5509-5516, (1993).
- Godwin, H.A., et al., "A Fluorescent Zinc Probe Based on Metal-Induced Peptide Folding", *J. Am. Chem. Soc.*, vol. 118, pp. 6514-6515, (1996).
- Grabar, K., et al., "Preparation and characterization of Au colloid Monolayers", *Analytical chemistry*, vol. 67, No. 4, pp. 735-743, (1995).
- Granadillo, V.A., et al., "The influence of the blood levels of lead, aluminum and vanadium upon the arterial hypertension", *Clinica Chimica Acta*, vol. 233, pp. 47-59, (1995).
- Grate, D., et al., "Laser-mediated, site-specific inactivation of RNA transcripts", *Proc. Natl. Acad. Sci. USA*, vol. 96, pp. 6131-6136, (1999).
- Guschin, D., et al., "Manual manufacturing of oligonucleotide, DNA, and protein microchips", *Analytical Biochemistry*, vol. 250, pp. 203-211, (1997).
- Haller, A.A., et al., "In vitro selection of a 7-methyl-guanosine binding RNA that inhibits translation of capped mRNA molecules", *Proc. Natl. Acad. Sci. USA*, vol. 94, pp. 8521-8526, (1997).
- Harada, K., et al., "Identification of two novel arginine binding DNAs", *The EMBO Journal*, vol. 14, No. 23, pp. 5798-5811, (1995).
- Hartig, J.S., et al., "Reporter ribozymes for real-time analysis of domain-specific interactions in biomolecules: HIV-1 reverse transcriptase and the primer-template complex", *Angew. Chem. Int. Ed.*, vol. 41, No. 22, pp. 4263-4266, (2002).
- He, X.-x., et al., "Bioconjugated nanoparticles for DNA protection from cleavage", *J. Am. Chem. Soc.*, vol. 125, No. 24, pp. 7168-7169, (2003).
- Hennrich, G., et al., "Redox switchable fluorescent probe selective for either Hg(II) or Cd(II) and Zn(II)", *J. Am. Chem. Soc.*, vol. 121, No. 21, pp. 5073-5074, (1999).
- Hesselberth, J., et al., "In vitro selection of nucleic acids for diagnostic applications", *Reviews in Molecular Biotechnology*, vol. 74, pp. 15-25, (2000).
- Hesselberth, J.R., et al., "Simultaneous detection of diverse analytes with an aptazyme ligase array", *Analytical Biochemistry* vol. 312, pp. 106-112, (2003).
- Ho, H.-A., et al., "Optical sensors based on hybrid aptamer/conjugated polymer complexes", *J. Am. Chem. Soc.*, vol. 126, No. 5, pp. 1384-1387, (2004).
- Hock, B., "Antibodies for immunosensors, A review", *Analytica Chimica Acta*, vol. 347, pp. 177-186, (1997).
- Hofmann, H.P., et al., "Ni<sup>2+</sup>-binding RNA motifs with an asymmetric purine-rich internal loop and a G-A base pair", *RNA*, vol. 3, pp. 1289-1300, (1997).
- Holeman, L.A., et al., "Isolation and characterization of fluorophore-binding RNA aptamers", *Folding & Design*, vol. 3, pp. 423-431, (1998).
- Hoogstraten, C.G., et al., "NMR solution structure of the lead-dependent ribozyme: Evidence for dynamics in RNA catalysis", *J. Mol. Biol.*, vol. 284, pp. 337-350, (1998).
- Hoogstraten, C.G., et al., "Structural analysis of metal ion ligation to nucleotides and nucleic acids using pulsed EPR spectroscopy", *J. Am. Chem. Soc.*, vol. 124, No. 5, pp. 834-842, (2002).
- Huizenga, D.E., et al., "A DNA aptamer that binds adenosine and ATP", *Biochemistry*, vol. 34, No. 2, pp. 656-665, (1995).
- Iler, R.K., "The Chemistry of Silica: Solubility, Polymerization, Colloid and Surface Properties, and Biochemistry, Chapter 6, The surface chemistry of silica", pp. 622-729, A Wiley-Interscience Publication, New York, (1979).
- Illangasekare, M., et al., "Small-molecule-substrate interactions with a self-aminoacylating ribozyme", *J. Mol. Biol.*, vol. 268, pp. 631-639, (1997).
- Imperiali, B., et al., "Peptide platforms for metal ion sensing", *Proc. SPIE—The international society for optical engineering*, vol. 3858, pp. 135-143, (1999).
- International Search Report dated Jan. 15, 2003 for PCT application No. PCT/US01/20557.
- International Search Report dated Aug. 1, 2003 for PCT application No. PCT/US03/08483.
- Iqbal, S.S., et al., "A review of molecular recognition technologies for detection of biological threat agents", *Biosensors & Bioelectronics*, vol. 15, pp. 549-578, (2000).
- Abstract of: Iwasaki, K., Mizota, T., Kenkyu Hokoku—Kanagawa-ken Kogyo Shikensho 1991, 62, 57.
- Jagner, D., et al., "Determination of lead in microliter amounts of whole blood by stripping potentiometry", *Electroanalysis*, vol. 6, pp. 285-291, (1994).
- Jayasena, S.D., "Aptamers: an emerging class of molecules that rival antibodies in diagnostics", *Clinical Chemistry*, vol. 45, No. 9, pp. 1628-1650, (1999).
- Jenison, R., et al., "Interference-based detection of nucleic acid targets on optically coated silicon", *Nature Biotechnology*, vol. 19, pp. 62-65, (2001).
- Jenison, R.D., et al., "High-resolution molecular discrimination by RNA", *Science*, vol. 263, pp. 1425-1429, (1994).
- Jenne, A., et al., "Rapid Identification and Characterization of Hammerhead-Ribozyme Inhibitors Using Fluorescence-Based Technology", *Nature Biotechnology*, vol. 19, pp. 56-61, (2001).
- Jenne, A., et al., "Real-time Characterization of Ribozymes by Fluorescence Resonance Energy Transfer (FRET)", *Angewandte Chemie. International Edition*, vol. 38, No. 9, pp. 1300-1303, (1999).
- Jhaveri, S., et al., "In vitro selection of signaling aptamers", *Nature Biotechnology*, vol. 18, pp. 1293-1297, (2000).
- Jhaveri, S.D., et al., "Designed signaling aptamers that transduce molecular recognition to changes in fluorescence intensity", *J. Am. Chem. Soc.*, vol. 122, No. 11, pp. 2469-2473, (2000).
- Jin, R., et al., "What controls the melting properties of DNA-linked gold nanoparticle assemblies?", *J. Am. Chem. Soc.*, vol. 125, No. 6, pp. 1643-1654, (2003).
- Joos, B., et al., "Covalent attachment of hybridizable oligonucleotides to glass supports", *Analytical Biochemistry*, vol. 247, pp. 96-101, (1997).
- Josephson, L., et al., "Magnetic nanosensors for the detection of oligonucleotide sequences", *Angewandte Chemie. International Edition*, vol. 40, No. 17, pp. 3204-3206, (2001).
- Joyce, G.F., "Appendix 3: Reactions Catalyzed by RNA and DNA Enzymes", *The RNA World*, vol. 37, pp. 687-690, Cold Spring Harbor Laboratory Press, Cold Spring Harbor, New York, (1999).
- Joyce, G.F., "In vitro evolution of nucleic acids", *Current Opinion in Structural Biology*, vol. 4, pp. 331-336, (1994).
- Katahira, M., et al., "Two metal-binding sites in a lead ribozyme bound to competitively by Pb<sup>2+</sup> and Mg<sup>2+</sup>: Induced structural changes as revealed by NMR", *European Journal of Biochemistry*, vol. 255, pp. 727-733, (1998).
- Kato, T., et al., "In vitro selection of DNA aptamers which bind to cholic acid", *Biochimica et Biophysica Acta*, vol. 1493, pp. 12-18, (2000).
- Kawakami, J., et al., "In vitro selection of aptamers that act with Zn<sup>2+</sup>", *Journal of Inorganic Biochemistry*, vol. 82, pp. 197-206, (2000).
- Khan, R., et al., "Interaction of retroviral nucleocapsid proteins with transfer RNA<sup>Phe</sup>: a lead ribozyme and <sup>1</sup>H NMR study", *Nucleic Acids Research*, vol. 24, No. 18, pp. 3568-3575, (1996).

- Khosraviani, M., et al., "Detection of heavy metals by immunoassay: Optimization and validation of a rapid, portable assay for ionic cadmium", *Environ. Sci. Technol.*, vol. 32, No. 1, pp. 137-142, (1998).
- Kiga, D., et al., "An RNA aptamer to the xanthine/guanine base with a distinctive mode of purine recognition", *Nucleic Acids Research*, vol. 26, No. 7, pp. 1755-1760, (1998).
- Kim, M.H., et al., "Activation and repression of the activity of a lead ribozyme by the combination of  $Pb^{2+}$  and  $Mg^{2+}$ ", *J. Biochem.*, vol. 122, No. 5, pp. 1062-1067, (1997).
- Kluffmann, S., et al., "Mirror-image RNA that binds D-adenosine", *Nature Biotechnology*, vol. 14, pp. 1112-1115, (1996).
- Kohama, T., et al., "Molecular Cloning and Functional Characterization of Murine Sphingosine Kinase", *The Journal of Biological Chemistry*, vol. 273, No. 37, pp. 23722-23728, (1998).
- Koizumi, M., et al., "Allosteric selection of ribozymes that respond to the second messengers cGMP and cAMP", *Nature Structural Biology*, vol. 6, No. 11, pp. 1062-1071, (1999).
- Koizumi, M., et al., "Molecular Recognition of cAMP by an RNA Aptamer", *Biochemistry*, vol. 39, No. 30, pp. 8983-8992, (2000).
- Koizumi, M., et al., "Allosteric ribozymes sensitive to the second messengers cAMP and cGMP", *Nucleic Acids Symposium Series*, No. 42, pp. 275-276, (1999).
- Kruger, K., et al., "Self-splicing RNA: autoexcision and autocyclization of the ribosomal RNA intervening sequence of the Tetrahymena", *Cell*, vol. 31, pp. 147-157, (1982).
- Lato, S.M., et al., "In vitro selection of RNA lectins: Using combinatorial chemistry to interpret ribozyme evolution", *Chemistry & Biology*, vol. 2, No. 5, pp. 291-303, (1995).
- Lauhon, C.T., et al., "RNA aptamers that bind flavin and nicotinamide redox cofactors", *J. Am. Chem. Soc.*, vol. 117, No. 4, pp. 1246-1257, (1995).
- Lebruska, L.L., "Selection and Characterization of an RNA Decoy for Transcription Factor NF- $\kappa$ B", *Biochemistry*, vol. 38, No. 10, pp. 3168-3174, (1999).
- Lee, M., et al., "A fiber-optic microarray biosensor using aptamers as receptors", *Analytical Biochemistry*, vol. 282, pp. 142-146, (2000).
- Lee, S-W., et al., "Ordering of quantum dots using genetically engineered viruses", *Science*, vol. 296, pp. 892-895, (2002).
- Legault, P., et al., "Order, dynamics and metal-binding in the lead-dependent ribozyme", *J. Mol. Biol.*, vol. 284, pp. 325-335, (1998).
- Lehman, N., et al., "Evolution in vitro of an RNA enzyme with altered metal dependence", *Nature*, vol. 361, pp. 182-185, (1993).
- Lemieux, S., et al., "Modeling active RNA structures using the intersection of conformational space: application to the lead-activated ribozyme", *RNA*, vol. 4, pp. 739-749, (1998).
- Levy, M., et al., "ATP-Dependent Allosteric DNA Enzymes", *Chemistry & Biology*, vol. 9, pp. 417-426, (2002).
- Li, J., et al., "A highly sensitive and selective catalytic DNA biosensor for lead ions", *J. Am. Chem. Soc.*, vol. 122, No. 42, pp. 10466-10467, (2000).
- Li, J., et al., "In vitro selection and characterization of a highly efficient Zn(II)-dependent RNA-cleaving deoxyribozyme", *Nucleic Acids Research*, vol. 28, No. 2, pp. 481-488, (2000).
- Li, J.J., et al., "Using molecular beacons as a sensitive fluorescence assay for enzymatic cleavage of single-stranded DNA", *Nucleic Acids Research*, vol. 28, No. 11, e52, pp. i-vi, (2000).
- Li, Y., et al., "A catalytic DNA for porphyrin metallation", *Nature Structural Biology*, vol. 3, No. 9, pp. 743-747, (1996).
- Li, Y., et al., "Capping DNA with DNA", *Biochemistry*, vol. 19, No. 11, pp. 3106-3114, (2000).
- Li, Y., et al., "Deoxyribozymes: new players in the ancient game of biocatalysis", *Current Opinion in Structural Biology*, vol. 9, pp. 315-323, (1999).
- Li, Y., et al., "Phosphorylating DNA with DNA", *Proc. Natl. Acad. Sci. USA*, vol. 96, pp. 2746-2751, (1999).
- Link, S., et al., "Alloy formation of gold-silver nanoparticles and the dependence of the plasmon absorption on their composition", *J. Phys. Chem. B*, vol. 103, No. 18, pp. 3529-3533, (1999).
- Liu, H-W., et al., "Determination of cadmium, mercury and lead in seawater by electrothermal vaporization isotope dilution inductively coupled plasma mass spectrometry", *Spectrochimica Acta Part B Atomic Spectroscopy* 54, pp. 1367-1375, (1999).
- Liu, J., et al., "A colorimetric lead biosensor using DNzyme-directed assembly of gold nanoparticles", *J. Am. Chem. Soc.*, vol. 125, No. 22, pp. 6642-6643, (2003).
- Liu, J., et al., "Accelerated color change of gold nanoparticles assembled by DNzymes for simple and fast colorimetric  $Pb^{2+}$  detection", *J. Am. Chem. Soc.*, vol. 126, No. 39, pp. 12298-12305, (2004).
- Liu, J., et al., "Adenosine-dependent assembly of aptazyme-functionalized gold nanoparticles and its application as a colorimetric biosensor", *Analytical Chemistry*, vol. 76, No. 6, pp. 1627-1632, (2004).
- Liu, J., et al., "Colorimetric biosensors based on DNzyme-assembled gold nanoparticles", *Journal of Fluorescence*, vol. 14, No. 4, pp. 343-354, (2004).
- Liu, J., et al., "Highly dispersible molecular sieve carbon nanoparticles", *Chem. Mater.*, vol. 16, No. 22, pp. 4205-4207, (2004).
- Liu, X., et al., "A fiber-optic evanescent wave DNA biosensor based on novel molecular beacons", *Analytical Chemistry*, vol. 71, No. 22, pp. 5054-5059, (1999).
- Liu, Z., et al., "Assemblage of signaling DNA enzymes with intriguing metal-ion specificities and pH dependences", *J. Am. Chem. Soc.*, vol. 125, No. 25, pp. 7539-7545, (2003).
- Lohse, P.A., et al., "Ribozyme-catalysed amino-acid transfer reactions", *Nature*, vol. 381, pp. 442-444, (1996).
- Lorsch, J.R., et al., "In vitro evolution of new ribozymes with polynucleotide kinase activity", *Nature*, vol. 371, pp. 31-36, (1994).
- Lorsch, J.R., et al., "In vitro selection of RNA aptamers specific for cyanocobalamin", *Biochemistry*, vol. 33, No. 4, pp. 973-982, (1994).
- Lott, W.B., et al., "A two-metal ion mechanism operates in the hammerhead ribozyme-mediated cleavage of an RNA substrate", *Proc. Natl. Acad. Sci. USA*, vol. 95, pp. 542-547, (1998).
- Lu, Y., "New transition-metal-dependent DNzymes as efficient endonucleases and as selective metal biosensors", *Chem. Eur. J.*, vol. 8, No. 20, pp. 4588-4596, (2002).
- Lu, Y., et al., "New fluorescent and colorimetric DNzyme biosensors for metal ions", *Journal of Inorganic Biochemistry*, vol. 96, issue 1, pp. 30, Abstract of the 11<sup>th</sup> International Conference on Biological Inorganic Chemistry; (Jul. 15, 2003).
- Majerfeld, I., et al., "An RNA pocket for an aliphatic hydrophobe", *Structural Biology*, vol. 1, No. 5, pp. 287-292, (1994).
- Majerfeld, I., et al., "Isoleucine:RNA sites with associated coding sequences", *RNA*, vol. 4, pp. 471-478, (1998).
- Mannironi, C., et al., "In vitro selection of dopamine RNA ligands", *Biochemistry*, vol. 36, No. 32, pp. 9726-9734, (1997).
- Maos, R., et al., "Penetration-controlled reactions in organized monolayer assemblies. 1. Aqueous permanganate interaction with monolayer and multilayer films of long-chain surfactants", *Langmuir*, vol. 3, No. 6, pp. 1034-1044, (1987).
- Marcus, A.H., et al., "Estimating the contribution of lead based paint to soil lead, dust lead, and childhood blood lead", *American Society for Testing and Materials Spec. STP 1226*, pp. 12-23, (1995).
- Marsh, T.C., et al., "A new DNA nanostructure, the G-wire, imaged by scanning probe microscopy", *Nucleic Acids Research*, vol. 23, No. 4, pp. 696-700, (1995).
- Matteucci, M.D., et al., "Synthesis of Deoxyoligonucleotides on a polymer support", *J. Am. Chem. Soc.*, vol. 103, No. 11, pp. 3185-3191, (1981).
- Mecklenburg, M., et al., "A strategy for the broad range detection of compounds with affinity for nucleic acids", *Analytica Chimica Acta*, vol. 347, pp. 79-86, (1997).
- Mei, S.H.J., et al., "An efficient RNA-cleaving DNA enzyme that synchronizes catalysis with fluorescence signaling", *J. Am. Chem. Soc.*, vol. 125, No. 2, pp. 412-420, (2003).
- Meli, M., et al., "Adenine-aptamer complexes: A bipartite RNA site that binds the adenine nucleic base", *The Journal of Biological Chemistry*, vol. 277, No. 3, pp. 2104-2111, (2002).
- Mirkin, C.A., et al., "A DNA-based method for rationally assembling nanoparticles into macroscopic materials", *Nature*, vol. 382, pp. 607-609, (1996).
- Mirkin, S.M., et al., "H-DNA and related structures", *Annu. Rev. Biophys. Biomol. Struct.*, vol. 23, pp. 541-576, (1994).

- Miyawaki, A., et al., "Fluorescent indicators for  $\text{Ca}^{2+}$  based on green fluorescent proteins and calmodulin", *Nature*, vol. 388, pp. 882-887, (1997).
- Mucic, R.C., et al., "Synthesis and characterization of DNA with ferrocenyl groups attached to their 5'-termini: electrochemical characterization of a redox-active nucleotide monolayer", *Chem. Commun.*, pp. 555-557, (1996).
- Mullah, B., et al., "Automated synthesis of double dye-labeled oligonucleotides using tetramethylrhodamine (TAMRA) solid supports", *Tetrahedron Letters*, vol. 38, No. 33, pp. 5751-5754, (1997).
- Nazarenko, I.A., et al., "A closed tube format for amplification and detection of DNA based on energy transfer", *Nucleic Acids Research*, vol. 26, No. 12, pp. 2516-2521, (1997).
- Nazarenko, I.A., et al., "Defining a Smaller RNA Substrate for Elongation Factor Tu", *Biochemistry*, vol. 34, No. 8, pp. 2545-2552, (1995).
- Niemeyer, C.M., "Nanoparticles, proteins, and nucleic acids: Biotechnology meets materials science", *Angew. Chem. Int. Edition*, vol. 40, pp. 4128-4158, (2001).
- Nieuwlandt, D., et al., "In Vitro Selection of RNA Ligands to Substance P", *Biochemistry*, vol. 34, No. 16, pp. 5651-5659, (1995).
- Nissen, P., et al., "The structural basis of ribosome activity in peptide bond synthesis", *Science*, vol. 289, pp. 920-930, (2000).
- Nolte, A., et al., "Mirror-design of L-oligonucleotide ligands binding to L-arginine", *Nature Biotechnology*, vol. 14, pp. 1116-1119, (1996).
- Nutiu, R., et al., "Structure-switching signaling aptamers", *J. Am. Chem. Soc.*, vol. 125, No. 16, pp. 4771-4778, (2003).
- Nuzzo, R.G., et al., "Spontaneously organized molecular assemblies. 3. Preparation and properties of solution adsorbed monolayers of organic disulfides on gold surfaces", *J. Am. Chem. Soc.*, vol. 109, No. 8, pp. 2358-2368, (1987).
- O'Donnell, M.J., et al., "High-Density, Covalent Attachment of DNA to Silicon Wafers for Analysis by MALDI-TOF Mass Spectrometry", *Analytical Chemistry*, vol. 69, No. 13, pp. 2438-2443, (1997).
- Oehme, I., et al., "Optical sensors for determination of heavy metal ions", *Mikrochim. Acta*, vol. 126, pp. 177-192, (1997).
- Ohmichi, T., et al., "Role of  $\text{Nd}^{3+}$  and  $\text{Pb}^{2+}$  on the RNA cleavage reaction by a small ribozyme", *Biochemistry*, vol. 36, No. 12, pp. 3514-3521, (1997).
- Ohmichi, T., et al., "Effect of substrate RNA sequence on the cleavage reaction by a short ribozyme", *Nucleic Acids Research*, vol. 26, No. 24, pp. 5655-5661, (1998).
- Okazawa, A., et al., "In vitro selection of hematoporphyrin binding DNA aptamers", *Bioorganic & Medicinal Chemistry, Letters* 10, pp. 2653-2656, (2000).
- Ota, N., et al., "Effects of helical structures formed by the binding arms of DNAzymes and their substrates on catalytic activity", *Nucleic Acids Research*, vol. 26, No. 14, pp. 3385-3391, (1998).
- Pan, T., et al., "A small metalloribozyme with a two-step mechanism", *Nature*, vol. 358, pp. 560-563, (1992).
- Pan, T., et al., "In vitro selection of RNAs that undergo autolytic cleavage with  $\text{Pb}^{2+}$ ", *Biochemistry*, vol. 31, No. 16, pp. 3887-3895, (1992).
- Pan, T., et al., "Properties of an in vitro selected  $\text{Pb}^{2+}$  cleavage motif", *Biochemistry*, vol. 33, No. 32, pp. 9561-9565, (1994).
- Pan, W., et al., "Isolation of virus-neutralizing RNAs from a large pool of random sequences", *Proc. Natl. Acad. Sci. USA*, vol. 92, pp. 11509-11513, (1995).
- Park, S.-J., et al., "Array-based electrical detection of DNA with nanoparticle probes", *Science*, vol. 295, pp. 1503-1506, (2002).
- Parsons, P.J., et al., "A rapid Zeeman graphite furnace atomic absorption spectrometric method for the determination of lead in blood", *Spectrochimica Acta*, vol. 48B, No. 6/7, pp. 925-939, (1993).
- Pavlov, A.R., et al., "Determination of lead in environmental water samples by a rapid and portable immunoassay", *ANYL, Book of Abstracts*, 219th ACS National Meeting, San Francisco, CA, Mar. 26-30, 2000.
- Pavlov, V., et al., "Aptamer-functionalized Au nanoparticles for the amplified optical detection of thrombin", *J. Am. Chem. Soc.*, vol. 126, No. 38, pp. 11768-11769, (2004).
- Pearce, D.A., et al., "Peptidyl chemosensors incorporating a FRET mechanism for detection of  $\text{Ni(II)}$ ", *Bioorganic & Medicinal Chemistry, Letters* 8, pp. 1963-1968, (1998).
- Pease, A.C., et al., "Light-generated oligonucleotide arrays for rapid DNA sequence analysis", *Proc. Natl. Acad. Sci. USA*, vol. 91, pp. 5022-5026, (1994).
- Piccirilli, J.A., et al., "Aminoacyl esterase activity of the tetrahymena ribozyme", *Science, New Series*, vol. 256, issue 5062, pp. 1420-1424, (1992).
- Pley, H.W., et al., "Three-dimensional structure of a hammerhead ribozyme", *Nature*, vol. 372, pp. 68-74, (1994).
- Potyrailo, R.A., et al., "Adapting selected nucleic acid ligands (aptamers) to biosensors", *Analytical Chemistry*, vol. 70, No. 16, pp. 3419-3425, (1998).
- Prudent, J.R., et al., "Expanding the scope of RNA catalysis", *Science, New Series*, vol. 264, issue 5167, pp. 1924-1927, (1994).
- Qiao, H., et al., "Transferability of blood lead determinations by furnace atomic absorption spectrophotometry and continuum background correction", *Clinical Chemistry*, vol. 41, No. 10, pp. 1451-1454, (1995).
- Rabinowitz, M., et al., "Home refinishing, lead paint, and infant blood lead levels", *American Journal of Public Health*, vol. 75, No. 4, pp. 403-404, (1985).
- Rajendran, M., et al., "Selecting nucleic acids for biosensor applications", *Combinatorial Chemistry and High Throughput Screening*, vol. 5, No. 4, pp. 263-270, (2002).
- Rakow, N.A., et al., "A colorimetric sensor array for odour visualization", *Nature*, vol. 406, pp. 710-713, (2000).
- Rink, S.M., et al., "Creation of RNA molecules that recognize the oxidative lesion 7,8-dihydro-8-hydroxy-2'-deoxyguanosine (8-oxodG) in DNA", *Proc. Natl. Acad. Sci. USA*, vol. 95, pp. 11619-11624, (1998).
- Robertson, M.P., et al., "Design and optimization of effector-activated ribozyme ligases", *Nucleic Acids Research*, vol. 28, No. 8, pp. 1751-1759, (2000).
- Robertson, M.P., et al., "In vitro selection of an allosteric ribozyme that transduces analytes to amplicons", *Nature Biotechnology*, vol. 17, pp. 62-66, (1999).
- Roth, A., et al., "An amino acid as a cofactor for a catalytic polynucleotide", *Proc. Natl. Acad. Sci. USA*, vol. 95, pp. 6027-6031, (1998).
- Roychowdhury-Saha, M., et al., "Flavin Recognition by an RNA Aptamer Targeted toward FAD", *Biochemistry*, vol. 41, No. 8, pp. 2492-2499, (2002).
- Ruckman, J., et al., "2'-Fluoropyrimidine RNA-based aptamers to the 165-amino acid form of vascular endothelial growth factor (VEGF<sub>165</sub>) Inhibition of receptor binding and VEGF-induced vascular permeability through interactions requiring the exon 7-encoded domain", *The Journal of Biological Chemistry*, vol. 273, No. 32, pp. 20556-20567, (1998).
- Rurack, K., et al., "A selective and sensitive fluoroionophore for  $\text{Hg}^{II}$ ,  $\text{Ag}^I$ , and  $\text{Cu}^{II}$  with virtually decoupled fluorophore and receptor units", *J. Am. Chem. Soc.*, vol. 122, No. 5, pp. 968-969, (2000).
- Rusconi, C.P., et al., "RNA aptamers as reversible antagonists of coagulation factor IXa", *Nature*, vol. 419, pp. 90-94, (2002).
- Sabanayagam, C.R., et al., "Oligonucleotide immobilization on micropatterned streptavidin surfaces", *Nucleic Acids Research*, vol. 28, No. 8, e33, pp. i-iv, (2000).
- Santoro, S.W., et al., "Mechanism and utility of an RNA-cleaving DNA enzyme", *Biochemistry*, vol. 37, No. 38, pp. 13330-13342, (1998).
- Santoro, S.W., et al., "A general purpose RNA-cleaving DNA enzyme", *Proc. Natl. Acad. Sci. USA*, vol. 94, pp. 4262-4266, (1997).
- Santoro, S.W., et al., "RNA Cleavage by a DNA Enzyme with Extended Chemical Functionality", *J. Am. Chem. Soc.*, vol. 122, No. 11, pp. 2433-2439, (2000).
- Sassanfar, M., et al., "An RNA motif that binds ATP", *Nature*, vol. 364, pp. 550-553, (1993).
- Schwartz, J., et al., "The risk of lead toxicity in homes with lead paint hazard", *Environmental Research*, vol. 54, No. 1, pp. 1-7, (1991).

- Scott, W.G., et al., "The crystal structure of an all-RNA hammerhead ribozyme: A proposed mechanism for RNA catalytic cleavage", *Cell*, vol. 81, pp. 991-1002, (1995).
- Scott, W.G., "RNA catalysis", *Current Opinion in Structural Biology*, vol. 8, pp. 720-726, (1998).
- Search results of key word search of medline, Mar. 26, 2000.
- Search results of key word search on Chemical Abstracts, Mar. 24, 2000.
- Search results of key word search from various databases, Mar. 24, 2000.
- Seeman, N.C., et al., "Synthetic DNA knots and catenanes", *New Journal of Chemistry*, vol. 17, pp. 739-755, (1993).
- Seeman, N.C., et al., "Emulating biology: Building nanostructures from the bottom up", *Proc. Natl. Acad. Sci.*, vol. 99, suppl. 2, pp. 6451-6455, (2002).
- Seeman, N.C., "DNA in a material world", *Nature*, vol. 421, pp. 427-431, (2003).
- Seetharaman, S., et al., "Immobilized RNA switches for the analysis of complex chemical and biological mixtures", *Nature Biotechnology*, vol. 19, pp. 336-341, (2001).
- Sen, D., et al., "DNA enzymes", *Current Opinion in Chemical Biology*, vol. 2, pp. 680-687, (1998).
- Shaiu, W-L., et al., "Atomic force microscopy of oriented linear DNA molecules labeled with 5nm gold spheres", *Nucleic Acids Research*, vol. 21, No. 1, pp. 99-103, (1993).
- Shaw, S.Y., et al., "Knotting of a DNA chain during ring closure", *Science, New Series*, vol. 260, issue 5107, pp. 533-536, (1993).
- Shekhtman, E.M., et al., "Stereostructure of replicative DNA catenanes from eukaryotic cells", *New Journal of Chemistry*, vol. 17, pp. 757-763, (1993).
- Sigurdsson, S.T., et al., "Small ribozymes", *RNA Structure and Function*, Cold Spring Harbor Laboratory Press (Monograph 35), pp. 339-375, (1998).
- Singh, K.K., et al., "Fluorescence Polarization for Monitoring Ribozyme Reactions in Real-Time", *Biotechniques*, vol. 29, No. 2, pp. 344-351, (2000).
- Smith, F.W., et al., "Quadruplex structure of oxytricha telomeric DNA oligonucleotides", *Nature*, vol. 356, pp. 164-168, (1992).
- Smith, J.O., et al., "Molecular recognition of PNA-containing hybrids: Spontaneous assembly of helical cyanine dye aggregates on PNA templates", *J. Am. Chem. Soc.*, vol. 121, No. 12, pp. 2686-2695, (1999).
- Soriaga, M.P., et al., "Determination of the orientation of aromatic molecules adsorbed on platinum electrodes: The effect of solute concentration", *J. Am. Chem. Soc.*, vol. 104, No. 14, pp. 3937-3945, (1982).
- Soukup, G.A., et al., "Engineering precision RNA molecular switches", *Proc. Natl. Acad. Sci. USA*, vol. 96, pp. 3584-3589, (1999).
- Soukup, G.A., et al., "Allosteric nucleic acid catalysts", *Current Opinion in Structural Biology*, vol. 10, pp. 318-325, (2000).
- Srisawat, C., et al., "Sephadex-binding RNA ligands: rapid affinity purification of RNA from complex RNA mixtures", *Nucleic Acids Research*, vol. 29, No. 2 e4, pp. 1-5, (2001).
- Stage-Zimmermann, T.K., et al., "Hammerhead ribozyme kinetics", *RNA*, vol. 4, pp. 875-889, (1998).
- Stojanovic, M.N., et al., "Aptamer-based colorimetric probe for cocaine", *J. Am. Chem. Soc.*, vol. 124, No. 33, pp. 9678-9679, (2002).
- Stojanovic, M.N., et al., "Aptamer-based folding fluorescent sensor for cocaine", *Journal of the American Chemical Society*, vol. 123, No. 21, pp. 4928-4931, (2001).
- Stojanovic, M.N., et al., "Fluorescent sensors based on aptamer self-assembly", *Journal of the American Chemical Society*, vol. 122, No. 46, pp. 11547-11548, (2000).
- Storhoff, J.J., et al., "Programmed materials synthesis with DNA", *Chem. Rev.*, vol. 99, No. 7, pp. 1849-1862, (1999).
- Storhoff, J.J., et al., "Facile colorimetric detection of polynucleotides based on gold nanoparticle probes", *Proceedings of the 1998 ERDEC Scientific Conference on Chemical and Biological Defense Research*, Nov. 17-20, 1998, Aberdeen Proving Ground, pp. 221-226, (1999).
- Storhoff, J.J., et al., "What Controls the Optical Properties of DNA-Linked Gold Nanoparticle Assemblies?", *J. Am. Chem. Soc.*, vol. 122, No. 19, pp. 4640-4650, (2000).
- Storhoff, J.J., et al., "One-pot colorimetric differentiation of polynucleotides with single base imperfections using gold nanoparticle probes", *Journal of the American Chemical Society*, vol. 120, No. 9, pp. 1959-1964, (1998).
- Streicher, B., et al., "Lead cleavage site in the core structure of group I intron-RNA", *Nucleic Acids Research*, vol. 21, No. 2, pp. 311-317, (1993).
- Sugimoto, N., et al., "Site-specific cleavage reaction catalyzed by leadzyme is enhanced by combined effect of lead and rare earth ions", *FEBS Letters*, vol. 393, pp. 97-100, (1996).
- Sun, L.Q., et al., "Catalytic nucleic acids: From lab to applications", *Pharmacological Reviews*, vol. 52, pp. 325-347, (2000).
- Tahan, J.E., et al., "Electrothermal atomic absorption spectrometric determination of Al, Cu, Ge, Pb, V and Zn in clinical samples and in certified environmental reference materials", *Analytica Chimica Acta*, vol. 295, pp. 187-197, (1994).
- Takagi, Y., et al., "Survey and Summary: Recent advances in the elucidation of the mechanisms of action of ribozymes", *Nucleic Acids Research*, vol. 29, No. 9, pp. 1815-1834, (2001).
- Tang, J., et al., "Rational design of allosteric ribozymes", *Chemistry & Biology*, vol. 4, No. 6, pp. 453-459, (1997).
- Tang, J., et al., "Structural diversity of self-cleaving ribozymes", *Proc. Natl. Acad. Sci. USA*, vol. 97, No. 11, pp. 5784-5789, (2000).
- Tanner, N.K., "Biochemistry of hepatitis delta virus catalytic RNAs", *Ribozymes in the Gene Therapy of Cancer*, Chapter 3, pp. 23-38, (1998).
- Tao, J., et al., "Arginine-Binding RNAs Resembling TAR Identified by in Vitro Selection", *Biochemistry*, vol. 35, No. 7, pp. 2229-2238, (1996).
- Tarasow, T.M., et al., "RNA-catalysed carbon-carbon bond formation", *Nature*, vol. 389, pp. 54-57, (1997).
- Telting-Diaz, M., et al., "Mass-produced ionophore-based fluorescent microspheres for trace level determination of lead ions", *Analytical Chemistry*, vol. 74, No. 20, pp. 5251-5256, (2002).
- Thompson, R.B., et al., "Determination of Picomolar Concentrations of Metal Ions Using Fluorescence Anisotropy: Biosensing with a "Reagentless" Enzyme Transducer", *Analytical Chemistry*, vol. 70, No. 22, pp. 4717-4723, (1998).
- Timmons, C.O., et al., "Investigation of Fatty Acid Monolayers on Metals by Contact Potential Measurements", *Journal of Physical Chemistry*, vol. 69, No. 3, pp. 984-990, (1965).
- Tompkins, H.G., et al., "The study of the gas-solid interaction of acetic acid with a cuprous oxide surface using reflection-absorption spectroscopy", *Journal of Colloid and Interface Science*, vol. 49, No. 3, pp. 410-421, (1974).
- Travascio, P., et al., "A ribozyme and a catalytic DNA with peroxidase activity: active sites versus cofactor-binding sites", *Chemistry & Biology*, vol. 6, No. 11, pp. 779-787, (1999).
- Tsang, J., et al., "In vitro evolution of randomized ribozymes", *Methods in Enzymology*, vol. 267, pp. 410-426, (1996).
- Tsien, R.Y., "Fluorescent and photochemical probes of dynamic biochemical signals inside living cells", *Fluorescent Chemosensors for Ion and Molecule Recognition*, (ed. Czarnik, A. W.), chapter 9, pp. 130-146, American Chemical Society, (1993).
- Tuerk, C., et al., "RNA pseudoknots that inhibit human immunodeficiency virus type 1 reverse transcriptase", *Proc. Natl. Acad. Sci. USA*, vol. 89, pp. 6988-6992, (1992).
- Tuerk, C., et al., "Systematic evolution of ligands by exponential enrichment: RNA ligands to bacteriophage T4 DNA polymerase", *Science, New Series*, vol. 249, issue 4968, pp. 505-510, (1990).
- Tyagi, S., et al., "Molecular Beacons: Probes that fluoresce upon hybridization", *Nature Biotechnology*, vol. 14, pp. 303-308, (1996).
- Tyagi, S., et al., "Multicolor molecular beacons for allele discrimination", *Nature Biotechnology*, vol. 16, pp. 49-53, (1998).
- Tyagi, S., et al., "Wavelength-shifting molecular beacons", *Nature Biotechnology*, vol. 18, pp. 1191-1196, (2000).
- Ueyama, H., "A novel potassium sensing in aqueous media with a synthetic oligonucleotide derivative. Fluorescence resonance energy

- transfer associated with guanine quartet-potassium ion complex formation", *J. Am. Chem. Soc.*, vol. 124, No. 48, pp. 14286-14287, (2002).
- Uphoff, K.W., et al., "In vitro selection of aptamers: the dearth of pure reason", *Current Opinion in Structural Biology*, vol. 6, pp. 281-288, (1996).
- Vaish, N.K., et al., "In vitro selection of a purine nucleotide-specific hammerhead-like ribozyme", *Proc. Natl. Acad. Sci. USA*, vol. 95, pp. 2158-2162, (1998).
- Valadkhan, S., et al., "Splicing-related catalysis by protein-free snRNAs", *Nature*, vol. 413, pp. 701-707, (2001).
- Vianini, E., et al., "In vitro selection of DNA aptamers that bind L-tyrosinamide", *Bioorganic & Medicinal Chemistry*, vol. 9, pp. 2543-2548, (2001).
- Walkup, G.K., et al., "Design and Evaluation of a Peptidyl Fluorescent Chemosensor for Divalent Zinc", *J. Am. Chem. Soc.*, vol. 118, No. 12, pp. 3053-3054, (1996).
- Wallace, S.T., et al., "In vitro selection and characterization of streptomycin-binding RNAs: recognition discrimination between antibiotics", *RNA*, vol. 4, pp. 112-123, (1998).
- Wallis, M.G., et al., "A novel RNA motif for neomycin recognition", *Chemistry & Biology*, vol. 2, No. 8, pp. 543-552, (1995).
- Wallis, M.G., et al., "In vitro selection of a viomycin-binding RNA pseudoknot", *Chemistry & Biology*, vol. 4, No. 5, pp. 357-366, (1997).
- Walter, F., et al., "Folding of the four-way RNA junction of the hairpin ribozyme", *Biochemistry*, vol. 37, No. 50, pp. 17629-17636, (1998).
- Walter, N.G., et al., "The hairpin ribozyme: structure, assembly and catalysis", *Current Opinion in Chemical Biology*, vol. 2, pp. 24-30, (1998).
- Wang, D.Y., et al., "A general strategy for effector-mediated control of RNA-cleaving ribozymes and DNA enzymes", *J. Mol. Biol.*, vol. 318, pp. 33-43, (2002).
- Wang, F., et al., "Sphingosine-1-phosphate Inhibits Motility of Human Breast Cancer Cells Independently of Cell Surface Receptors", *Cancer Research*, vol. 59, pp. 6185-6191, (1999).
- Wang, J., "Survey and Summary: From DNA biosensors to gene chips", *Nucleic Acids Research*, vol. 28, No. 16, pp. 3011-3016, (2000).
- Wang, K.Y., et al., "A DNA aptamer which binds to and inhibits thrombin exhibits a new structural motif for DNA", *Biochemistry*, vol. 32, No. 8, pp. 1899-1904, (1993).
- Wang, Y., et al., "Assembly and characterization of five-arm and six-arm DNA branched junctions", *Biochemistry*, vol. 30, pp. 5667-5674, (1991).
- Wang, Y., et al., "RNA molecules that specifically and stoichiometrically bind aminoglycoside antibiotics with high affinities", *Biochemistry*, vol. 35, No. 38, pp. 12338-12346, (1996).
- Wecker, M., et al., "In vitro selection of a novel catalytic RNA: characterization of a sulfur alkylation reaction and interaction with a small peptide", *RNA*, vol. 2, pp. 982-994, (1996).
- Wedekind, J.E., et al., "Crystal structure of a lead-dependent ribozyme revealing metal binding sites relevant to catalysis", *Nature Structural Biology*, vol. 6, No. 3, pp. 261-268, (1999).
- Wedekind, J.E., et al., "Crystal structure of the leadzyme at 1.8 Å Resolution: Metal ion binding and the implications for catalytic mechanism and allo site ion regulation", *Biochemistry*, vol. 42, No. 32, pp. 9554-9563, (2003).
- Wells, R.D., "Unusual DNA structures", *Journal of Biological Chemistry*, vol. 263, No. 3, pp. 1095-1098, (1988).
- Werstuck, G., et al., "Controlling gene expression in living cells through small molecule-RNA interactions", *Science*, vol. 282, pp. 296-298, (1998).
- Whaley, S.R., et al., "Selection of peptides with semiconductor binding specificity for directed nanocrystal assembly", *Nature*, vol. 405, pp. 665-668, (2000).
- Whitesides, G.M., et al., "Self-assembled monolayers and lithography", *Proceedings of the Robert A. Welch Foundation 39th Conference on Chemical Research on Nanophase Chemistry*, pp. 109-121, Houston, TX, Oct. 23-24, 1995.
- Wiegand, T.W., et al., "High-affinity oligonucleotide ligands to human IgE inhibit binding to Fc epsilon receptor I", *The Journal of Immunology*, vol. 157, pp. 221-230, (1996).
- Wiegand, T.W., et al., "Selection of RNA amide synthases", *Chemistry & Biology*, vol. 4, No. 9, pp. 675-683, (1997).
- Williams, K.P., et al., "Bioactive and nuclease-resistant L-DNA ligand of vasopressin", *Proc. Natl. Acad. Sci. USA*, vol. 94, pp. 11285-11290, (1997).
- Williams, K.P., et al., "Selection of novel Mg<sup>2+</sup>-dependent self-cleaving ribozymes", *The EMBO Journal*, vol. 14, No. 18, pp. 4551-4557, (1995).
- Wilson, C., et al., "Functional requirements for specific ligand recognition by a biotin-binding RNA Pseudoknot", *Biochemistry*, vol. 37, No. 41, pp. 14410-14419, (1998).
- Wilson, C., et al., "In vitro evolution of a self-alkylating ribozyme", *Nature*, vol. 374, pp. 777-782, (1995).
- Wilson, C., et al., "Isolation of a fluorophore-specific DNA aptamer with weak redox activity", *Chemistry & Biology*, vol. 5, No. 11, pp. 609-617, (1998).
- Wilson, D.S., et al., "In vitro selection of functional nucleic acids", *Annu. Rev. Biochem.* vol. 68, pp. 611-647, (1999).
- Winkler, J.D., et al., "Photodynamic Fluorescent Metal Ion Sensors with Parts per Billion Sensitivity", *J. Am. Chem. Soc.*, vol. 120, No. 13, pp. 3237-3242, (1998).
- Wittmann, C., et al., "Microbial and Enzyme sensors for environmental monitoring", *Handbook of Biosensors and Electronic Noses: Medicine, Food, and the Environment*, pp. 299-332, (1997).
- Xia, P., et al., "Activation of Sphingosine Kinase by Tumor Necrosis Factor-α Inhibits Apoptosis in Human Endothelial Cells", *Journal of Biological Chemistry*, vol. 274, No. 48, pp. 34499-34505, (1999).
- Yan, H., et al., "DNA-Templated self-assembly of protein arrays and highly conductive nanowires", *Science*, vol. 301, pp. 1882-1884, (2003).
- Yang, Q., et al., "DNA ligands that bind tightly and selectively to cellobiose", *Proc. Natl. Acad. Sci. USA*, vol. 95, pp. 5462-5467, (1998).
- English Translation of Yang, Y., et al., "Measurement of lead and magnesium in distilled spirits using inductively coupled plasma optical emission spectrometry viewed from the end", *Analytical Chemistry (Fenxi Huaxue)*, Chinese Journal of Analytical Chemistry, vol. 25, No. 9, pp. 1114-1117, (1997).
- Yurke, B., et al., "A DNA-fuelled molecular machine made of DNA", *Nature*, vol. 406, pp. 605-608, (2000).
- Zhang, B., et al., "Peptide bond formation by in vitro selected ribozymes", *Nature*, vol. 390, pp. 96-100, (1997).
- Zhang, P., et al., "Design of a molecular beacon DNA probe with two fluorophores", *Angewandte Chemie International Edition*, vol. 40, No. 2, pp. 402-405, (2001).
- Zillmann, M., et al., "In vitro optimization of truncated stem-loop II variants of the hammerhead ribozyme for cleavage in low concentrations of magnesium under non-turnover conditions", *RNA*, vol. 3, pp. 734-747, (1997).
- Zimmerman, J.M., et al., "In vivo selection of spectinomycin-binding RNAs", *Nucleic Acids Research*, vol. 30, No. 24, pp. 5425-5435, (2002).
- Zimmermann, G.R., et al., "Molecular interactions and metal binding in the theophylline-binding core of an RNA aptamer", *RNA*, vol. 6, pp. 659-667, (2000).
- International Search Report dated Nov. 21, 2005 for PCT application No. PCT/US2005/001060.
- Supplemental International Search Report dated Jan. 10, 2006 for PCT application No. PCT/US2005/001060.
- Liu, J., et al., "Size control, metal substitution, and catalytic application of cryptomelane nanomaterials prepared using cross-linking reagents", *Chem. Mater.*, vol. 16, No. 2, pp. 276-285, (2004).
- Cake, K.M., et al., "Partition of circulating lead between serum and red cells is different for internal and external sources of lead", *American Journal of Industrial Medicine*, vol. 29, pp. 440-445, (1996).
- International Search Report dated Aug. 31, 2004 for PCT application No. PCT/US2004/002946.



- Hazarika, P., et al., "Reversible switching of DNA-Gold nanoparticle aggregation", *Angewandte Chemie International Edition*, vol. 43, No. 47, pp. 6469-6471, (2004).
- International Search Report dated May 29, 2006 for PCT application No. PCT/US2005/037896.
- Liu, J., et al., "Improving fluorescent DNzyme biosensors by combining Inter- and Intramolecular quenchers", *Analytical Chemistry*, vol. 75, No. 23, pp. 6666-6672, (2003).
- Liu, J., et al., "Stimuli-responsive disassembly of nanoparticle aggregates for light-up colorimetric sensing", *Journal of the American Chemical Society*, vol. 127, No. 36, pp. 12677-12683, (2005).
- European Search Report dated Jul. 10, 2006 for PCT application No. PCT/US2003/12576.
- Tanner, F.C., et al., "Transfection of human endothelial cells", *Cardiovascular research*, vol. 35, pp. 522-528, (1997).
- International Search Report dated Nov. 17, 2006 for PCT application No. PCT/US2006/001627.
- Liu, J., et al., "DNzyme-directed assembly of gold nanoparticles as colorimetric sensor for a broad range of analytes", pp. 1-3, located at <http://ieeenano2003.arc.nasa.gov/THM@.pdf>, (2003).
- Wang, D.Y., et al., "A general approach for the use of oligonucleotide effectors to regulate the catalysis of RNA-cleaving ribozymes and DNzymes", *Nucleic Acids Research*, vol. 30, No. 8, pp. 1735-1742, (2002).
- Levy, M., et al., "Exponential growth by cross-catalytic cleavage of deoxyribozymogens", *PNAS*, vol. 100, No. 11, pp. 6416-6421, (2003).
- Beyer, S., et al., "A modular DNA signal translator for the controlled release of a protein by an aptamer", *Nucleic Acids Research*, vol. 34, No. 5, pp. 1581-1587, (2006).
- Frauenhofer, C., et al., "Detection of small organic analytes by fluorescing molecular switches", *Bioorganic & Medicinal Chemistry*, vol. 9, pp. 2521-2524, (2001).
- Glynou, K., et al., "Oligonucleotide-functionalized gold nanoparticles as probes in a dry-reagent strip biosensor for DNA analysis by hybridization", *Anal. Chem.*, vol. 75, No. 16, pp. 4155-4160, (2003).
- Liu, J., et al., "Optimization of a Pb<sup>2+</sup>-directed gold nanoparticle/DNzyme assembly and its application as a colorimetric biosensor for Pb<sup>2+</sup>", *Chem. Mater.*, vol. 16, No. 17, pp. 3231-3238, (2004).
- Jones, K.D., et al., "Anniversary Essays. 3. Assay development, Changes in the development of rapid assays since 1995", *Medical DeviceLink*, found at: <http://www.deviceLink.com/ivdt/archive/05/04/005.html>, 3 pages, (2005).
- Product Description: Pall Corporation, "Immunochromatographic, lateral flow or strip tests development ideas", found at: [http://www.pall.com/34445\\_4154.asp](http://www.pall.com/34445_4154.asp), 7 pages, (1998).
- Liu, J., et al., "Fast colorimetric sensing of adenosine and cocaine based on a general sensor design involving aptamers and nanoparticles", *Angew. Chem. Int. Ed.*, vol. 45, pp. 90-94, (2006).
- Liu, J., et al., "A simple and sensitive 'dipstick' test in serum based on lateral flow separation of aptamer-linked nanostructures", *Angewandte Chemie International Edition*, vol. 45, pp. 7955-7959, (2006).
- Jiang, P. et al., "Fluorescent detection of zinc in biological systems: recent development on the design of chemosensors and biosensors", *Coordination Chemistry Reviews*, vol. 248, pp. 205-229, (2004).
- Lim, M.H. et al., "Metal-based turn-on fluorescent probes for sensing nitric oxide", *Accounts of Chemical Research*, vol. 40, No. 1, pp. 41-51, (2007).
- Yoon, S. et al., "Screening mercury levels in fish with a selective fluorescent chemosensor", *Journal of the American Chemical Society*, vol. 127, pp. 16030-16031, (2005).
- Yang, L. et al., "Imaging of the intracellular topography of copper with a fluorescent sensor and by synchrotron x-ray fluorescence microscopy", *Proceedings of the National Academy of Science*, vol. 102, No. 32, pp. 11179-11184, (2005).
- He, Q. et al., "A selective fluorescent sensor for detecting lead in living cells", *Journal of the American Chemical Society*, vol. 128, pp. 9316-9317, (2006).
- Zeng, L. et al., "A selective turn-on fluorescent sensor for imaging copper in living cells", *Journal of the American Chemical Society*, vol. 128, pp. 10-11, (2006).
- Wegner, S.V. et al., "Design of an emission ratiometric biosensor from MerR family proteins: A sensitive and selective sensor for Hg<sup>2+</sup>", *Journal of the American Chemical Society*, vol. 129, pp. 3474-3475, (2007).
- Nolan, E.M. et al., "Turn-on and ratiometric mercury sensing in water with a red-emitting probe", *Journal of the American Chemical Society*, vol. 129, pp. 5910-5918, (2007).
- Sasaki, D.Y. et al., "Metal-induced dispersion of lipid aggregates: A simple, selective, and sensitive fluorescent metal ion sensor", *Angew. Chem. Int. Ed. England*, vol. 34, No. 8, pp. 905-907, (1995).
- Torrado, A. et al., "Exploiting polypeptide motifs for the design of selective Cu(II) ion chemosensors" *Journal of the American Chemical Society*, vol. 120, pp. 609-610, (1998).
- Grandini, P. et al., "Exploiting the self-assembly strategy for the design of selective Cu<sup>II</sup> ion chemosensors", *Angew. Chem. Int. Ed.*, vol. 38, No. 20, pp. 3061-3064, (1999).
- Klein, G. et al., "A fluorescent metal sensor based on macrocyclic chelation", *Chem. Comm.*, pp. 561-562, (2001).
- Zheng, Y. et al., "A new fluorescent chemosensor for copper ions based on tripeptide glycyl-histidyl-lysine (GHK)", *Organic Letters*, vol. 3, No. 21, pp. 3277-3280, (2001).
- Boiocchi, M. et al., "A two-channel molecular dosimeter for the optical detection of copper(II)" *Chem. Comm.*, pp. 1812-1813, (2003).
- Zheng, Y. et al., "Peptidyl fluorescent chemosensors for the detection of divalent copper", *Analytical Chemistry*, vol. 75, No. 7, pp. 1706-1712, (2003).
- Zheng, Y. et al., "Development of fluorescent film sensors for the detection of divalent copper", *Journal of the American Chemical Society*, vol. 125, pp. 2680-2686, (2003).
- Roy, B.C. et al., "Synthesis of new, pyrene-containing metal-chelating lipids and sensing of cupric ions", *Organic Letters*, vol. 5, No. 1, pp. 11-14, (2003).
- Kaur, S. et al., "Photoactive chemosensors 4: a Cu<sup>2+</sup> protein cavity mimicking fluorescent chemosensor for selective Cu<sup>2+</sup> recognition", *Tetrahedron Letters*, vol. 45, pp. 5081-5085, (2004).
- Mei, Y. et al., "A selective and sensitive chemosensor for Cu<sup>2+</sup> based on 8-hydroxyquinoline", *Tetrahedron Letters*, vol. 47, pp. 2447-2449, (2006).
- Zhang, X-B. et al., "A highly selective fluorescent sensor for Cu<sup>2+</sup> based on 2-(2'-hydroxyphenyl) benzoxazole in a poly(vinyl chloride) matrix", *Analytica Chimica Acta*, vol. 567, pp. 189-195, (2006).
- Comba, P. et al., "Synthesis of new phenanthroline-based heteroditopic ligands—highly efficient and selective fluorescence sensors for copper (II) ions", *European Journal of Inorganic Chemistry*, pp. 4442-4448, (2006).
- Kim, S. H. et al., "Hg<sup>2+</sup>-selective off-on and Cu<sup>2+</sup>-selective on-off type fluoroionophore based upon cyclam", *Organic Letters*, vol. 8, No. 3, pp. 371-374, (2006).
- White, B. R. et al., "Fluorescent peptide sensor for the selective detection of Cu<sup>2+</sup>", *Talanta*, vol. 71, pp. 2015-2020, (2007).
- Oter, O. et al., "Spectral characterization of a newly synthesized fluorescent semicarbazone derivative and its usage as a selective fiber optic sensor for copper(II)", *Analytica Chimica Acta*, vol. 584, pp. 308-314, (2007).
- Dujols, V. et al., "A long-wavelength fluorescent chemodosimeter selective for Cu(II) ion in water", *Journal of the American Chemical Society*, vol. 119, pp. 7386-7387, (1997).
- Yang, J-S. et al., "Cu<sup>2+</sup>-induced blue shift of the pyrene excimer emission: a new signal transduction mode of pyrene probes", *Organic Letters*, vol. 3, No. 6, pp. 889-892, (2001).
- Kaur, S. et al., "Photoactive chemosensors 3: a unique case of fluorescence enhancement with Cu(II)", *Chem. Comm.*, pp. 2840-2841, (2002).
- Wu, Q. et al., "Catalytic signal amplification using a heck reaction. An example in the fluorescence sensing of Cu(II)", *Journal of the American Chemical Society*, vol. 126, pp. 14682-14683, (2004).
- Royzen, M. et al., "Ratiometric displacement approach to Cu(II) sensing by fluorescence", *Journal of the American Chemical Society*, vol. 127, pp. 1612-1613, (2005).
- Xu, Z. et al., "Ratiometric and selective fluorescent sensor for Cu<sup>II</sup> based on internal charge transfer (ICT)", *Organic Letters*, vol. 7, No. 5, pp. 889-892, (2005).

- Wen, Z.-C. et al., "A highly selective charge transfer fluoroionophore for  $\text{Cu}^{2+}$ ", *Chem. Commun.*, pp. 106-108, (2006).
- Yang, H. et al., "Highly selective ratiometric fluorescent sensor for  $\text{Cu(II)}$  with two urea groups", *Tetrahedron Letters*, vol. 47, pp. 2911-2914, (2006).
- Martinez, R. et al., "2-aza-1,3-butadiene derivatives featuring an anthracene or pyrene unit: highly selective colorimetric and fluorescent signaling of  $\text{Cu}^{2+}$  cation", *Organic Letters*, vol. 8, No. 15, pp. 3235-3238, (2006).
- Navani, N.K. et al., "Nucleic acid aptamers and enzymes as sensors", *Current Opinion in Chemical Biology*, vol. 10, pp. 272-281, (2006).
- Liu, J. et al., "A catalytic beacon sensor for uranium with parts-per-trillion sensitivity and millionfold selectivity", *Proceedings of the National Academy of Science*, vol. 104, No. 7, pp. 2056-2061, (2007).
- Georgopoulos, P.G. et al., "Environmental copper: its dynamics and human exposure issues", *Journal of Toxicology and Environmental Health, Part B*, vol. 4, pp. 341-394, (2001).
- Hertzberg, R.P. et al., "Cleavage of DNA with methidiumpropyl-EDTA-iron(II): reaction conditions and product analyses", *Biochemistry*, vol. 23, pp. 3934-3945, (1984).
- Yazzie, M. et al., "Uranyl acetate causes DNA single strand breaks in vitro in the presence of ascorbate (Vitamin C)", *Chem. Res. Toxicol.*, vol. 16, pp. 524-530, (2003).
- Bolletta, F. et al., "A  $[\text{Ru}^{II}(\text{bipy})_3]$ -[1,9-diamino-3,7-diazanonane-4,6-dione] two-component system as an efficient on-off luminescent chemosensor for  $\text{Ni}^{2+}$  and  $\text{Cu}^{2+}$  in water, based on an ET (energy transfer) mechanism", *Journal of the Chemical Society, Dalton Transactions*, pp. 1381-1385, (1999).
- Carmi, N. et al., "Characterization of a DNA-cleaving deoxyribozyme", *Bioorganic & Medicinal Chemistry*, vol. 9, issue 10, pp. 2589-2600, (2001).
- Liu, J. et al., "A DNzyme catalytic beacon sensor for paramagnetic  $\text{Cu}^{2+}$  ions in aqueous solution with high sensitivity and selectivity", *Journal of the American Chemical Society*, vol. 129, No. 32, pp. 9838-9839, (2007), ASAP Web Release Date: Jul. 24, 2007.
- Tanaka, K. et al., "Programmable self-assembly of metal ions inside artificial DNA duplexes", *Nature Nanotechnology*, vol. 1, pp. 190-194, (2006).
- Achenbach, J.C. et al., "DNzymes: From creation in vitro to application in vivo", *Current Pharmaceutical Biotechnology*, vol. 5, pp. 321-336, (2004).
- Balaji, T. et al., "Optical sensor for the visual detection of mercury using mesoporous silica anchoring porphyrin moiety", *The Analyst*, vol. 130, pp. 1162-1167, (2005).
- Caballero, A. et al., "Highly selective chromogenic and redox or fluorescent sensors of  $\text{Hg}^{2+}$  in aqueous environment based on 1,4-disubstituted azines", *Journal of the American Chemical Society*, vol. 127, pp. 15666-15667, (2005).
- Chan, W.H. et al., "Development of a mercury ion-selective optical sensor based on fluorescence quenching of 5,10,15,20-tetraphenylporphyrin", *Analytica Chimica Acta*, vol. 444, pp. 261-269, (2001).
- Chen, P. et al., "A general strategy to convert the merR family proteins into highly sensitive and selective fluorescent biosensors for metal ions", *Journal of the American Chemical Society*, vol. 126, pp. 728-729, (2004).
- Chiuman, W. et al., "Efficient signaling platforms built from a small catalytic DNA and doubly labeled fluorogenic substrates", *Nucleic Acids Research*, vol. 35, No. 2, pp. 401-405, (2007).
- Cruz, R.P.G. et al., "Dinucleotide junction cleavage versatility of 8-17 deoxyribozyme", *Chemistry & Biology*, vol. 11, pp. 57-67, (2004).
- Frasco, M.F. et al., "Mechanisms of cholinesterase inhibition by inorganic mercury", *the FEBS Journal*, vol. 274, pp. 1849-1861, (2007).
- Guo, X. et al., "A highly selective and sensitive fluorescent chemosensor for  $\text{Hg}^{2+}$  in neutral buffer aqueous solution", *The Journal of the American Chemical Society*, vol. 126, pp. 2272-2273, (2004).
- Harris, H.H. et al., "The chemical form of mercury in fish", *Science*, vol. 301, pp. 1203, (2003).
- Ha-Thi, M.-H. et al., "Highly selective and sensitive phosphane sulfide derivative for the detection of  $\text{Hg}^{2+}$  in an organo-aqueous medium", *Organic Letters*, vol. 9, No. 6, pp. 1133-1136, (2007).
- Joyce, G.F. et al., "Directed evolution of nucleic acid enzymes", *Annual Review Biochem.*, vol. 73, pp. 791-836, (2004).
- Ko, S.-K. et al., "In vivo monitoring of mercury ions using a rhodamine-based molecular probe", *Journal of the American Chemical Society*, vol. 128, pp. 14150-14155, (2006).
- Kuswandi, B. et al., "Capillary optode: determination of mercury(II) in aqueous solution", *Analytical Letters*, vol. 32, No. 4, pp. 649-664, (1999).
- Kuswandi, B. et al., "Selective pool optode for mercury ion sensing in aqueous solution", *Sensors and Actuators B*, vol. 74, pp. 131-137, (2001).
- Lee, J.-S. et al., "Colorimetric detection of mercuric ion ( $\text{Hg}^{2+}$ ) in aqueous media using DNA-functionalized gold nanoparticles", *Angewandte Chemie International Edition*, vol. 46, pp. 4093-4096, (2007).
- Liu, B. et al., "A selective fluorescent ratiometric chemodosimeter for mercury ion", *Chem. Communications*, pp. 3156-3158, (2005).
- Liu, J. et al., "Fluorescent DNzyme biosensors for metal ions based on catalytic molecular beacons", *Methods in Molecular Biology*, vol. 335, pp. 275-288, (2006).
- Matsushita, M. et al., "A blue fluorescent antibody-cofactor sensor for mercury", *Organic Letters*, vol. 7, No. 22, pp. 4943-4946, (2005).
- Miyake, Y. et al., "Mercury $^{II}$ -mediated formation of thymine- $\text{Hg}^{II}$ -thymine base pairs in DNA duplexes", *Journal of the American Chemical Society*, vol. 128, No. 7, pp. 2172-2173, (2006).
- Nolan, E.M. et al., "A 'turn-on' fluorescent sensor for the selective detection of mercuric ion in aqueous media", *Journal of the American Chemical Society*, vol. 125, pp. 14270-14271, (2003).
- Ono, A. et al., "Highly selective oligonucleotide-based sensor for mercury (II) in aqueous solutions", *Angew. Chem. Int. Ed.*, vol. 43, pp. 4300-4302, (2004).
- Ostatna, V. et al., "Self-assembled monolayers of thiol-end-labeled DNA at mercury electrodes", *Langmuir*, vol. 22, pp. 6481-6484, (2006).
- Prodi, L. et al., "An effective fluorescent chemosensor for mercury ions", *Journal of the American Chemical Society*, vol. 122, No. 28, pp. 6769-6770, (2000).
- Silverman, S.K., "Survey and Summary: In vitro selection, characterization, and application of deoxyribozymes that cleave RNA", *Nucleic Acids Research*, vol. 33, No. 19, pp. 6151-6163, (2005).
- Song, K.C. et al., "Fluorogenic  $\text{Hg}^{2+}$ -selective chemodosimeter derived from 8-hydroxyquinoline", *Organic Letters*, vol. 8, No. 16, pp. 3413-3416, (2006).
- Szurdoki, F. et al., "A combinatorial approach to discover new chelators for optical metal ion sensing", *Analytical Chemistry*, vol. 72, No. 21, pp. 5250-5257, (2000).
- Tanaka, Y. et al., " $^{15}\text{N}$ - $^{15}\text{N}$  J-coupling across  $\text{Hg}^{II}$ : Direct observation of  $\text{Hg}^{II}$ -mediated T-T base pairs in a DNA duplex" *Journal of the American Chemical Society*, vol. 129, No. 2, pp. 244-245, (2007).
- Jacoby, M. "Mercury Sensor—Analytical Chemistry: Colorimetric method is sensitive and selective", *Chemical & Engineering News*, pp. 15, May 7, 2007.
- Vannela, R. et al., "In vitro selection of  $\text{Hg(II)}$  and as (V)-dependent RNA-cleaving DNzymes", *Environmental Engineering Science*, vol. 24, No. 1, pp. 73-84, (2007).
- Vaughan, A.A. et al., "Optical fibre reflectance sensors for the detection of heavy metal ions based on immobilized Br-PADAP", *Sensors and Actuators B*, vol. 51, pp. 368-376, (1998).
- Virta, M. et al., "A luminescence-based mercury biosensor", *Analytical Chemistry*, vol. 67, No. 3, pp. 667-669, (1995).
- Wang, J. et al., "Detecting  $\text{Hg}^{2+}$  ions with an ICT fluorescent sensor molecule: Remarkable emission spectra shift and unique selectivity", *Journal of Organic Chemistry*, vol. 71, pp. 4308-4311, (2006).
- Wang, J. et al., "A series of polyamide receptor based PET fluorescent sensor molecules: Positively cooperative  $\text{Hg}^{2+}$  ion binding with high sensitivity", *Organic Letters*, vol. 8, No. 17, pp. 3721-3724, (2006).
- Widmann, A. et al., "Mercury detection in seawater using a mercaptoacetic acid modified gold microwire electrode", *Electroanalysis*, vol. 17, No. 10, pp. 825-831, (2005).

- Xiao, Y. et al., "Electrochemical detection of parts-per-billion lead via an electrode-bound DNzyme assembly", *Journal of the American Chemical Society*, vol. 129, pp. 262-263, (2007).
- Yang, W. et al., "Solid phase extraction and spectrophotometric determination of mercury in tobacco and tobacco additives with 5-(p-aminobenzylidene)-thiothiorhodanine", *Journal of the Brazilian Chemical Society*, vol. 17, No. 5, pp. 1039-1044, (2006).
- Yang, Y.-K. et al., "A rhodamine-based fluorescent and colorimetric chemodosimeter for the rapid detection of Hg<sup>2+</sup> ions in aqueous media", *Journal of the American Chemical Society*, vol. 127, pp. 16760-16761, (2005).
- Zhang, X.-B. et al., "An optical fiber chemical sensor for mercury ions based on a porphyrin dimmer", *Analytical Chemistry*, vol. 74, No. 4, pp. 821-825, (2002).
- Zhao, Y. et al., "A 'turn-on' fluorescent sensor for selective Hg(II) detection in aqueous media based on metal-induced dye formation", *Inorganic Chemistry*, vol. 45, No. 25, pp. 10013-10015, (2006).
- Zhao, Y. et al., "Tuning the sensitivity of a foldamer-based mercury sensor by its folding energy", *Journal of the American Chemical Society*, vol. 128, No. 31, pp. 9988-9989, (2006).
- Zhao, Y. et al., "Detection of Hg<sup>2+</sup> in aqueous solutions with a foldamer-based fluorescent sensor modulated by surfactant micelles", *Organic Letters*, vol. 8, No. 21, pp. 4715-4717, (2006).
- Zuker, M., "Mfold web server for nucleic acid folding and hybridization prediction", *Nucleic Acids Research*, vol. 31, No. 13, pp. 3406-3415, (2003).
- International Search Report dated May 10, 2007 for PCT application No. PCT/US2006/030617.
- Liu, J. et al., "Smart nanomaterials responsive to multiple chemical stimuli with controllable cooperativity", *Advanced Materials*, vol. 18, No. 13, pp. 1667-1671, (2006).
- Nutiu, R. et al., "Signaling aptamers for monitoring enzymatic activity and for inhibitor screening", *Chembiochem—A European Journal of Chemical Biology*, vol. 5, No. 8, pp. 1139-1144, (2004).
- Nutiu, R. et al., "Structure-switching signaling aptamers: Transducing molecular recognition into fluorescence signaling", *Chemistry—A European Journal*, vol. 10, No. 8, pp. 1868-1876, (2004).
- International Search Report dated Jul. 31, 2007 for PCT application No. PCT/US2007/064055.
- Ahern, H., "Biochemical, reagent kits offer scientists good return on investment", *The Scientist*, vol. 9, No. 15, pp. 20-22, (1995).
- Homann, M. et al., "Dissociation of long-chain duplex RNA can occur via strand displacement in vitro: biological implication", *Nucleic Acids Research*, vol. 24, No. 22, pp. 4395-4400, (1996).
- Alivisatos, A.P. et al., "Quantum dots as cellular probes", *Annual Review Biomed. Eng.*, vol. 7, pp. 55-76, (2005).
- Dyadyusha, L. et al., "Quenching of CdSe quantum dot emission, a new approach for biosensing", *Chemical Communication*, pp. 3201-3203, (2005).
- Ellington, A.D. et al., "In vitro selection of RNA molecules that bind specific ligands", *Nature*, vol. 346, pp. 818-822, (1990).
- Gerion, D. et al., "Room-temperature single-nucleotide polymorphism and multiallele DNA detection using fluorescent nanocrystals and microarrays", *Analytical Chemistry*, vol. 75, No. 18, pp. 4766-4772, (2003).
- Goldman, E.R. et al., "Multiplexed toxin analysis using four colors of quantum dot fluororeagents", *Analytical Chemistry*, vol. 76, No. 3, pp. 684-688, (2004).
- Gueroui, Z. et al., "Single-molecule measurements of gold-quenched quantum dots", *Physical Review Letters*, vol. 93, No. 16, pp. 166108/1-166108/4, (2004).
- Han, M. et al., "Quantum-dot-tagged microbeads for multiplexed optical coding of biomolecules", *Nature Biotechnology*, vol. 19, pp. 631-635, (2001).
- Hansen, J.A. et al., "Quantum-dot/Aptamer-based ultrasensitive multi-analyte electrochemical biosensor", *Journal of the American Chemical Society*, vol. 128, No. 7, pp. 2228-2229, (2006).
- Hartig, J.S. et al., "Protein-dependent ribozymes report molecular interactions in real time", *Nature Biotechnology*, vol. 20, pp. 717-722, (2002).
- Herman, T. et al., "Adaptive recognition by nucleic acid aptamers", *Science*, vol. 287, pp. 820-825, (2000).
- Kurreck, J., "Antisense technologies Improvement through novel chemical modifications", *Eur. J. Biochem*, vol. 270, pp. 1628-1644, (2003).
- Lee, J.F. et al., "Aptamer database", *Nucleic Acids Research*, vol. 32, Database Issue, pp. D95-D100, (2004).
- Levy, M. et al., "Quantum-dot aptamer beacons for the detection of proteins", *ChemBioChem*, vol. 6, pp. 2163-2166, (2005).
- Liu, J. et al., "Smart nanomaterials responsive to multiple chemical stimuli with controllable cooperativity", *Advanced Materials*, vol. 18, pp. 1667-1671, (2006).
- Liu, J. et al., "Preparation of aptamer-linked gold nanoparticle purple aggregates for colorimetric sensing of analytes", *Nature Protocols*, vol. 1, No. 1, pp. 246-252, (2006).
- Medintz, I.L. et al., "Quantum dot bioconjugates for imaging, labeling and sensing", *Nature Materials*, vol. 4, pp. 435-446, (2005).
- Miduturu, C. V. et al., "Modulation of DNA constraints that control macromolecular folding", *Angew. Chem. Int. Ed.*, vol. 45, pp. 1918-1921, (2006).
- Mitchell, G.P. et al., "Programmed assembly of DNA functionalized quantum dots", *Journal of the American Chemical Society*, vol. 121, No. 35, pp. 8122-8123, (1999).
- Nutiu, R. et al., "Structure-switching signaling aptamers: Transducing molecular recognition into fluorescence signaling", *Chem. Eur. J.*, vol. 10, pp. 1868-1876, (2004).
- Oh, E. et al., "Inhibition assay of biomolecules based on fluorescence resonance energy transfer (FRET) between quantum dots and gold nanoparticles", *Journal of the American Chemical Society*, vol. 127, No. 10, pp. 3270-3271, (2005).
- Rajendran, M. et al., "In vitro selection of molecular beacons", *Nucleic Acids Research*, vol. 31, No. 19, pp. 5700-5713, (2003).
- Vet, J.A.M. et al., "Multiplex detection of four pathogenic retroviruses using molecular beacons", *Proceedings of the National Academy of Science, USA.*, vol. 96, pp. 6394-6399, (1999).
- Wargnier, R. et al., "Energy transfer in aqueous solutions of oppositely charged CdSe/ZnS core/shell quantum dot-nanogold assemblies", *Nano Letters*, vol. 4, No. 3, pp. 451-457, (2004).
- Wilson, R. et al., "Encoded microcarriers for high-throughput multiplexed detection", *Angewandte Chemie International Edition*, vol. 45, pp. 6104-6117, (2006).
- Winkler, W.C. et al., "Regulation of bacterial gene expression by riboswitches", *The Annual Review of Microbiology*, vol. 59, pp. 487-517, (2005).
- Yang, C.J. et al., "Light-switching excimer probes for rapid protein monitoring in complex biological fluids", *PNAS*, vol. 102, No. 48, pp. 17278-17283, (2005).
- Liu, J. et al., "Quantum dot encoding of aptamer-linked nanostructures for one-pot simultaneous detection of multiple analytes", *Analytical Chemistry*, vol. 79, No. 11, pp. 4120-4125, (2007).
- Lu, Y. et al., "Smart nanomaterials inspired by biology: Dynamic assembly of error-free nanomaterials in response to multiple chemical and biological stimuli", *Accounts of Chemical Research*, vol. 40, No. 5, pp. 315-323, (2007).
- Allen, M.J. et al., "Magnetic resonance contrast agents for medical and molecular imaging", *Met. Ions Biol. Syst.*, vol. 42, pp. 1-38, (2004).
- Artemov, D. et al., "MR molecular imaging of the Her-2/neu receptor in breast cancer cells using targeted iron oxide nanoparticles", *Magnetic Resonance in Medicine*, vol. 49, pp. 403-408, (2003).
- Buerger, C. et al., "Sequence-specific peptide aptamers, interacting with the intracellular domain of the epidermal growth factor receptor, interfere with stat3 activation and inhibit the growth of tumor cells", *The Journal of Biological Chemistry*, vol. 278, No. 39, pp. 37610-37621, (2003).
- Buerger, C. et al., "Bifunctional recombinant proteins in cancer therapy: cell penetrating peptide aptamers as inhibitors of growth factor signaling", *J. Cancer Research Clin. Oncol.*, vol. 129, pp. 669-675, (2003).
- Carr, D.H. et al., "Gadolinium-DTPA as a contrast agent in MRI: initial clinical experience in 20 patients", *American Journal of Roentgenol.*, vol. 143, pp. 215-224, (1984).
- Chen, Y. et al., "An autonomous DNA nanomotor powered by a DNA enzyme", *Angew. Chem. Int. Ed.*, vol. 43, pp. 3554-3557, (2004).

- Corot, C. et al., "Macrophage imaging in central nervous system and in carotid atherosclerotic plaque using ultrasmall superparamagnetic iron oxide in magnetic resonance imaging", *Investigative Radiology*, vol. 39, No. 10, pp. 619-625, (2004).
- Dodd, C.H. et al., "Normal T-cell response and in vivo magnetic resonance imaging of T cells loaded with HIV transactivator-peptide-derived superparamagnetic nanoparticles", *Journal of Immunological Methods*, vol. 256, pp. 89-105, (2001).
- Drolet, D.W. et al., "An enzyme-linked oligonucleotide assay", *Nature Biotechnology*, vol. 14, pp. 1021-1025, (1996).
- Enochs, W.S. et al., "Improved delineation of human brain tumors on MR images using a long-circulating, superparamagnetic iron oxide agent", *Journal of Magnetic Resonance Imaging*, vol. 9, pp. 228-232, (1999).
- Famulok, M. et al., "Nucleic acid aptamers-from selection in vitro to applications in vivo", *Accounts of Chemical research*, vol. 33, No. 9, pp. 591-599, (2000).
- Fang, X. et al., "Molecular aptamer for real-time oncoprotein platelet-derived growth factor monitoring by fluorescence anisotropy", *Analytical Chemistry*, vol. 73, No. 23, pp. 5752-5757, (2001).
- Frullano, L. et al., "Synthesis and characterization of a doxorubicin-Gd(III) contrast agent conjugate: A new approach toward prodrug-procontrast complexes", *Inorganic Chemistry*, vol. 45, No. 21, pp. 8489-8491, (2006).
- Hamaguchi, N. et al., "Aptamer beacons for the direct detection of proteins", *Analytical Biochemistry*, vol. 294, pp. 126-131, (2001).
- Harisinghani, M.G. et al., "Noninvasive detection of clinically occult lymph-node metastases in prostate cancer", *The New England Journal of Medicine*, vol. 348, No. 25, pp. 2491-2499, (2003).
- Hermann, T. et al., "Adaptive recognition by nucleic acid aptamers", *Science*, vol. 287, pp. 820-825, (2000).
- Hoppe-Seyler, F. et al., "Peptide aptamers: Specific inhibitors of protein function", *Current Molecular Medicine*, vol. 4, pp. 529-538, (2004).
- Huang, C-C. et al., "Aptamer-modified gold nanoparticles for colorimetric determination of platelet-derived growth factors and their receptors", *Analytical Chemistry*, vol. 77, No. 17, pp. 5735-5741, (2005).
- Josephson, L. et al., "High-efficiency intracellular magnetic labeling with novel superparamagnetic-tat peptide conjugates", *Bioconjugate Chem.*, vol. 10, No. 2, pp. 186-191, (1999).
- Josephson, L. et al., "The effects of iron oxides on proton relaxivity", *Magnetic Resonance Imaging*, vol. 6, pp. 647-653, (1988).
- Josephson, L. et al., "Magnetic nanosensors for the detection of oligonucleotide sequences", *Angew. Chem. Int. Ed.*, vol. 40, No. 17, pp. 3204-3206, (2001).
- Kabalka, G. et al., "Gadolinium-labeled liposomes: Targeted MR contrast agents for the liver and spleen", *Radiology*, vol. 163, pp. 255-258, (1987).
- Kooi, M.E. et al., "Accumulation of ultrasmall superparamagnetic particles of iron oxide in human atherosclerotic plaques can be detected by in vivo magnetic resonance imaging", *Circulation*, vol. 107, pp. 2453-2458, (2003).
- Kresse, M. et al., "Targeting of ultrasmall superparamagnetic iron oxide (USPIO) particles to tumor cells in vivo by using transferring receptor pathways", *Magn. Reson. Med.*, vol. 40, pp. 236-242, (1998).
- Lee, J. et al., "A steroid-conjugated contrast agent for magnetic resonance imaging of cell signaling", *Journal of American Chemical Society*, vol. 127, No. 38, pp. 13164-13166, (2005).
- Lewin, M. et al., "Tat peptide-derivatized magnetic nanoparticles allow in vivo tracking and recovery of progenitor cells", *Nature Biotechnology*, vol. 18, pp. 410-414, (2000).
- Li, J.J. et al., "Molecular aptamer beacons for real-time protein recognition", *Biochemical and Biophysical Research Communications*, vol. 292, No. 1, pp. 31-40, (2002).
- Li, W-H. et al., "A calcium-sensitive magnetic resonance imaging contrast agent", *Journal of the American Chemical Society*, vol. 121, No. 6, pp. 1413-1414, (1999).
- Lin, C.H. et al., "Structural basis of DNA folding and recognition in an AMP-DNA aptamer complex: distinct architectures but common recognition motifs for DNA and RNA aptamers complexed to AMP", *Chemistry and Biology*, vol. 4, pp. 817-832, (1997).
- Liss, M. et al., "An aptamer-based quartz crystal protein biosensor", *Analytical Chemistry*, vol. 74, No. 17, pp. 4488-4495, (2002).
- Liu, Y. et al., "Aptamer-directed self-assembly of protein arrays on a DNA nanostructure", *Angew. Chem. Int. Ed.*, vol. 44, pp. 4333-4338, (2005).
- Macaya, R.F. et al., "Thrombin-binding DNA aptamer forms a unimolecular quadruplex structure in solution", *Proceedings of the National Academy of Science USA*, vol. 90, pp. 3745-3749, (1993).
- Nagel-Wolfrum, K. et al., "The interaction of specific peptide aptamers with the DNA binding domain and the dimerization domain of the transcription factor stat3-inhibits transactivation and induces apoptosis in tumor cells", *Molecular Cancer Research*, vol. 2, pp. 170-182, (2004).
- Nitin, N. et al., "Functionalization and peptide-based delivery of magnetic nanoparticles as an intracellular MRI contrast agent", *J. Biol. Inorg. Chem.*, vol. 9, pp. 706-712, (2004).
- Nutiu, R. et al., "Engineering DNA aptamers and DNA enzymes with fluorescence-signaling properties", *Pure Appl. Chem.*, vol. 76, Nos. 7-8, pp. 1547-1561, (2004).
- Padmanabhan, K. et al., "The structure of a-thrombin inhibited by a 15-mer single-stranded DNA aptamer", *The Journal of Biological Chemistry*, vol. 268, No. 24, pp. 17651-17654, (1993).
- Pavlov, V. et al., "Aptamer-functionalized au nanoparticles for the amplified optical detection of thrombin", *The Journal of the American Chemical Society*, vol. 126, No. 38, pp. 11768-11769, (2004).
- Pendergrast, P.S. et al., "Nucleic acid aptamers for target validation and therapeutic applications", *Journal of Biomolecular Techniques*, vol. 16, issue 3, pp. 224-234, (2005).
- Perez, J.M. et al., "Use of magnetic nanoparticles as nanosensors to probe for molecular interactions", *ChemBioChem*, vol. 5, pp. 261-264, (2004).
- Perez, J.M. et al., "Viral-induced self-assembly of magnetic nanoparticles allows the detection of viral particles in biological media", *Journal of the American Chemical Society*, vol. 125, No. 34, pp. 10192-10193, (2003).
- Radi, A-E. et al., "Reagentless, reusable, ultrasensitive electrochemical molecular beacon aptasensor", *Journal of the American Chemical Society*, vol. 128, No. 1, pp. 117-124, (2006).
- Saeed, M. et al., "Occlusive and reperfused myocardial infarcts: differentiation with Mn-DPDP-enhanced MR imaging", *Radiology*, vol. 172, pp. 59-64, (1989).
- Shen, T. et al., "Monocrystalline iron oxide nanocompounds (MION): Physicochemical properties", *Magn. Reson. Med.*, vol. 29, pp. 599-604, (1993).
- Soriaga, M.P. et al., "Determination of the orientation of adsorbed molecules at solid-liquid interfaces by thin-layer electrochemistry: Aromatic compounds at platinum electrodes", *Journal of the American Chemical Society*, vol. 104, pp. 2735-2742, (1982).
- Soriaga, M.P. et al., "Determination of the orientation of aromatic molecules adsorbed on platinum electrodes: The influence of iodide a surface-active anion", *Journal of the American Chemical Society*, vol. 104, pp. 2742-2747, (1982).
- Soriaga, M.P. et al., "Determination of the orientation of aromatic molecules adsorbed on platinum electrodes: The effect of solute concentration", *Journal of the American Chemical Society*, vol. 104, pp. 3937-3945, (1982).
- Sosnovik, D.E. et al., "Emerging concepts in molecular MRI", *Current Opinion in Biotechnology*, vol. 18, pp. 4-10, (2007).
- Taboada, E. et al., "Relaxometric and magnetic characterization of ultrasmall iron oxide nanoparticles with high magnetization. Evaluation as potential T<sub>1</sub> magnetic resonance imaging contrast agents for molecular imaging", *Langmuir*, vol. 23, No. 8, pp. 4583-4588, (2007).
- Tasset, D.M. et al., "Oligonucleotide inhibitors of human thrombin that bind distinct epitopes", *J. Mol. Biol.*, vol. 272, pp. 688-698, (1997).
- Tian, Y. et al., "DNAzyme amplification of molecular beacon signal", *Talanta*, vol. 67, pp. 532-537, (2005).
- Tompkins, H.G. et al., "The study of the gas-solid interaction of acetic acid with a cuprous oxide surface using reflection-absorption spectroscopy", *Journal of colloid and interface science*, vol. 49, No. 3, pp. 410-421, (1974).

- Tsourkas, A. et al., "Magnetic relaxation switch immunosensors detect enantiomeric impurities", *Angew. Chem. Int. Ed.*, vol. 43, pp. 2395-2399, (2004).
- Wang, S. et al., "Core/shell quantum dots with high relaxivity and photoluminescence for multimodality imaging", *Journal of the American Chemical Society*, vol. 129, No. 13, pp. 3848-3856, (2007).
- Weissleder, R. et al., "MR imaging of splenic metastases: Ferrite-enhanced detection in rats", *American Journal Roentgenol.*, vol. 149, pp. 723-726, (1987).
- Xiao, Y. et al., "Label-free electronic detection of thrombin in blood serum by using an aptamer-based sensor", *Angew. Chem. Int. Ed.*, vol. 44, pp. 5456-5459, (2005).
- Xiao, Y. et al., "A reagentless signal-on architecture for electronic, aptamer-based sensors via target-induced strand displacement", *Journal of the American Chemical Society*, vol. 127, No. 51, pp. 17990-17991, (2005).
- Xu, D. et al., "Label-free electrochemical detection for aptamer-based array electrodes", *Analytical Chemistry*, vol. 77, No. 16, pp. 6218-6224, (2005).
- Yamamoto, R. et al., "Molecular beacon aptamer fluoresces in the presence of Tat protein of HIV-1", *Genes to Cells*, vol. 5, pp. 389-396, (2000).
- Zhao, M. et al., "Magnetic sensors for protease assays", *Angew. Chem. Int. Ed.*, vol. 42, No. 12, pp. 1375-1378, (2003).
- Zhao, M. et al., "Differential conjugation of tat peptide to superparamagnetic nanoparticles and its effect on cellular uptake", *Bioconjugate Chem.*, vol. 13, pp. 840-844, (2002).
- Liu, J. et al., "Colorimetric Cu<sup>2+</sup> detection with a ligation DNAzyme and nanoparticles", *Chemical Communications, Advance Articles*, DOI: 10.1039/b712421j, 6 pages, Oct. 24, 2007.
- Liu, J. et al., "Non-Base pairing DNA provides a new dimension for controlling aptamer-linked nanoparticles and sensors", *Journal of the American Chemical Society*, vol. 129, No. 27, pp. 8634-8643, (2007).
- Liu, J. et al., Supporting Information for "Colorimetric Cu<sup>2+</sup> detection with a ligation DNAzyme and nanoparticles", *Chemical Communications, Advance Articles*, 4 pages, Oct. 24, 2007.
- Stratagene Catalog, "Gene Characterization Kits", 2 pages, (1988).
- Fahlman, R.P. et al., "DNA conformational switches as sensitive electronic sensors of analytes", *Journal of the American Chemical Society*, vol. 124, 4610-4616, (2002).
- Mayer, G. et al., "High-throughput-compatible assay for glmS riboswitch metabolite dependence", *ChemBioChem*, vol. 7, pp. 602-604, (2006).
- Elowe, N., et al., "Small-molecule screening made simple for a difficult target with a signaling nucleic acid aptamer that reports on deaminase activity", *Angew. Chem. Int. Ed.*, vol. 45, pp. 5648-5652, (2006).
- Yigit, M. et al., "Smart "turn-on" magnetic resonance contrast agents based on aptamer-functionalized superparamagnetic iron oxide nanoparticles", *ChemBioChem*, vol. 8, pp. 1675-1678, (2007).
- Xu, D. et al., "Label-free electrochemical detection for aptamer-based array electrodes", *Analytical Chemistry*, vol. 77, No. 16, pp. 5107-5113, (2005).
- Yigit, M. et al., "MRI detection of thrombin with aptamer functionalized superparamagnetic iron oxide nanoparticles", *Bioconjugate Chem.*, vol. 19, pp. 412-417, (2008).
- International Search Report dated Mar. 4, 2009 for PCT application No. PCT/US2008/070177.
- International Search Report dated Apr. 17, 2009 for PCT application No. PCT/US2008/051185.
- International Search Report dated Aug. 13, 2009 for PCT application No. PCT/US2008/072327.
- Liu, J. et al., "Rational design of turn-on allosteric DNAzyme catalytic beacons for aqueous mercury ions with ultrahigh sensitivity and selectivity", *Angewandte Chemie. International Edition*, vol. 46, No. 40, pp. 7587-7590, (2007).
- Stadler, B. et al., "Micropatterning of DNA-tagged vesicles", *Langmuir*, vol. 20, No. 26, pp. 11348-11354, (2004).
- Pfeiffer, I. et al., "Bivalent cholesterol-Based coupling of oligonucleotides to lipid membrane assemblies", *Journal of the American Chemical Society*, vol. 126, No. 33, pp. 10224-10225, (2004).
- Shin, J. et al., "Acid-triggered release via dePEGylation of DOPE liposomes containing acid-labile vinyl ether PEG-lipids", *Journal of Controlled Release*, vol. 91, issues 1-2, pp. 187-200, (2003).
- Cram, D.J. et al., "Organic Chemistry", McGraw-Hill, pp. 560-569, (1959).
- Rusconi, C.P. et al., "Antidote-mediated control of an anticoagulant aptamer in vivo", *Nature Biotechnology Letters*, vol. 22, No. 11, pp. 1423-1428, (2004).
- Willis M.C. et al., "Liposome-anchored vascular endothelial growth factor aptamers", *Bioconjugate Chem.*, vol. 9, No. 5, pp. 573-582, (1998).
- Healy, J.M. et al., "Pharmacokinetics and biodistribution of novel aptamer compositions", *Pharm. Research*, vol. 21, No. 12, pp. 2234-2246, (2004).
- Farokhzad, O.C. et al., "Targeted nanoparticle-aptamer bioconjugates for cancer chemotherapy in vivo", *Proceedings of the National Academy of Science*, vol. 103, No. 16, pp. 6315-6320, (2006).
- Farokhzad, O.C. et al., "Nanoparticle-aptamer bioconjugates: A new approach for targeting prostate cancer cells", *Cancer Research*, vol. 64, pp. 7668-7672, (2004).
- American Cancer Society Statistics for 2006. [http://www.cancer.org/docroot/stt/stt\\_0.asp](http://www.cancer.org/docroot/stt/stt_0.asp) 2006.
- Eifel, P. et al., "National Institutes of Health Consensus Development Panel, National Institutes of Health Consensus Development Conference statement: Adjuvant therapy for breast cancer, Nov. 1-3, 2000", *Journal of the National Cancer Institute*, vol. 93, No. 13, pp. 979-989, (2001).
- Park, J.W. et al., "Tumor targeting using anti-her2 immunoliposomes", *Journal of Controlled Release*, vol. 74, pp. 95-113, (2001).
- Kallab, V. et al., "HER2/EGFR internalization: a novel biomarker for ErbB-targeted therapeutics", *Breast Cancer Research Treat.*, vol. 88, pp. S126-S127, (2004).
- Wilson, K.S. et al., "Differential gene expression patterns in HER2/neu-positive and -negative breast cancer cell lines and tissues", *American Journal of Pathology*, vol. 161, No. 4, pp. 1171-1185, (2002).
- Weigelt, B. et al., "Breast cancer metastasis: Markers and models", *Nature Reviews, Cancer*, vol. 5, pp. 591-602, (2005).
- Pegram, M.D. et al., "Rational combinations of trastuzumab with chemotherapeutic drugs used in the treatment of breast cancer", *Journal of the National Cancer Institute*, vol. 96, No. 10, pp. 739-749, (2004).
- Kirpotin, D.B. et al., "Antibody targeting of long-circulating lipidic nanoparticles does not increase tumor localization but does increase internalization in animal models", *Cancer Research*, vol. 66, No. 13, pp. 6732-6740, (2006).
- Cheng, C. et al., "Formulation of Functionalized PLGA-PEG Nanoparticles for In Vivo Targeted Drug Delivery", *Biomaterials*, vol. 28, issue 5, pp. 869-876, (2007).
- Bass, B.L. et al., "Specific interaction between the self-splicing RNA of Tetrahymena and its guanosine substrate: implications for biological catalysis by RNA", *Nature*, vol. 308, pp. 820-826, (1984).
- Ellington, A.D. et al., "Combinatorial methods: aptamers and aptazymes", Part of the SPIE Conference on Advanced Materials and Optical Systems for Chemical and Biological Detection, SPIE, vol. 3858, pp. 126-134, (1999).
- Robertson, M.P. et al., "Aptazymes as generalized signal transducers", *Nucleic Acids Symp. Ser.*, vol. 41, pp. 1-3, (1999).
- Pagratís, N.C. et al., "Potent 2'-amino-, and 2'-fluoro-2'-deoxyribonucleotide RNA inhibitors of keratinocyte growth factor", *Nature Biotechnology*, vol. 15, pp. 68-73, (1997).
- Lupold, S.E. et al., "Identification and characterization of nuclease-stabilized RNA molecules that bind human prostate cancer cells via the prostate-specific membrane antigen", *Cancer research*, vol. 62, pp. 4029-4033, (2002).
- Jenison, R.D. et al., "Oligonucleotide inhibitors of P-selectin-dependent neutrophil-platelet adhesion", *Antisense Nucleic Acid Drug Dev.*, vol. 8, pp. 265-279, (1998).
- Hicke, B.J. et al., "DNA aptamers block L-selectin function in vivo. Inhibition of human lymphocyte trafficking in SCID mice", *J. Clinical Invest.*, vol. 98, No. 12, pp. 2688-2692, (1996).

- O'Connell, D. et al., "Calcium-dependent oligonucleotide antagonists specific for L-selectin", *Proceedings of the National Academy of Science, U.S.A.*, vol. 93, pp. 5883-5887, (1996).
- Soukup, G.A. et al., "Design of allosteric hammerhead ribozymes activated by ligand-induced structure stabilization", *Structure*, vol. 7, pp. 783-791, (1999).
- Straubinger, R.M. et al., "Preparation and characterization of taxane-containing liposomes", *Methods in Enzymology*, vol. 391, pp. 97-117, (2005).
- Rivera, E. "Liposomal anthracyclines in metastatic breast cancer: Clinical update", *The Oncologist*, vol. 8, supplement 2, pp. 3-9, (2003).
- Kornblith, P. et al., "Breast cancer—Response rates to chemotherapeutic agents studied in vitro", *Anticancer Research*, vol. 23, pp. 3405-3411, (2003).
- Pei, J. et al., "Combination with liposome-entrapped, ends-modified raf antisense oligonucleotide (LErafAON) improves the anti-tumor efficacies of cisplatin, epirubicin, mitoxantrone, docetaxel and gemcitabine", *Anti-Cancer Drugs*, vol. 15, pp. 243-253, (2004).
- Allen, T.M. et al., "Therapeutic opportunities for targeted liposomal drug delivery", *Advanced Drug Delivery Reviews*, vol. 21, pp. 117-133, (1996).
- Hofheinz, R.D. et al., "Liposomal encapsulated anti-cancer drugs", *Anti-Cancer Drugs*, vol. 16, pp. 691-707, (2005).
- Schluep, T. et al., "Preclinical efficacy of the camptothecin-polymer conjugate IT-101 in multiple cancer models", *Clinical Cancer Research*, vol. 12, No. 5, pp. 1606-1614, (2006).
- Schluep, T. et al., "Pharmacokinetics and biodistribution of the camptothecin-polymer conjugate IT-101 in rats and tumor-bearing mice", *Cancer Chemoth. Pharm.*, vol. 57, pp. 654-662, (2006).
- Cheng, J. et al., "Antitumor Activity of beta-Cyclodextrin Polymer-Camptothecin Conjugates", *Molecular Pharmaceutics*, vol. 1, No. 3, pp. 183-193, (2004).
- Cheng, J. et al., "Synthesis of linear, beta-cyclodextrin-based polymers and their camptothecin conjugates", *Bioconjugate Chem.*, vol. 14, pp. 1007-1017, (2003).
- Guo, X. et al., "Steric stabilization of fusogenic liposomes by a low-pH sensitive PEG-diortho ester-lipid conjugate", *Bioconjugate Chem.*, vol. 12, pp. 291-300, (2001).
- Gerasimov, O.V. et al., "Cytosolic drug delivery using pH- and light-sensitive liposomes", *Advanced Drug Delivery Reviews*, vol. 38, pp. 317-338, (1999).
- Rovira-Bru, M. et al., "Size and structure of spontaneously forming liposomes in lipid/PEG-lipid mixtures", *Biophysical Journal*, vol. 83, pp. 2419-2439, (2002).
- Liu, J. et al., "Proofreading and error removal in a nanomaterial assembly", *Angewandte Chemie, International Edition*, vol. 44, pp. 7290-7293, (2005).
- Liu, J. et al., "Design of asymmetric DNAzymes for dynamic control of nanoparticle aggregation states in response to chemical stimuli", *Organic & Biomolecular Chemistry*, vol. 4, pp. 3435-3441, (2006).
- Cho, H.S. et al., "Structure of the extracellular region of HER2 alone and in complex with the Herceptin Fab", *Nature*, vol. 421, pp. 756-760, (2003).
- Leahy, D.J. et al., "A Mammalian Expression Vector for Expression and Purification of Secreted Proteins for Structural Studies", *Protein Expression and Purification*, vol. 20, pp. 500-506, (2000).
- Bartel, D.P. et al., "Isolation of new ribozymes from a large pool of random sequences", *Science*, vol. 261, pp. 1411-1418, (1993).
- Jellinek, D. et al., "Inhibition of receptor binding by high-affinity RNA ligands to vascular endothelial growth factor", *Biochemistry*, vol. 33, pp. 10450-10456, (1994).
- Jellinek, D. et al., "Potent 2'-Amino-2'-deoxyypyrimidine RNA Inhibitors of Basic Fibroblast Growth Factor", *Biochemistry*, vol. 34, pp. 11363-11372, (1995).
- Green, L.S. et al., "Inhibitory DNA Ligands to Platelet-Derived Growth Factor B-Chain", *Biochemistry*, vol. 35, pp. 14413-14424, (1996).
- Lee, T.C. et al., "Overexpression of RRE-derived sequences inhibits HIV-1 replication in CEM cells", *New Biologist*, vol. 4, p. 66, (1992).
- Andersen, T.L. et al., "Advanced strategies in liposomal cancer therapy: Problems and prospects of active and tumor specific drug release", *Progress in Lipid Research*, vol. 44, pp. 68-97, (2005).
- Woodle, M.C. et al., "Sterically Stabilized Liposomes—Reduction in electrophoretic mobility but not electrostatic surface potential", *Biophysical Journal*, vol. 61, pp. 902-910, (1992).
- Zalipsky, S. et al., "Long Circulating, Cationic Liposomes Containing Amino-Peg-Phosphatidylethanolamine", *FEBS Letters*, vol. 353, pp. 71-74, (1994).
- Morrison, W., "A fast, simple and reliable method for the microdetermination of phosphorus in biological materials", *Analytical Biochemistry*, vol. 7, issue 2, pp. 218-224, (1964).
- Kirpotin, D. et al., "Sterically Stabilized Anti-HER2 Immunoliposomes: Design and Targeting to Human Breast Cancer Cells in Vitro", *Biochemistry*, vol. 36, pp. 66-75, (1997).
- Klibanov, A.L. et al., "Activity of Amphipathic Poly(Ethylene Glycol)-5000 to Prolong the Circulation Time of Liposomes Depends on the Liposome Size and Is Unfavorable for Immunoliposome Binding to Target", *Biochim. Biophys. Acta*, vol. 1062, pp. 142-148, (1991).
- Park, J.W. et al., "Development of Anti-P185<sup>HER2</sup> Immunoliposomes for Cancer-Therapy", *Proceedings of the National Academy of Science U.S.A.*, vol. 92, pp. 1327-1331, (1995).
- Zalipsky, S., "Synthesis of an End-Group Functionalized Polyethylene Glycol-Lipid Conjugate for Preparation of Polymer-Grafted Liposomes", *Bioconjugate Chem.*, vol. 4, pp. 296-299, (1993).
- Allen, T.M. et al., "A New Strategy for Attachment of Antibodies to Sterically Stabilized Liposomes Resulting in Efficient Targeting to Cancer-Cells", *Biochimica et Biophysica Acta*, vol. 1237, pp. 99-108, (1995).
- Gillies, E.R. et al., "A new approach towards acid sensitive copolymer micelles for drug delivery", *Chemical Communications*, Issue 14, pp. 1640-1641, (2003).
- Joensuu, O.I., "Fossil Fuels as a Source of Mercury Pollution", *Science*, vol. 172, No. 3987, pp. 1027-1028, (1971).
- Malm, O., "Gold mining as a source of mercury exposure in the Brazilian Amazon", *Environmental Research*, vol. 77, No. 2, pp. 73-78, (1998).
- Tchounwou, P.B. et al., "Environmental exposure to mercury and its toxicopathologic implications for public health", *Environmental Toxicology*, vol. 18, No. 3, pp. 149-175, (2003).
- Yoon, S. et al., "A bright and specific fluorescent sensor for mercury in water, cells, and tissue", *Angewandte Chemie International Edition*, vol. 46, No. 35, pp. 6658-6661, (2007).
- Liu, X.F. et al., "Optical detection of mercury(II) in aqueous solutions by using conjugated polymers and label-free oligonucleotides", *Advanced Materials*, vol. 19, No. 11, p. 1471, (2007).
- Chiang, C.K. et al., "Oligonucleotide-based fluorescence probe for sensitive and selective detection of mercury(II) in aqueous solution", *Analytical Chemistry*, vol. 80, No. 10, pp. 3716-3721, (2008).
- Yamini, Y. et al., "Solid phase extraction and determination of ultra trace amounts of mercury(II) using octadecyl silica membrane disks modified by hexathia-18-crown-6-tetraene and cold vapour atomic absorption spectrometry", *Analytica Chimica Acta*, vol. 355, issue 1, pp. 69-74, (1997).
- Darbha, G.K. et al., "Gold nanoparticle-based miniaturized nanomaterial surface energy transfer probe for rapid and ultrasensitive detection of mercury in soil, water, and fish", *Acs Nano*, vol. 1, No. 3, pp. 208-214, (2007).
- Li, D. et al., "Optical analysis of Hg<sup>2+</sup> ions by oligonucleotide-gold-nanoparticle hybrids and DNA-based machines", *Angewandte Chemie International Edition*, vol. 47, No. 21, pp. 3927-3931, (2008).
- Liu, C.W. et al., "Detection of mercury(II) based on Hg<sup>2+</sup>-DNA complexes inducing the aggregation of gold nanoparticles", *Chemical Communications*, vol. 19, pp. 2242-2244, (2008).
- Xue, X. et al., "One-step, room temperature, colorimetric detection of mercury (Hg<sup>2+</sup>) using DNA/nanoparticle conjugates", *Journal of the American Chemical Society*, vol. 130, No. 11, pp. 3244-3245, (2008).
- Wang, L. et al., "Gold nanoparticle-based optical probes for target-responsive DNA structures", *Gold Bulletin*, vol. 41, No. 1, pp. 37-41, (2008).
- Clarkson, T.W. et al., "Mercury—Major Issues in Environmental-Health", *Environmental Health Perspectives*, vol. 100, pp. 31-38, (1993).

- Wren, C.D. "A Review of Metal Accumulation and Toxicity in Wild Mammals, I Mercury", *Environmental Research*, vol. 40, No. 1, pp. 210-244, (1986).
- Koos, B.J. et al., "Mercury Toxicity in Pregnant Woman, Fetus, and Newborn-Infant -Review", *American Journal of Obstetrics and Gynecology*, vol. 126, No. 3, pp. 390-409, (1976).
- Yu, Y. et al., "p-dimethylaminobenzaldehyde thiosemicarbazone: A simple novel selective and sensitive fluorescent sensor for mercury(II) in aqueous solution", *Talanta*, vol. 69, No. 1, pp. 103-106, (2006).
- Braman, R.S., "Membrane Probe—Spectral Emission Type Detection System for Mercury in Water", *Analytical Chemistry*, vol. 43, No. 11, pp. 1462-1467, (1971).
- Wernette, D.P. et al., "Surface immobilization of catalytic beacons based on ratiometric fluorescent DNzyme sensors: a systematic study", *Langmuir*, vol. 23, No. 18, pp. 9513-9521, (2007).
- Wang, Z. et al., "Highly sensitive 'turn-on' fluorescent sensor for Hg<sup>2+</sup> in aqueous solution based on structure-switching DNA", *Chemical Communications*, pp. 6005-6007, (2008).
- Lu, Y. "New catalytic DNA fluorescent and colorimetric sensors for on-sit and real-time monitoring of industrial and drinking water", *ISTC Reports*, Illinois Sustainable Technology Center Institute of Natural Resource Sustainability, University of Illinois at Urbana-Champaign, [http://www.istc.illinois.edu/info/library\\_docs/RR/RR-114.pdf](http://www.istc.illinois.edu/info/library_docs/RR/RR-114.pdf), pp. i-ix, and 1-30, (2009).
- Turner, A. P. F., "Biochemistry: Biosensors—Sense and Sensitivity", *Science*, vol. 290, No. 5495, pp. 1315-1317, (2000).
- Abbasi, S. A., "Atomic absorption spectrometric and spectrophotometric trace analysis of uranium in environmental samples with n-p-methoxyphenyl-2-4-(2-pyridylazo) resorcinol", *Int. J. Environ. Anal. Chem.*, vol. 36, pp. 163-172, (1989).
- Arnez, J. G. et al., "Crystal structure of unmodified tRNA<sup>Gln</sup> complexed with glutamyl-tRNA synthetase and ATP suggests a possible role for pseudo-uridines in stabilization of RNA structure", *Biochemistry*, vol. 33, pp. 7560-7567, (1994).
- Blake, R. C., II, et al., "Novel monoclonal antibodies with specificity for chelated uranium (VI): isolation and binding properties", *Bioconjug. Chem.*, vol. 15, pp. 1125-1136, (2004).
- Boomer, D. W., et al., "Determination of uranium in environmental samples using inductively coupled plasma mass spectrometry", *Anal. Chem.*, vol. 59, pp. 2810-2813, (1987).
- Breaker, R. R., "Natural and engineered nucleic acids as tools to explore biology", *Nature*, vol. 432, pp. 838-845, (2004).
- Brina, R. et al., "Direct detection of trace levels of uranium by laser-induced kinetic phosphorimetry", *Anal. Chem.*, vol. 64, pp. 1413-1418, (1992).
- Chung N. et al., "Selective extraction of gold(III) in the presences of Pd(II) and Pt(IV) by saltin-out of the mixture of 2-propanol and water", *Talanta*, vol. 58, pp. 927-933, (2002).
- Craft, E. et al., "Depleted and natural uranium: chemistry and toxicological effects", *J. Toxicol. Environ. Health, Part B*, vol. 7, pp. 297-317, (2004).
- Demers, L. M. et al., "Thermal desorption behavior and binding properties of DNA bases and nucleosides on gold", *J. Am. Chem. Soc.* vol. 124, pp. 11248-11249, (2002).
- Frankforter G. et al., "Equilibria in the systems of the higher alcohols, water and salts", *J. Am. Chem. Soc.*, vol. 37, pp. 2697-2716 (1915).
- Frankforter G., et al., "Equilibria in the systems, water, acetone and inorganic salts", *J. Am. Chem. Soc.*, vol. 36, pp. 1103-1134, (1914).
- Frankforter G., et al., "Equilibria in systems containing alcohols, salts and water, including a new method of alcohol analysis", *J. Phys. Chem.*, vol. 17, pp. 402-473, (1913).
- Ginnings, P. et al., "Ternary systems: water, tertiary butanol and salts at 30° C", *J. Am. Chem. Soc.*, vol. 52, pp. 2282-2286, (1930).
- Gongalsky, K., "Impact of pollution caused by uranium production on soil macrofauna", *Environ. Monit. Assess.*, vol. 89, pp. 197-219, (2003).
- Homola, J. et al., "Surface Plasmon Resonance (SPR) Sensors", *Springer Series on Chemical Sensors and Biosensors*, vol. 4, pp. 45-67, (2006).
- US EPA, "Drinking water contaminants", found at <http://www.epa.gov/safewater/contaminants/index.html>, pp. 1-17, printed on Nov. 23, 2009.
- Jones, L. A., et al., "Extraction of phenol and its metabolites from aqueous solution", *J. Agric. Food Chem.*, vol. 41, pp. 735-741, (1993).
- Katz, E. et al., "Integrated nanoparticle-biomolecule hybrid systems: sythesis, properties, and applications", *Angew. Chem. Int. Ed.*, vol. 43, pp. 6042-6108, (2004).
- Kobe, K. A. et al., "The ternary systems ethylene glycol-potassium carbonate-water and dioxane-potassium carbonate-water", *J. Phys. Chem.*, vol. 446, pp. 629-633, (1940).
- Laromaine, A. et al., "Protease-triggered dispersion of nanoparticle assemblies", *J. Am. Chem. Soc.*, vol. 129, pp. 4156-4157, (2007).
- Lazarova, Z. et al., "Solvent extraction of lactic acid from aqueous solution", *Journal of Biotechnology*, vol. 32, pp. 75-82, (1994).
- Lee, J. H. et al., "Site-specific control of distances between gold nanoparticles using phosphorothioate anchors on DNA and a short bifunctional molecular fastener", *Angew. Chem. Int. Ed.*, vol. 46, pp. 9006-9010, (2007).
- Leggett, D. C. et al., "Salting-out solvent extraction for preconcentration of neutral polar organic solutes from water", *Anal. Chem.*, vol. 62, pp. 1355-1356, (1990).
- Leinonen, H., "Stress corrosion cracking and life prediction evaluation of austenitic stainless steels in calcium chloride solution", *Corrosion Science*, vol. 52, No. 5, pp. 337-346, (1996).
- Li, D. et al., "Amplified electrochemical detection of DNA through the aggregation of Au nanoparticles on electrodes and the incorporation of methylene blue into the DNA-crosslinked structure", *Chem. Comm.*, pp. 3544-3546, (2007).
- Li, H. et al., "Detection of specific sequences in rna using differential adsorption of single-stranded oligonucleotides on gold nanoparticles", *Anal. Chem.*, vol. 77 No. 19, pp. 6229-6233, (2005).
- Li, H. et al., "Colorimetric detection of dna sequences based on electrostatic interactions with unmodified gold nanoparticles", *Proc. Natl. Acad. Sci. U.S.A.*, vol. 101, pp. 14036-14039, (2004).
- Li, H. et al., "Label-free colorimetric detection of specific sequences in genomic dna amplified by the polymerase chain reaction", *J. Am. Chem. Soc.*, vol. 126, pp. 10958-10961, (2004).
- Likidis, Z. et al., "Recovery of penicillin G from fermentation broth with reactive extraction in a mixer-settler", *Biotechnology Letters*, vol. 9, No. 4, pp. 229-232, (1987).
- Lim, I. et al., "Homocysteine-mediated reactivity and assembly of gold nanoparticles", *Langmuir*, vol. 23, pp. 826-833, (2007).
- Lu, Y. et al., "Functional DNA nanotechnology: emerging applications of DNzymes and aptamers", *Curr. Opin. Biotech.*, vol. 17, pp. 580-588, (2006).
- Long, F. A., et al., "Activity coefficients of nonelectrolyte solutes in aqueous salt solutions", *Chem. Rev.*, vol. 51, pp. 119-169, (1952).
- Lu, X. et al., "Salting-out separation and liquid-liquid equilibrium of tertiary butanol aqueous solution", *Chemical Engineering Journal*, vol. 78, pp. 165-171, (2000).
- Lu, Y. et al., "Smart nanomaterials inspired by biology: dynamic assembly of error-free nanomaterials in response to multiple chemical and biological stimuli", *Accounts of Chemical Research*, vol. 40, pp. 315-323, (2007).
- Malakar, M. et al., "Stripping voltammetric determination of trace levels of uranium by synergic adsorptions", *Analytica Chimica Acta*, vol. 221, pp. 279-287, (1989).
- Nishihama, S., "Review of advanced liquid-liquid extraction systems for the separation of metal ions by a combination of conversion of the metal species with chemical reaction", *Ind. Eng. Chem. Res.*, vol. 40, pp. 3085-3091, (2001).
- Pierotti, R. A., "A scaled particle theory of aqueous and nonaqueous solutions", *Chemical Reviews*, vol. 76, No. 6, pp. 717-726, (1976).
- Centers for Disease Control, "Preventing lead poisoning in young children", U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control: Atlanta, GA, (1991).
- Public Law 102-550; Residential Lead-Based Paint Hazard Reduction Act of the housing and Community Development Act of 1992; 28 pages, (1992).
- Qiang, Z. et al., "Potentiometric determination of acid dissociation constants (pK<sub>a</sub>) for human and veterinary antibiotics", *Water Research*, vol. 38, pp. 2874-2890, (2004).

- Rohwer, H. et al., "Interactions of uranium and thorium with arsenazo III in an aqueous medium", *Analytica Chimica Acta*, vol. 341, pp. 263-268, (1997).
- Safavi, A. et al., "A novel optical sensor for uranium determination", *Analytica Chimica Acta* vol. 530, pp. 55-60, (2005).
- Sato, K. et al., "Rapid aggregation of gold nanoparticles induced by non-cross-linking DNA hybridization", *J. Am. Chem. Soc.*, vol. 125, pp. 8102-8103, (2003).
- Schenk, F. J. et al., "Comparison of magnesium sulfate and sodium sulfate for removal of water from pesticide extracts of foods", *J. AOAC International*, vol. 85, No. 5, pp. 1177-1180, (2002).
- Sessler, J. L. et al., "Hexaphyrin (1.0.1.0.0.0), a new colorimetric actinide sensor", *Tetrahedron*, vol. 60, pp. 11089-11097, (2004).
- Shafer-Peltier, K. E. et al., "Toward a glucose biosensor based on surface-enhanced raman scattering", *J. Am. Chem. Soc.*, vol. 125, pp. 588-593, (2003).
- Sharma, J. et al., "DNA-templated self-assembly of two-dimensional and periodical gold nanoparticle arrays", *Angew. Chem. Int. Ed.*, vol. 45, pp. 730-735, (2006).
- Si, S. et al., "pH-controlled reversible assembly of peptide-functionalized gold nanoparticles", *Langmuir*, vol. 23, pp. 190-195, (2007).
- Simard, J. et al., "Formation and pH-controlled assembly of amphiphilic gold nanoparticles", *Chemical Commun.*, pp. 1943-1944, (2000).
- Singleton, V. L., "An extraction technique for recovery of flavors, pigments, and other constituents from wines and other aqueous solutions", *Am. J. Enol. Vitic.*, vol. 12, pp. 1-8, (1961).
- Rao, C.V.S.R. et al., "Extraction of acetonitrile from aqueous solutions. 1. Ternary liquid equilibria", *Journal of Chemical and Engineering Data*, vol. 23, No. 1, pp. 23-25, (1978).
- Rao, D.S. et al., "Extraction of acetonitrile from aqueous solutions. 2. ternary liquid equilibria", *Journal of Chemical and Engineering Data*, vol. 24, No. 3, pp. 241-244, (1979).
- Tabata, M. et al., "Ion-pair extraction of metalloporphyrins into acetonitrile for determination of copper(II)", *Analytical Chemistry*, vol. 68, No. 5, pp. 758-762, (1996).
- Tabata, M. et al., "Chemical properties of water-miscible solvents separated by salting-out and their application to solvent extraction", *Analytical sciences*, vol. 10, pp. 383-388, (1994).
- Van der Wal, S.J., "Low viscosity organic modifiers in reversed-phase HPLC", *Chromatographia*, vol. 20, No. 5, pp. 274-278, (1985).
- Wang, J. et al., "A gold nanoparticle-based aptamer target binding readout for ATP assay", *Adv. Mater.*, vol. 19, pp. 3943-3946, (2007).
- Wang, L. et al., "Unmodified gold nanoparticles as a colorimetric probe for potassium DNA aptamers", *Chem. Comm.*, vol. 36, 3780-3782, (2006).
- Wang, Z. et al., "Label-free colorimetric detection of lead ions with a nanomolar detection limit and tunable dynamic range by using gold nanoparticles and DNazyme", *Advanced Materials*, vol. 20, pp. 3263-3267, (2008).
- Warren, K. W., Reduction of corrosion through improvements in desalting, Benelux Refinery Symposium, Lanaken, Belgium, 11 pages, (1995).
- Wei, H. et al., "Simple and sensitive aptamer-based colorimetric sensing of protein using unmodified gold nanoparticle probes", *Chem. Comm.*, vol. 36, pp. 3735-3737, (2007).
- Wernette, D. P. et al., "Surface immobilization of catalytic beacons based on ratiometric fluorescent DNazyme sensors: A systematic study", *Langmuir*, vol. 23, pp. 9513-9521, (2007).
- Willner, I. et al., "Electronic aptamer-based sensors", *Angew. Chem., Int. Ed.*, vol. 46, pp. 6408-6418, (2007).
- Wu, Y. G., et al., "An extended Johnson-Furter equation to salting-out phase separation of aqueous solution of water-miscible organic solvents", *Fluid Phase Equilibria*, vol. 192, pp. 1-12, (2001).
- Yan, H., "Nucleic acid nanotechnology", *Science*, vol. 306, pp. 2048-2049, (2004).
- Yang, W. H. et al., "Discrete dipole approximation for calculating extinction and raman intensities for small particles with arbitrary shapes", *J. Chem. Phys.*, vol. 103, pp. 869-875, (1995).
- Deng, Z. et al., "DNA-Encoded self-assembly of gold nanoparticles into one-dimensional arrays", *Angew. Chem. Int. Ed.*, vol. 44, pp. 3582-3585, (2005).
- Zhao, W. et al., "Simple and rapid colorimetric biosensors based on DNA aptamer and noncrosslinking gold nanoparticle aggregation", *ChemBioChem*, vol. 8, pp. 727-731, (2007).
- Zhao, W. et al., "Highly stabilized nucleotide-capped small gold nanoparticles with tunable size", *Advanced Materials*, vol. 19, pp. 1766-1771, (2007).
- Zhao, W. et al., "DNA polymerization on gold nanoparticles through rolling circle amplification: towards novel scaffolds for three-dimensional periodic nanoassemblies", *Angew. Chem. Int. Ed.*, vol. 45, pp. 2409-2413, (2006).
- Zhao, W. et al., "DNA aptamer folding on gold nanoparticles: from colloid chemistry to biosensors", *J. Am. Chem. Soc.*, vol. 130, (11), pp. 3610-3618, (2008).
- Zhou, P. et al., "Extraction of oxidized and reduced forms of uranium from contaminated soils: effects of carbonate concentration pH", *Environmental Science Technology*, vol. 39, No. 12, pp. 4435-4440, (2005).
- Jacoby, M., "Sensitive, selective mercury sensor nanoparticle-based colorimetric method detects part-per-billion levels of mercury", *Chemical & Engineering News*, pp. 1-3, May 2, 2007.
- Cruz, R.P.G. et al., supplemental to "Dinucleotide junction cleavage versatility of 8-17 deoxyribozyme", *Chemistry & Biology*, vol. 11, pp. 57-67, (pp. 1-8) (2004).
- Saleh, O. A. et al., "Direct detection of antibody-antigen binding using an on-chip artificial pore", *Proceedings of the National Academy of Science*, vol. 100, No. 3, pp. 820-824, (2003).
- Han, C. et al., "Highly selective and sensitive colorimetric probes for Yb<sup>3+</sup> ions based on supramolecular aggregates assembled from B-cyclodextrin-4,4'-dipyridine inclusion complex modified silver nanoparticles", *Chem. Commun.*, pp. 3545-3547, (2009).
- Aldaye, F.A., et al., "Sequential Self-Assembly of a DNA Hexagon as a Template for the Organization of Gold Nanoparticles", *Angew. Chem. Int. Ed.*, 45, pp. 2204-2209, 2006.
- Loweth, C.J. et al., "DNA-Based Assembly of Gold Nanocrystals", *Angew. Chem. Int. Ed.*, 38, No. 12, pp. 1808-1812, 1999.
- Carbone, A., et al., "Circuits and programmable self-assembling DNA structures", *Proceedings of the National Academy of Sciences of the United States of America*, vol. 99, No. 20, pp. 12577-12582, 2002.
- Chelyapov, N., et al., "DNA Triangles and Self-Assembled Hexagonal Tilings", *J. Am. Chem. Soc.*, 126, pp. 13924-13925, 2004.
- Conway, N.E., et al., "The Covalent Attachment of Multiple Fluorophores to DNA Containing Phosphorothioate Diesters Results in Highly Sensitive Detection of Single-Stranded DNA", *Bioconjugate Chem.*, 2, pp. 452-457, 1991.
- Ding, B., et al., "Pseudohexagonal 2D DNA Crystals from Double Crossover Cohesion", *J. Am. Chem. Soc.*, 126, pp. 10230-10231, 2004.
- Endo, M., et al., "DNA Tube Structures Controlled by a Four-Way-Branched DNA Connector", *Angew. Chem. Int. Ed.*, 44, pp. 6074-6077, 2005.
- Fidanza, J.A. et al. "Site-Specific Labeling of DNA Sequences Containing Phosphorothioate Diesters", *J. Am. Chem. Soc.*, 114, pp. 5509-5517, 1992.
- Goodman, R.P., et al., "Rapid Chiral Assembly of Rigid DNA Building Blocks for Molecular Nanofabrication", *Science*, 310, pp. 1661-1665, 2005.
- Hagleitner, C., et al., "Smart single-chip gas sensor microsystem", *Nature*, vol. 414, pp. 293-296, 2001.
- He, Y., et al., "Sequence Symmetry as a Tool for Designing DNA Nanostructures", *Angew. Chem. Int. Ed.*, 44, pp. 6694-6696, 2005.
- Heath, J.R., et al., "A Defect-Tolerant Computer Architecture: Opportunities for Nanotechnology", *Science*, vol. 280, pp. 1716-1719, 1998.
- Holloway, G., et al., "An Organometallic Route to Oligonucleotides Containing Phosphoroselenoate", *ChemBioChem*, 3, pp. 1061-1065, 2002.
- Li, H., et al., "DNA-Templated Self-Assembly of Protein and Nanoparticle Linear Arrays", *J. Am. Chem. Soc.*, 126, pp. 418-419, 2004.
- Cunningham, L., et al., "Spectroscopic Evidence for Inner-Sphere Coordination of Metal Ions to the Active Site of a Hammerhead Ribozyme", *J. Am. Chem. Soc.*, 120, pp. 4518-4519, 1998.



- Ludueno, R.F., et al., N,N-Bis( $\alpha$ -iodoacetyl)-2,2'-dithiobis(ethylamine), a Reversible Crosslinking Reagent for Protein Sulfhydryl Groups, *Analytical Biochemistry*, 117, pp. 76-80, 1981.
- Lund, K., et al., "Self-Assembling a Molecular Pegboard", *J. Am. Chem. Soc.*, 127, pp. 17606-17607, 2005.
- Mathieu, F., et al., "Six-Helix Bundles Designed from DNA", *Nano Letters*, vol. 5, No. 4, pp. 661-665, 2005.
- Liu, H., et al., "Approaching the Limit: Can One DNA Oligonucleotide Assemble into Large Nanostructures?", *Angew. Chem.*, 118, pp. 1976-1979, 2006.
- Fidanza, J. et al., "Introduction of Reporter Groups at Specific Sites in DNA Containing Phosphorothioate Diesters", *J. Am. Chem. Soc.*, 111, pp. 9117-9119, 1989.
- Nakao, H., et al., "Highly Ordered Assemblies of Au Nanoparticles Organized on DNA", *Nano Letters*, vol. 3, No. 10, pp. 1391-1394, 2003.
- Patolsky, F., et al., "Au-Nanoparticle Nanowires Based on DNA and Polylysine Templates", *Angew. Chem. Int. Ed.*, 41, No. 13, pp. 2323-2327, 2002.
- Pinto, Y., et al., "Sequence-Encoded Self-Assembly of Multiple-Nanocomponent Arrays by 2D DNA Scaffolding", *Nano Letters*, vol. 5, No. 12, pp. 2399-2402, 2005.
- Rothmund, P., "Folding DNA to create nanoscale shapes and patterns", *Nature*, vol. 440, pp. 297-302, 2006.
- Yang, X., et al., "Ligation of DNA Triangles Containing Double Crossover Molecules", *J. Am. Chem. Soc.*, 120, pp. 9779-9786, 1998.
- Seeman, N.C., "Nucleic Acid Nanostructures and Topology", *Angew. Chem. Int. Ed.*, 37, pp. 3220-3238, 1998.
- Seeman, N. C., "At the Crossroads of Chemistry, Biology, and Materials: Structural DNA Nanotechnology", *Chemistry & Biology*, vol. 10, pp. 1151-1159, 2003.
- Le, J.D., et al., "DNA-Templated Self-Assembly of Metallic Nanocomponent Arrays on a Surface", *Nano Letters*, vol. 4, No. 12, pp. 2343-2347, 2004.
- Seeman, N.C., et al., "Nucleic acid nanostructures: bottom-up control of geometry on the nanoscale", *Reports on Progress in Physics*, 68, pp. 237-270, 2005.
- Warner, M.G., et al., "Linear assemblies of nanoparticles electrostatically organized on DNA scaffolds", *Nature Materials*, vol. 2, pp. 272-277, 2003.
- Winfrey, E., et al., "Design and self-assembly of two-dimensional DNA crystals", *Nature*, vol. 394, pp. 539-544, 1998.
- Woehrle, G.H., et al., "Molecular-Level Control of Feature Separation in One-Dimensional Nanostructure Assemblies Formed by Biomolecular Nanolithography", *Langmuir*, 20, pp. 5982-5988, 2004.
- Zhang, J., et al., "Periodic Square-Like Gold Nanoparticle Arrays Templated by Self-Assembled 2D DNA Nanogrids on a Surface", *Nano Letters*, vol. 6, No. 2, pp. 248-251, 2006.
- Yang, T. et al., "Tunneling Phase Logic Cellular Nonlinear Networks", *International Journal of Bifurcation and Chaos*, vol. 11, No. 12, pp. 2895-2911, 2001.
- Liu, Z., et al., "Imaging DNA Molecules on Mica Surface by Atomic Force Microscopy in Air and in Liquid", *Microscopy Research and Technique*, 66, pp. 179-185, 2005.
- Niemeyer, C.M., et al., "Covalent DNA-Streptavidin Conjugates as Building Blocks for Novel Biometallic Nanostructures", *Angew. Chem. Int. Ed.*, 37, No. 16, pp. 2265-2268, 1998.
- "What wavelength goes with a color" from eosweb. larc. Nasa.gov. Printed on Jan. 7, 2011.
- Cadmium sulfide from Wikipedia, the free encyclopedia. Printed on Jan. 7, 2011.
- Yeh et al., Quantum dot-mediated biosensing assays for specific nucleic acid detection. *Nanomedicine*, 1, 115-121, 2005.

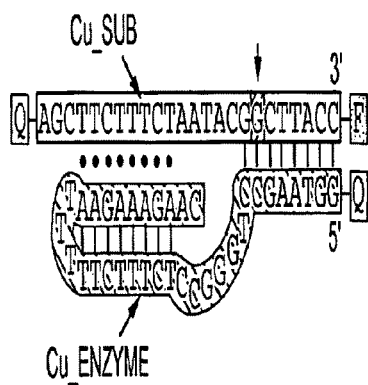


FIG. 1A

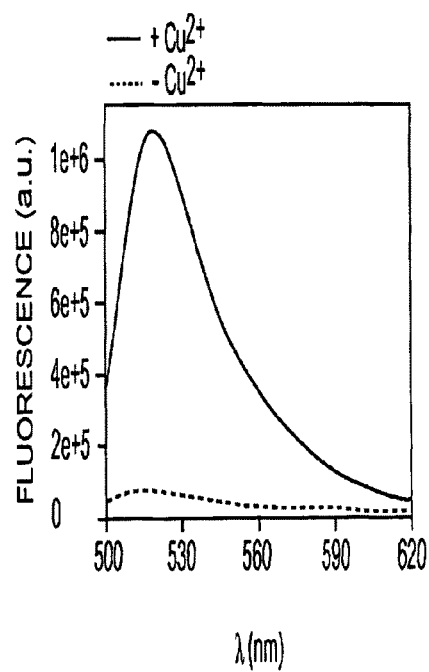


FIG. 1C

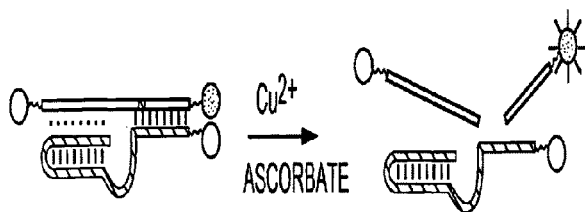


FIG. 1B

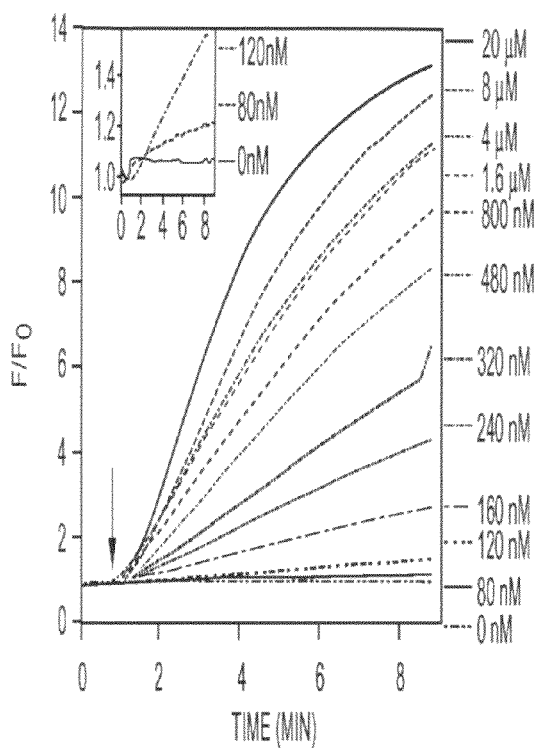


FIG. 2A

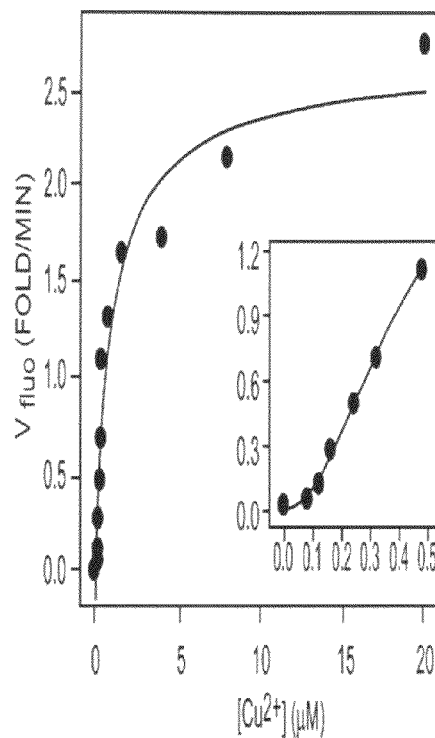


FIG. 2B

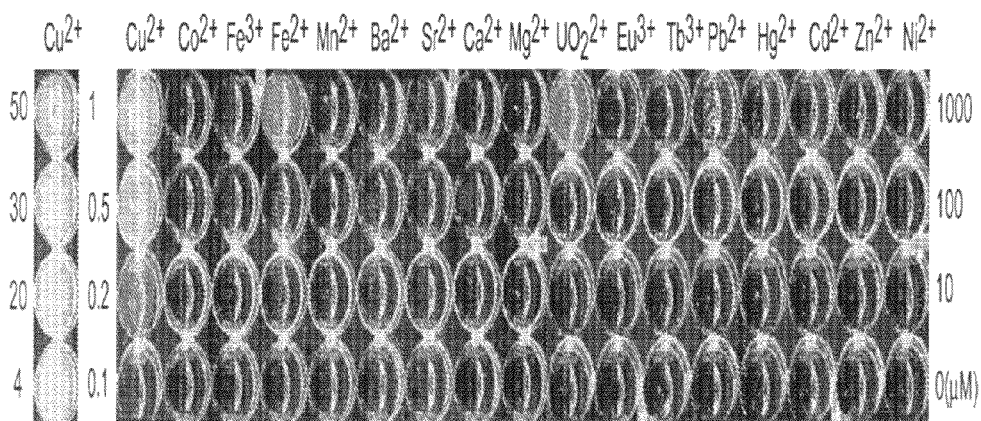


FIG. 2C

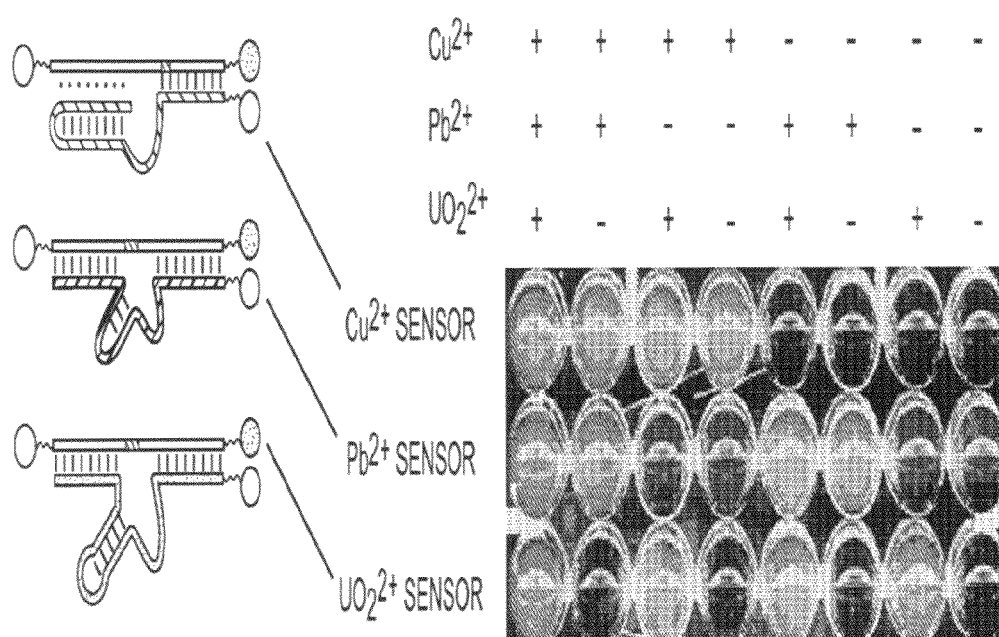


FIG. 3

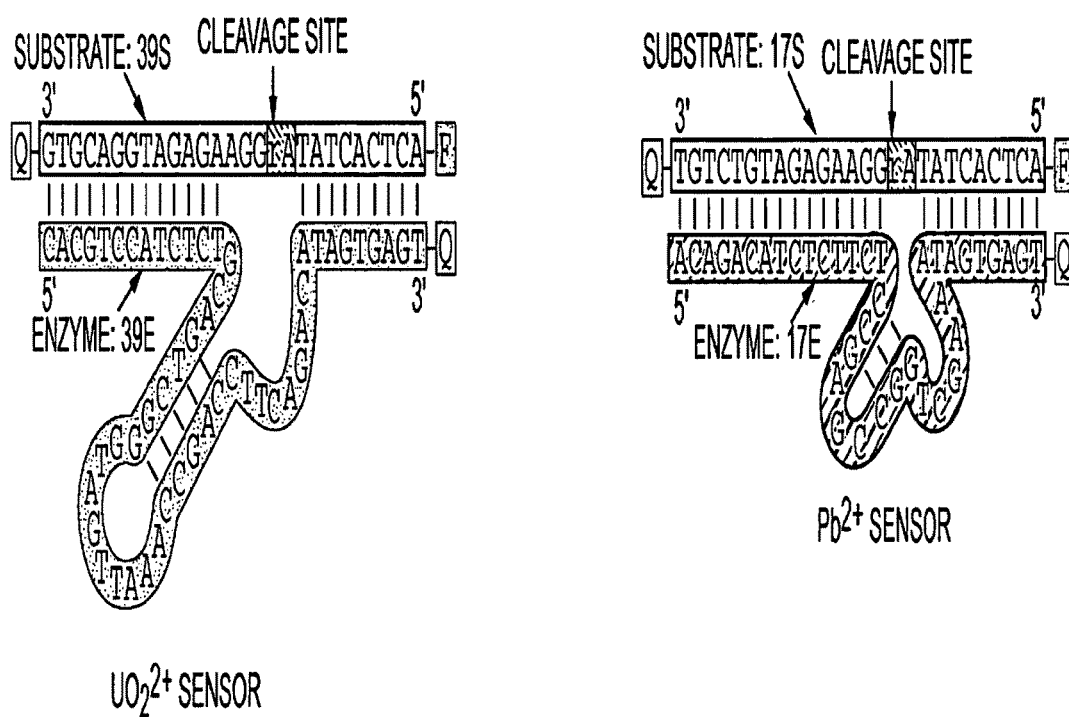


FIG. 4

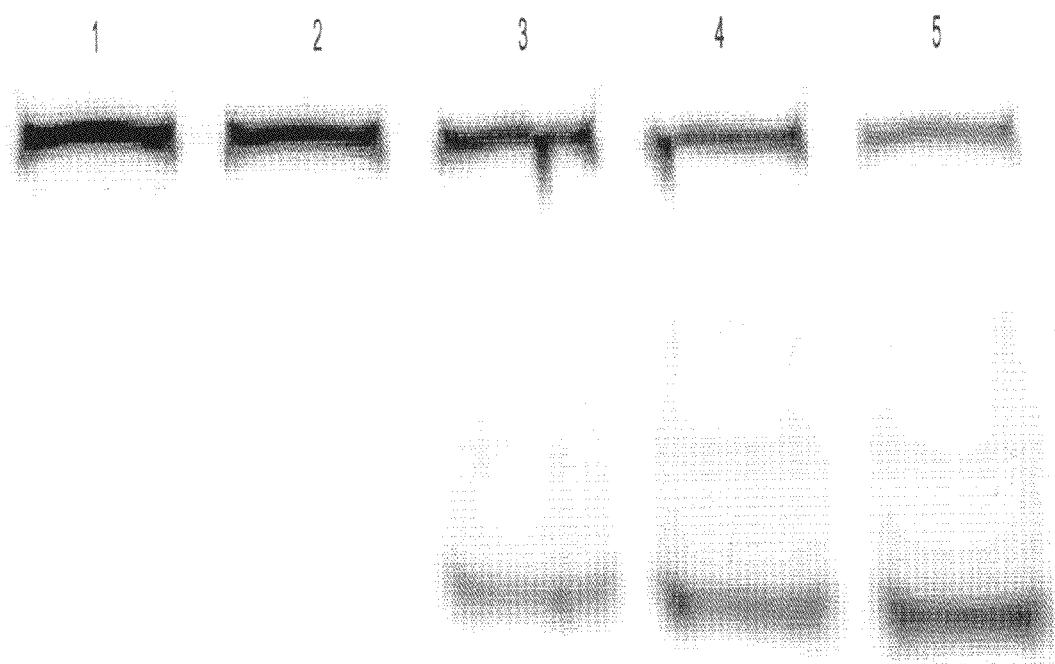


FIG. 5

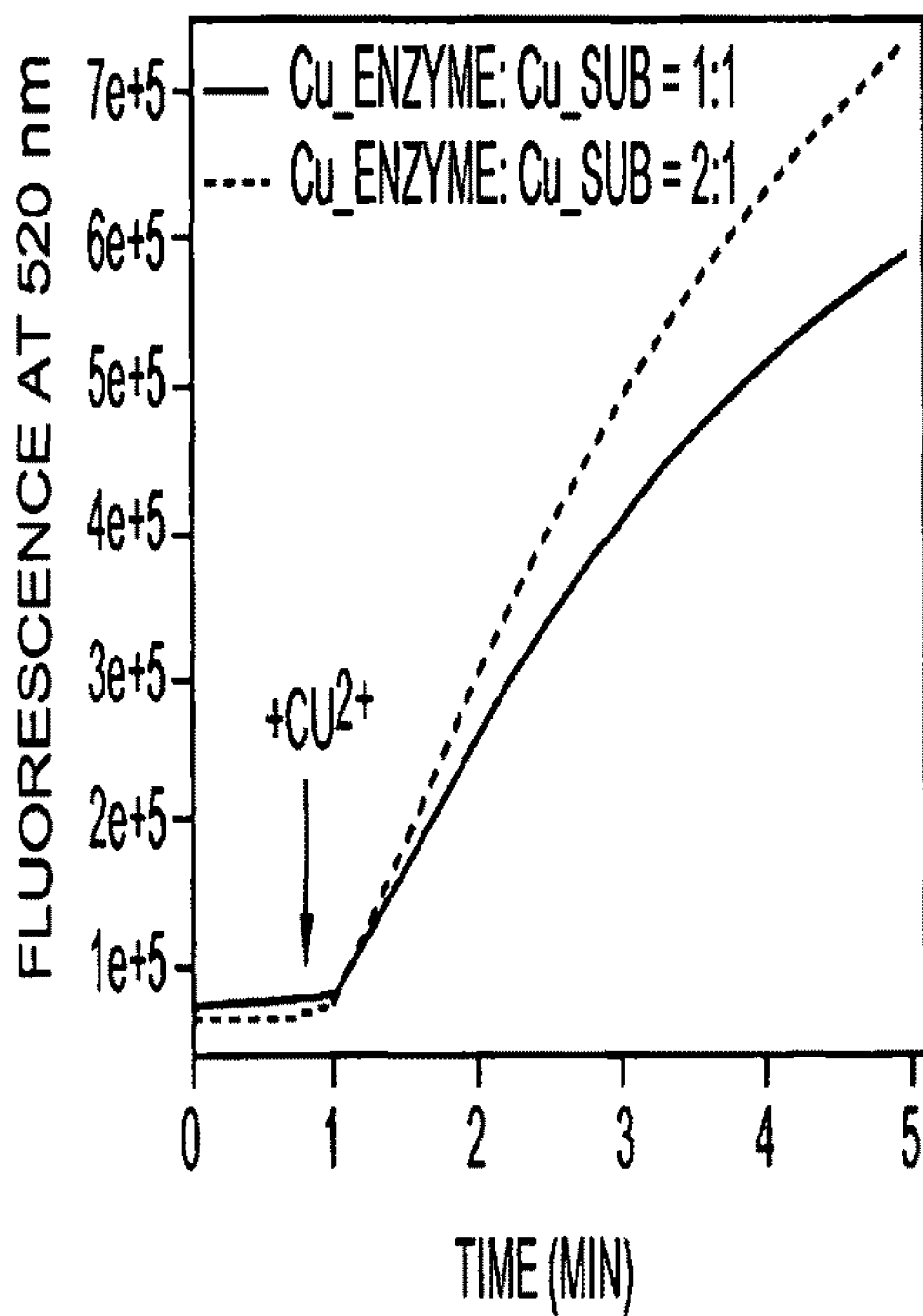


FIG. 6

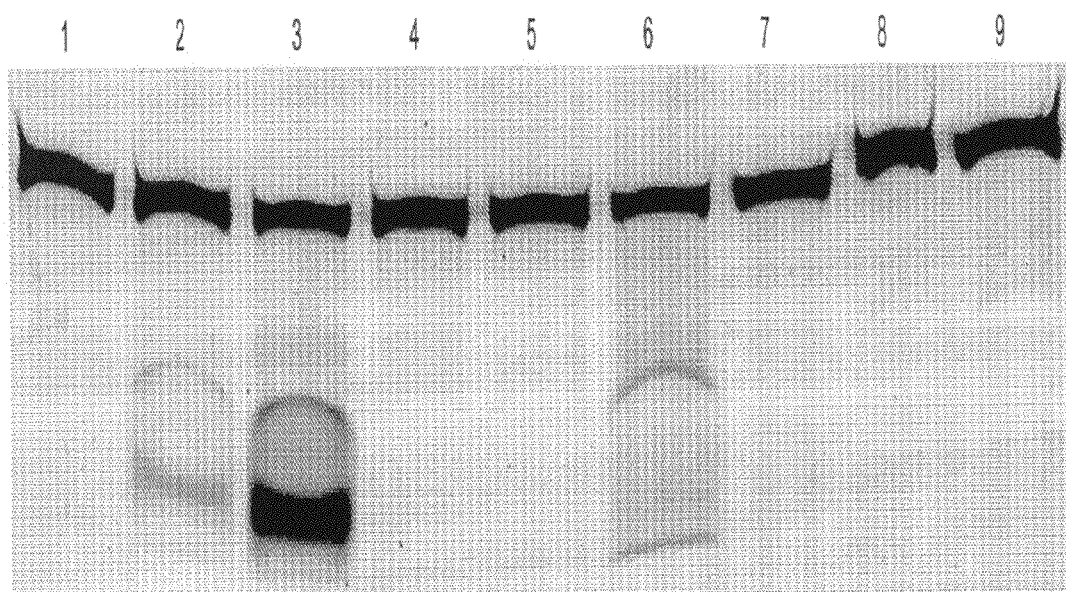


FIG. 7



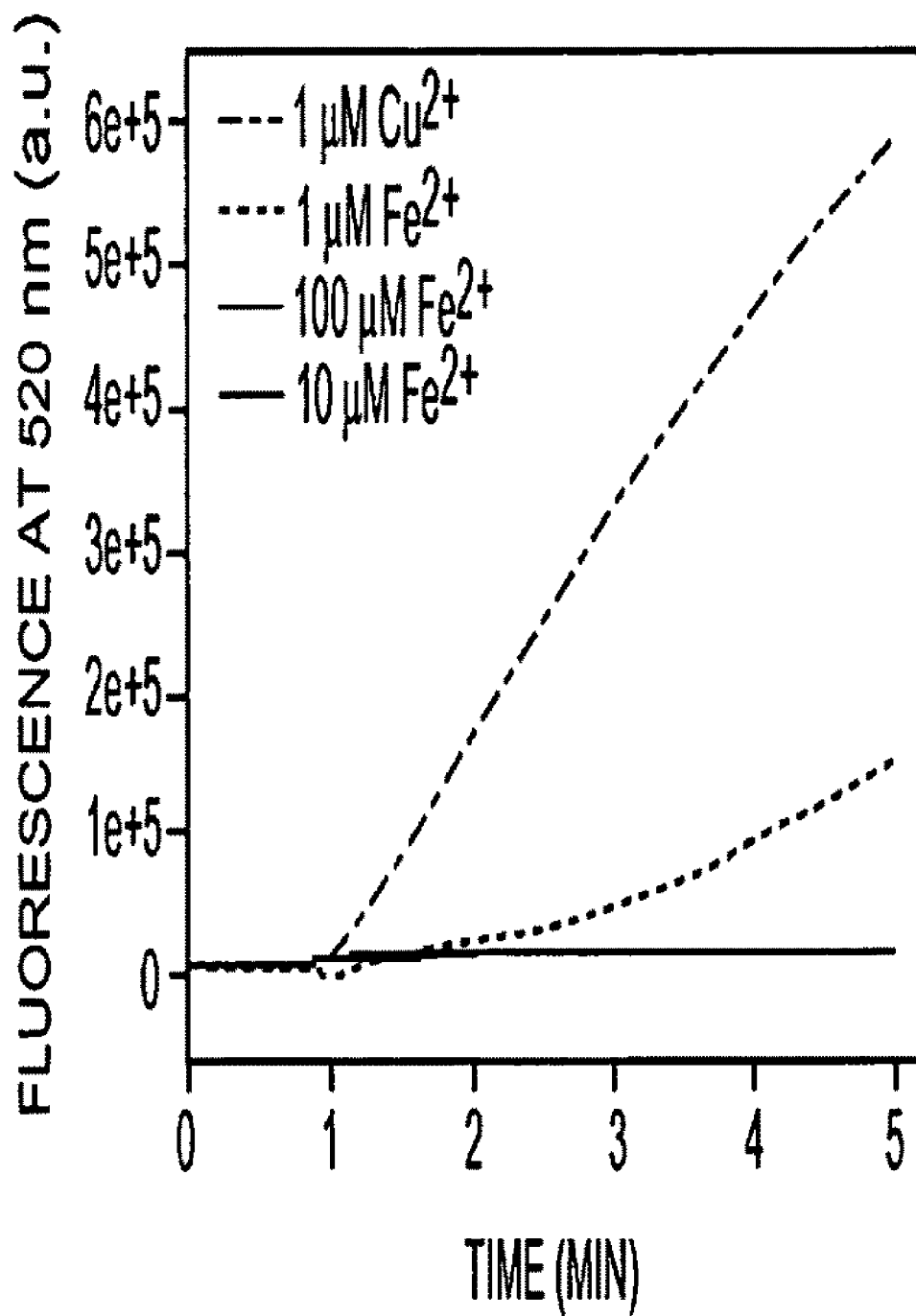


FIG. 8

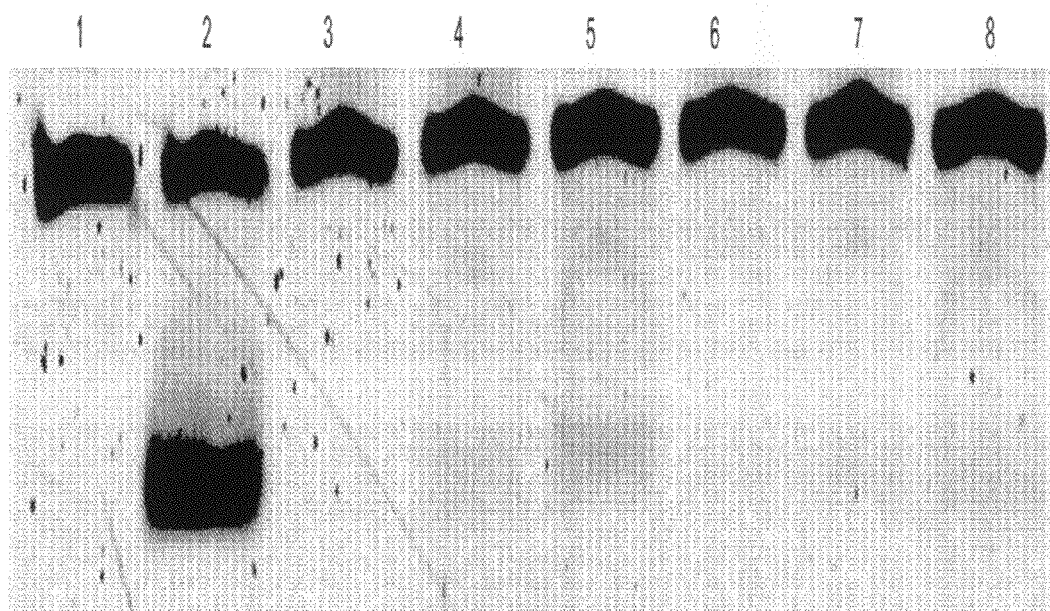


FIG. 9

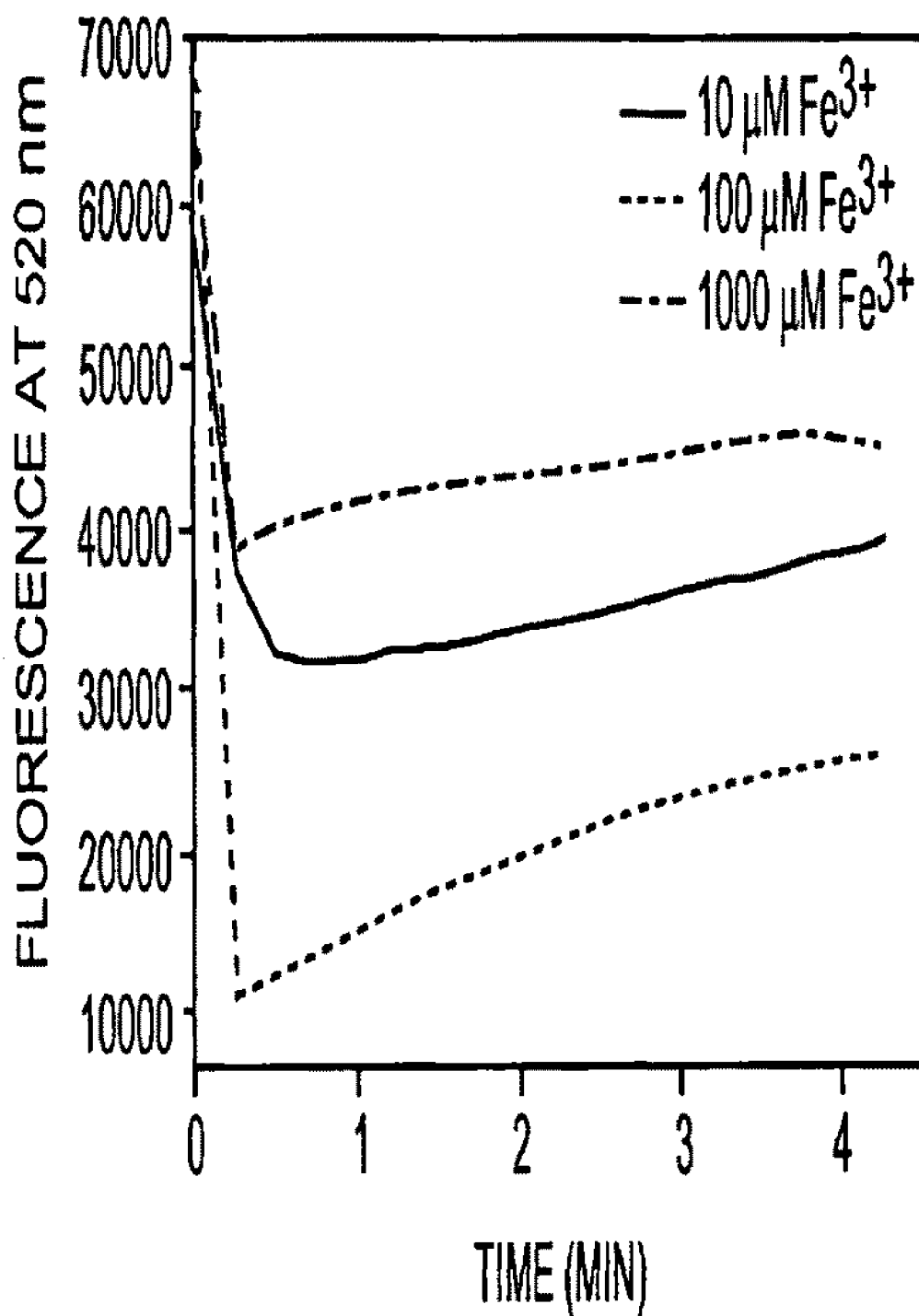


FIG. 10

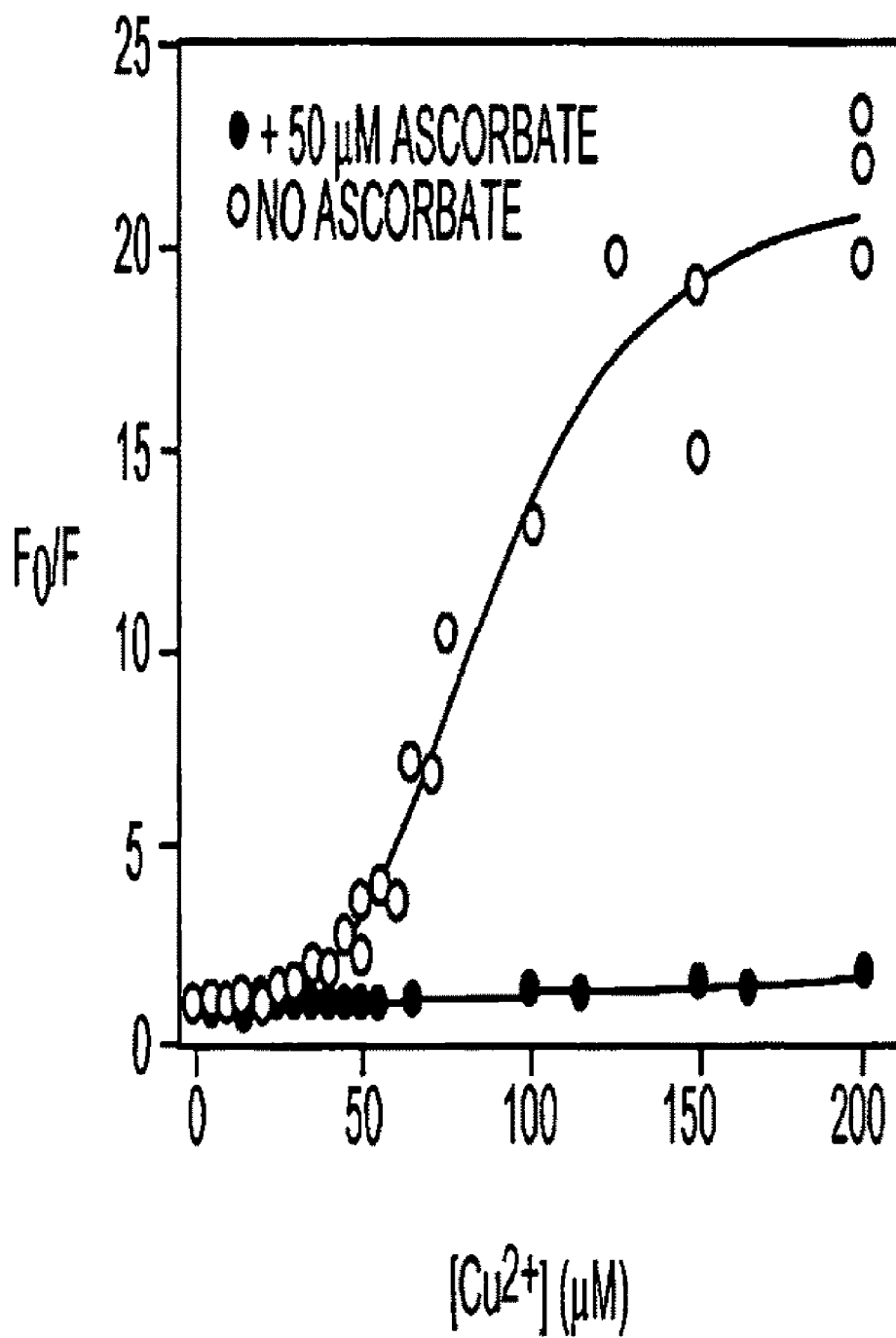


FIG. 11

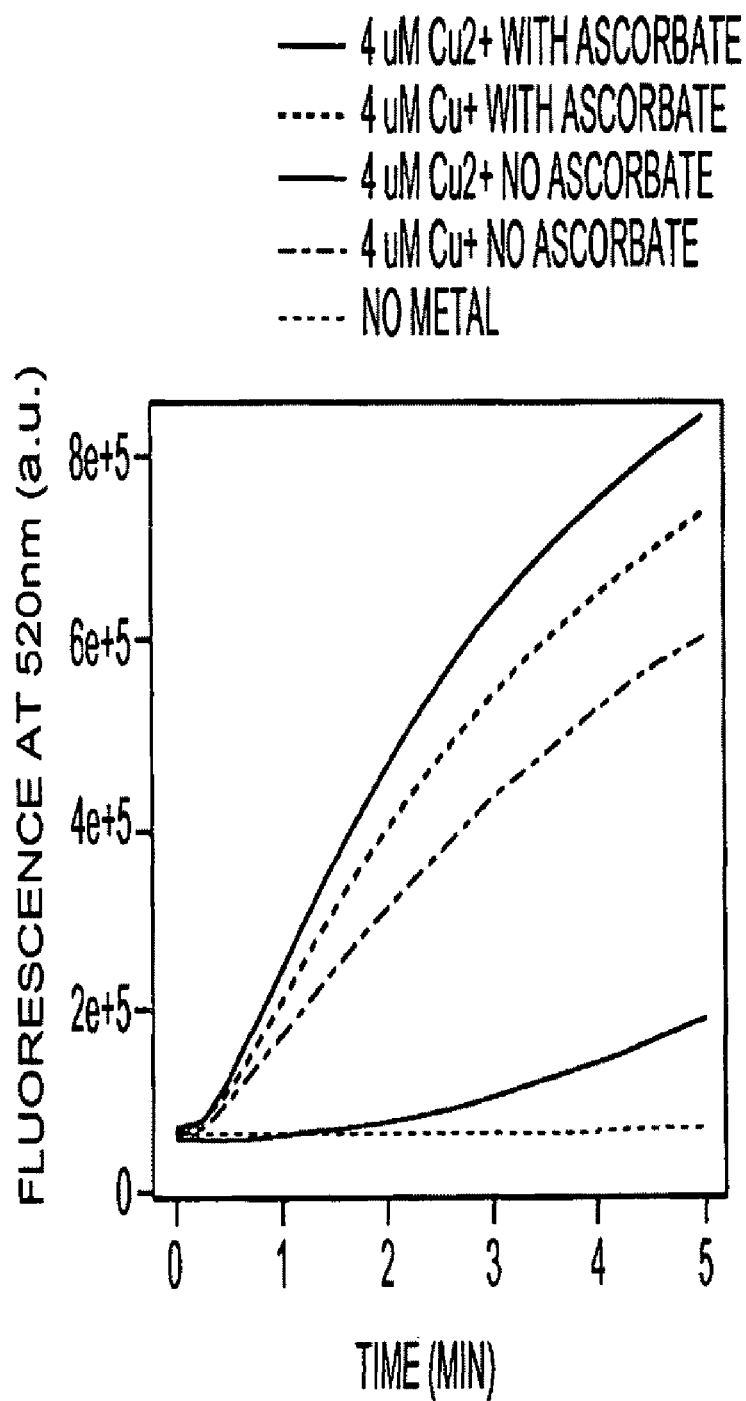


FIG. 12

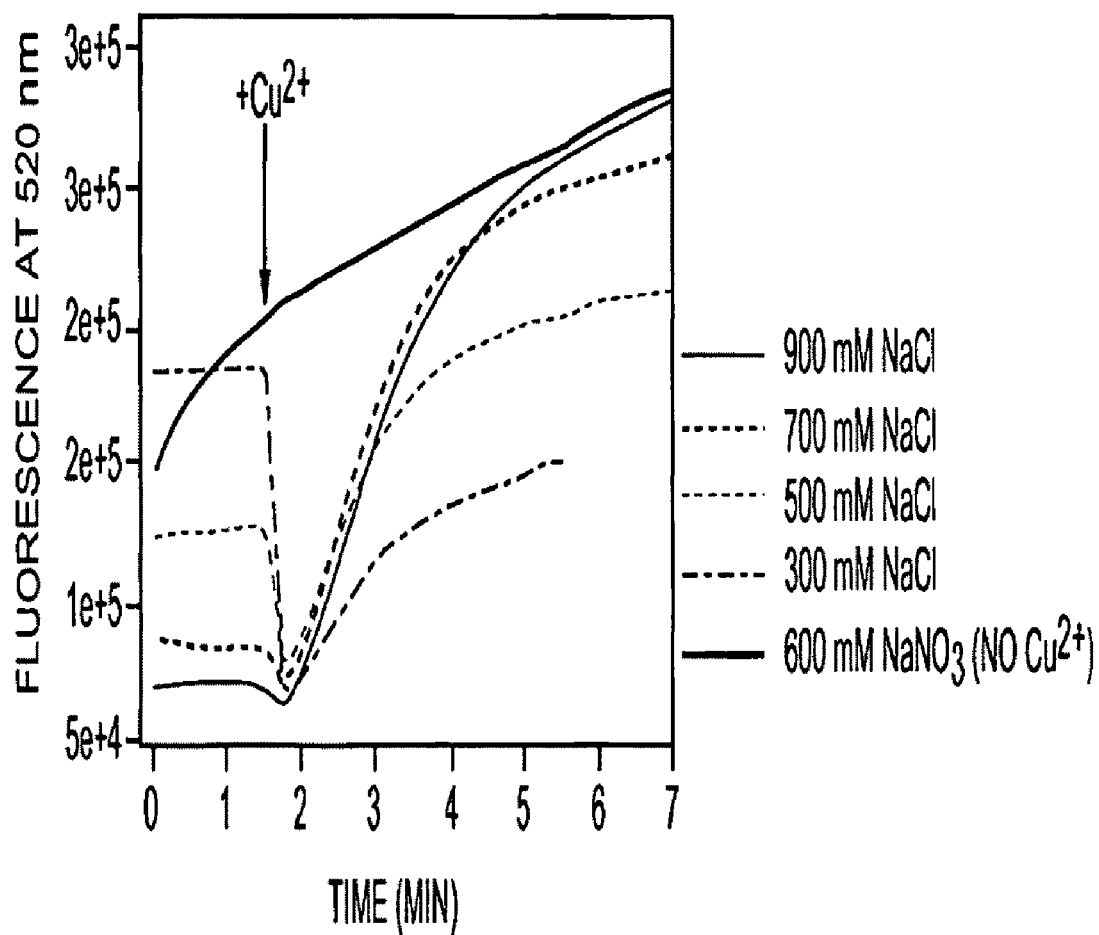


FIG. 13

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# NUCLEIC ACID BASED FLUORESCENT SENSOR FOR COPPER DETECTION

## CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to provisional application No. 60/950,062, entitled "NUCLEIC ACID BASED FLUORESCENT SENSOR FOR COPPER DETECTION" filed Jul. 16, 2007, the entire contents of which are hereby incorporated by reference, except where inconsistent with the present application.

## FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This subject matter of this application may have been funded in part under the following research grants and contracts: National Science Foundation Contract Numbers CTS-0120978 and DMI-0328162, and U.S. Department of Energy Contract Number DE-FG02-01-ER63179. The U.S. Government may have rights in this invention.

## BACKGROUND

Design of fluorescent metal sensors has recently become one of the most active research areas because the sensors can provide in situ and real-time information for a number of applications including environment monitoring, industrial process control, metalloneurochemistry, and biomedical diagnostics.<sup>1</sup> A widely used strategy is to link the metal recognition portion closely with a signal generation moiety such as a fluorophore. While quite successful in designing sensors for diamagnetic metal ions such as Pb<sup>2+</sup>, Hg<sup>2+</sup>, Zn<sup>2+</sup> and Cu<sup>+</sup>,<sup>2</sup> this method has been applied to paramagnetic metal ions such as Cu<sup>2+</sup> with only limited success, due to their intrinsic fluorescence quenching properties.<sup>3,4</sup> Most Cu<sup>2+</sup> sensors showed decreased emission upon Cu<sup>2+</sup> binding,<sup>3</sup> which was undesirable for analytical purposes. First, the room for signal change was at most one-fold. Second, such "turn-off" sensors may give false positive results by quenchers in real samples. Among the reported "turn-on" Cu<sup>2+</sup> sensors,<sup>4</sup> few have nanomolar sensitivity,<sup>4a,d,f,g</sup> with high selectivity,<sup>4a,d</sup> and are free of organic solvents.<sup>4a</sup>

One way to circumvent this quenching problem is to spatially separate the metal recognition part from the fluorescent signaling moiety so that they are independent of each other. A significant challenge then is to transduce metal binding to signal enhancement when the two parts are well separated. Previously reported was a novel metal sensing platform with DNAzyme catalytic beacons that spatially separated the two parts by rigid double-stranded DNA,<sup>5,6</sup> and sensors for diamagnetic metal ions such as Pb<sup>2+</sup> and UO<sub>2</sub><sup>2+</sup> have been demonstrated.<sup>7,8</sup>

Copper is a widely used metal that can leak into the environment through various routes. Low concentration copper is an essential nutrient. However, exposure to high level of copper even for a short period of time can cause gastrointestinal disturbance; while long term exposure causes liver or kidney damage.<sup>9</sup> The U.S. Environmental Protection Agency (EPA) set the limit of copper in drinking water to be 1.3 ppm (~20 μM).

## SUMMARY

In a first aspect, the present invention is a nucleic acid enzyme responsive to copper, comprising an oligonucleotide

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comprising a nucleotide sequence of SEQ ID NO:1. The nucleic acid enzyme is not self-cleaving.

In a second aspect, the present invention is a nucleic acid enzyme responsive to copper, comprising: an oligonucleotide comprising a nucleotide sequence of SEQ ID NO:1, and a quencher, attached at a 3' end of the nucleic acid enzyme.

In a third aspect, the present invention is a sensor system for determining an amount of copper in a sample, comprising a nucleic acid enzyme responsive to copper, a substrate for the nucleic acid enzyme, a quencher attached to the substrate, and a fluorophore, attached to the substrate.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1. (A) The secondary structure of the Cu<sup>2+</sup> sensor DNAzyme. F and Q denote fluorophore and quencher, respectively. The cleavage site is indicated by an arrow. Top strand is shown in SEQ ID NO: 6, bottom strand in SEQ ID NO: 5. (B) Signal generation scheme of the Cu<sup>2+</sup> catalytic beacon. (C) Fluorescence spectra of the sensor before and 10 min after addition of 20 μM Cu<sup>2+</sup>.

FIG. 2. (A) Kinetics of fluorescence increase over background at varying Cu<sup>2+</sup> levels. The arrow indicates the point of Cu<sup>2+</sup> addition. Inset: responses at low Cu<sup>2+</sup> levels. (B) The rate of fluorescence enhancement plotted against Cu<sup>2+</sup> concentration. Inset: rates at the low Cu<sup>2+</sup> region. (C) Sensor selectivity. The buffer contained 1.5 M NaCl, 50 mM HEPES, pH 7.0, and 50 μM ascorbate. Cu<sup>2+</sup> concentrations were labeled on the left side of each well while others were on the right end (in μM).

FIG. 3. Responses of a DNAzyme sensor array to metal mixtures.

FIG. 4. Sequences and modifications of the DNAzyme-based UO<sub>2</sub><sup>2+</sup> and Pb<sup>2+</sup> sensors. In both sensors, the 5'-F denotes a FAM fluorophore. The 3'-Q on the substrate strands denotes a Black Hole Quencher. The 3'-Q on the enzyme strands denotes for a Black Hole Quencher and a Dabcyl for the UO<sub>2</sub><sup>2+</sup> sensor and the Pb<sup>2+</sup> sensor, respectively. Top strand of the UO<sub>2</sub><sup>2+</sup> sensor is shown in SEQ ID NO: 9, bottom strand in SEQ ID NO: 10 and the top strand of the Pb<sup>2+</sup> sensor is shown in SEQ ID NO: 11, bottom strand in SEQ ID NO: 12.

FIG. 5. Gel-based assay of the sensor DNAzyme. Lanes 2 to 5 are 0, 5, 10, and 25 min after addition of Cu<sup>2+</sup>, respectively.

FIG. 6. The effect of enzyme to substrate ratio on signal enhancement. The Cu<sup>2+</sup> concentration was 4 μM and the experiments were performed in parallel to have a fair comparison. Other conditions are the same as previously described.

FIG. 7. Gel-based assay on Fe<sup>2+</sup> and UO<sub>2</sub><sup>2+</sup> cleavage of the Cu<sup>2+</sup> sensor DNAzyme.

FIG. 8. Kinetics of the Cu<sup>2+</sup> sensor fluorescence enhancement in the presence of 1 μM Cu<sup>2+</sup> or varying concentrations of Fe<sup>2+</sup>.

FIG. 9. Gel-based assay on Fe<sup>3+</sup> cleavage of the Cu<sup>2+</sup> sensor DNAzyme.

FIG. 10. Kinetics of the Cu<sup>2+</sup> sensor fluorescence enhancement in the presence of varying concentrations of Fe<sup>3+</sup>.

FIG. 11. Stern-Volmer plot of a FAM-labeled double stranded DNA quenched by Cu<sup>2+</sup>. The DNA concentration was 10 nM for the FAM-labeled DNA and 20 nM for its complementary DNA strand (annealed in the same buffer as Cu<sup>2+</sup> detection). The sequence of the 5'-FAM labeled 20-mer DNA was: FAM-5'-ACTCACTATAGGAAGAGATG-3' (SEQ ID NO: 8).

FIG. 12. Comparing Cu<sup>2+</sup> and Cu<sup>+</sup> and the effect of ascorbate on the rate of cleavage of the DNAzyme.

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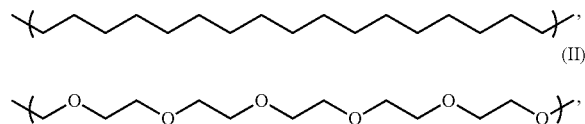
FIG. 13. The effect of anions in the sensor system. Dash curves are the kinetics with varying concentration of NaCl ( $\text{Cu}^{2+}$  added at the time indicated by the arrow) and the solid curve is the background fluorescence with  $\text{NaNO}_3$  (no  $\text{Cu}^{2+}$  added). For all the samples with NaCl, the background levels were stable. For the sample with  $\text{NaNO}_3$ , however, the background was not stabilized (no  $\text{Cu}^{2+}$  added for the curve). Therefore, NaCl was used in the sensor system.

## DETAILED DESCRIPTION

The present invention makes use of the discovery of a new nucleic acid enzyme, which may be used in a sensor system for Cu, and in a method of determining the concentration of copper in a sample, especially in the presence of other ions. The sequence of the nucleic acid enzyme is indicated in the table below, along a specific example of the nucleic acid enzyme, the substrate for the enzyme, and an example of the substrate. For comparison, the DNAzyme of Breaker et al. and the substrate for this DNAzyme are also included in the table. R, Y and n represent purine, pyrimidine and any nucleotide, respectively. X, X' and X" each indicate an optional spacer, F indicates a fluorophore, and Q indicates a quencher. In the table, m is at least 7, u is 0 or 1, w is 0 to 3, y is 0 or 1, and z is 0 or 1.

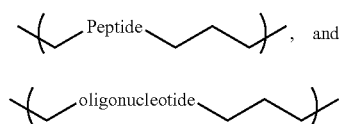
Nucleic acid enzyme for copper (consensus sequences)	3' CAR RRR RRR Rnn nYY YYY YYY CCG GGT Cnn nnn nn 5'	SEQ ID NO: 1
Nucleic acid enzyme for copper	3' CAR RRR RRR Rnn nYY YYY YYY CCG GGT Cn <sub>m</sub> 5'	SEQ ID NO: 2
Nucleic acid enzyme for copper, with quencher	3' CAR RRR RRR Rnn nYY YYY YYY CCG GGT Cn <sub>m</sub> X <sub>z</sub> -Q 5'	SEQ ID NO: 3
Substrate for nucleic acid enzyme, with fluorophore and quencher.	3' F-X',n <sub>m</sub> G CAT AAY YYY YYY Yn <sub>w</sub> -X"-Q	SEQ ID NO: 4
Example of nucleic acid enzyme	3' CAA GAA AGA ATT TTT CTT TCT CCG GGT CCG AAT GG-Q 5'	SEQ ID NO: 5
Example of substrate for nucleic acid enzyme	3' F-CCA TTC GGC ATA ATC TTT CTT CGA-Q 5'	SEQ ID NO: 6
Self cleaving Breaker et al. nucleic acid enzyme and substrate	3' CAA GAA TTT TTC TCC GGG TCT GAG TAA GAC TCA GCA TAA TCT TAA G 5'	SEQ ID NO: 7

X, X' and X" each indicate an optional spacer. The spacer is preferably an organic group, such as an alkanene, alkenene, alkynene, arylene, polyether, peptide, oligonucleotide, or combinations thereof. Examples include the following:



4

-continued



The subscript m is at least 7, and preferably is 7 to 100, more preferably 7 to 50, even preferably 7 to 20, and most preferably 7 to 15.

F indicates a fluorophore, and Q indicates a quencher. Essentially any fluorophore may be used, including BODIPY, fluorescein, fluorescein substitutes (Alexa Fluor dye, Oregon green dye), long wavelength dyes, and UV-excited fluorophores. These and additional fluorophores are listed in Fluorescent and Luminescent Probes for Biological Activity. A Practical Guide to Technology for Quantitative Real-Time Analysis, Second Ed. W. T. Mason, ed. Academic Press (1999)<sup>16</sup>. In preferred embodiments, the fluorophore is 6-carboxyfluorescein (FAM). FAM has an excitation range of 460-500 nm.

Other fluorophores included quantum dots and silica nanoparticles. Each type of quantum dot displays a unique emission wavelength. Preferred quantum dot particles include quantum dot semiconductors, such as CdS, CdSe, CdTe, ZnS, ZnSe, ZnTe, In, and PbSe. Additional preferred quantum dots may include ternary quantum dots, such as  $\text{Cd}_x\text{Zn}_{1-x}\text{Se}$  or  $\text{CdS}_x\text{Se}_{1-x}$ . Additional preferred quantum dots may include core-shell quantum dots, such as those having a CdSe core and ZnS shell. The quantum dots can also have different morphologies, including dots, rods, tetrapods, and the like. In a preferred aspect, the particles are quantum dot semiconductors having average diameter from 2 to 50 nanometers.

A quencher is a molecule that absorbs the energy of the excited fluorophore. Close proximity of a fluorophore and a quencher allow for the energy to be transferred from the fluorophore to the quencher. By absorbing this energy, the quencher prevents the fluorophore from releasing the energy in the form of a photon, thereby preventing fluorescence.

Quenchers may be categorized as non-fluorescent and fluorescent quenchers. Non-fluorescent quenchers are capable of quenching the fluorescence of a wide variety of fluorophores. Generally, non-fluorescent quenchers absorb energy from the fluorophore and release the energy as heat. Examples of non-fluorescent quenchers include 4-(4'-dimethylaminophenylazo)benzoic acid (Dabcyl), QSY-7, and QSY-33.

Fluorescent quenchers tend to be specific to fluorophores that emit at a specific wavelength range. Fluorescent quenchers often involve fluorescence resonance energy transfer (FRET). In many instances the fluorescent quencher molecule is also a fluorophore. In such cases, close proximity of the fluorophore and fluorescent quencher is indicated by a decrease in fluorescence of the "fluorophore" and an increase in fluorescence of the fluorescent quencher. Commonly used fluorescent fluorophore pairs (fluorophore/fluorescent quencher) include fluorescein/tetramethylrhodamine, IAEDANS/fluorescein, fluorescein/fluorescein, and BODIPY FL/BODIPY FL.

When choosing a fluorophore, a quencher, or where to position these molecules, it is important to consider, and preferably to test, the effect of the fluorophore or quencher on the enzymatic activity of the nucleic acid enzyme. Also, it is preferable that the fluorophore display a high quantum yield and energy transfer efficiency. Long-wavelength (excitation and emission) fluorophores are preferred because of less



interference from other absorbing species. The fluorophore should also be less sensitive to pH change or to non-specific quenching by metal ions or other species.

Methods and devices for detecting fluorescence are well developed. Essentially any instrument or method for detecting fluorescent emissions may be used. For example, WO 99/27351 describes a monolithic bioelectrical device comprising a bioreporter and an optical application specific integrated circuit (OASIC).<sup>17</sup> The device allows remote sampling for the presence of substances in solution. Furthermore, the fluorescence may be measured by a number of different modes. Examples include fluorescence intensity, lifetime, and anisotropy in either steady state or kinetic rate change modes.<sup>18</sup>

Sometimes other factors in a solution such as pH, salt concentration or ionic strength, or viscosity will have an effect on fluorescence, and may even affect the hybridization of the substrate and enzyme. Therefore, in preferred methods, controls are run to determine if the solution itself, regardless of enzymatic activity, is altering the fluorescence. Such controls include the use of non-cleavable substrates and or substrate without the presence of enzyme.

The sensor system may be used to determine an amount of copper in a sample, such as a water sample, a biological sample (such as blood or serum), or a solid sample, such as soil or paint. Preferably, a solid sample is first dissolved into solution. The samples may be diluted or concentrated prior to testing, and may also be buffered. The sensor system is able to determine an amount of copper in the presence of other ions, preferably other metal ions, such as  $Pb^{2+}$ , or in the presence of other transition metal ions.

The sensor system may also contained ascorbate, because it can significantly enhance the reaction rate. The sensor will operate without ascorbate, but preferably ascorbate is included. Another difference, as compared to prior sensor systems, such as those used to detect  $Pb^{2+}$ , is that the substrate does not require a ribonucleotide as a condition for cleavage; the mechanism of the nucleic acid enzyme responsive to copper is oxidative, while previous sensors cleaved substrates by hydrolysis.

A  $Cu^{2+}$ -dependent DNA-cleaving DNzyme reported by Breaker et al. is known and has a reported consensus sequence; the sequence of the self-cleaving DNzyme is included in the table.<sup>10-12</sup> Based on the original DNzyme sequences, we rationally designed a  $Cu^{2+}$  sensor as shown in FIG. 1A. The sensor contained two DNA strands that formed a complex. The substrate ( $Cu\_sub$ ) was labeled with a FAM fluorophore (6-carboxyfluorescein) on the 3'-end, and a quencher (Iowa Black FQ) on the 5'-end; while the enzyme ( $Cu\_enzyme$ ) contained a 5'-quencher. Such a dual-quencher approach was employed to suppress background signals.<sup>13</sup> The substrate and enzyme associate through two base pairing regions. The 5' portion of the enzyme binds the substrate via Watson-Crick base pairs; while the 3' region through formation of a DNA triplex. Initially, the FAM emission was quenched by the nearby quenchers. In the presence of  $Cu^{2+}$ , the substrate was irreversibly cleaved at the cleavage site (the guanine indicated by the arrow). Following cleavage, it has been hypothesized that the cleaved pieces were released due to decreased affinities to the enzyme, leading to increased fluorescence (FIG. 1B). This hypothesis was supported by the observation that the FAM emission increased by ~13-fold after addition of  $Cu^{2+}$  (FIG. 1C). Such a signal generation method was termed catalytic beacon because the involvement of catalytic reactions.<sup>7,8</sup>

The sensor system also contained 50  $\mu M$  ascorbate, because it can significantly enhance the reaction rate (FIG.

12).<sup>10-12</sup> Ascorbate was also useful for suppressing quenching. For example, FAM quenching was <15% with 50  $\mu M$   $Cu^{2+}$  (FIG. 11).

To test sensitivity, the kinetics of fluorescence increase at 520 nm in the presence of varying concentrations of  $Cu^{2+}$  were monitored. As shown in FIG. 2A, fluorescence enhancement rates were higher with increasing levels of  $Cu^{2+}$ . The rates in the time window of 2 to 4 min were plotted in FIG. 2B. A detection limit of 35 nM (2.3 ppb) was determined, which represents one of the most sensitive "turn-on"  $Cu^{2+}$  sensors.<sup>4a,d,f,g</sup> The sensor has a dynamic range up to 20  $\mu M$ , which is useful for detecting  $Cu^{2+}$  in drinking water, because the U.S. EPA has defined a maximum contamination level of 20  $\mu M$ . In addition to being highly sensitive and possessing "turn-on" signals, the sensor response was also fast, and quantitative results can be obtained within several minutes.

To test selectivity, 16 competing metal ions were assayed at three concentrations: 1 mM, 100  $\mu M$ , and 10  $\mu M$ . The assay was performed in a 96-well plate and emission intensities at 12-min after addition of metal ions were compared. As shown in FIG. 2C, besides  $Cu^{2+}$ , only the spots with 1 mM  $Fe^{2+}$  and 1 mM  $UO_2^{2+}$  lit up and the intensities were lower than that with 0.5  $\mu M$  of  $Cu^{2+}$ . Therefore, the sensor selectivity for  $Cu^{2+}$  was at least 2,000-fold higher than these two metals, and >10,000-fold higher than any other tested metal ions. The relatively high selectivity of  $Cu^{2+}$  over paramagnetic  $Fe^{2+}$  may be due to either lack of DNzyme recognition of  $Fe^{2+}$  as the DNzyme was in vitro selected for  $Cu^{2+}$ ,<sup>11,12</sup> or lack of  $H_2O_2$  in the sensor solution that is needed for  $Fe^{2+}$  to go through the Fenton chemistry for DNA cleavage.<sup>14</sup> In gel-based assays,  $UO_2^{2+}$  did not produce well-defined cleavage bands (FIG. 7). Therefore, the increased emission by  $UO_2^{2+}$  was attributed to DNA denaturation, although minor oxidative cleavage cannot be ruled out.<sup>15</sup>  $Cu^+$  is unstable in water and  $Cu^+$  was tested using  $[Cu(MeCN)_4](PF_6)_2$  in acetonitrile as a metal source. With ascorbate, the rate of fluorescence increase was similar to that with  $Cu^{2+}$  (FIG. 12). In the absence of ascorbate, both  $Cu^{2+}$  and  $Cu^+$  can induce fluorescence increase, with the rate with  $Cu^+$  being much faster. Therefore, it is likely that  $Cu^{2+}$  was reduced by ascorbate to  $Cu^+$ , which subsequently reacted with oxygen to oxidatively cleave DNA.  $Ag^+$  was not tested because the reaction buffer contained 1.5 M NaCl, which can form insoluble  $AgCl$ .  $Au^+$  was not tested because it is unstable in the open air aqueous solution. For testing environment samples, such as detection of  $Cu^{2+}$  in drinking water,  $Cu^+$  or  $Fe^{2+}$  is unlikely to interfere due to the oxidative aqueous environment.  $UO_2^{2+}$  is also unlikely to be present in millimolar concentration in drinking water.  $Fe^{3+}$  with ascorbate can also cleave the DNzyme. However, little fluorescence increase was observed due to the slow reaction rate and the quenching effect of  $Fe^{3+}$  (FIGS. 9 and 10). It needs to be pointed out that the previously reported lead and uranium sensors were based on hydrolytic RNA cleavage.<sup>7,8</sup> In the current copper DNzyme, the substrate was made completely of DNA and the cleavage was oxidative.<sup>10</sup>

Finally, a sensor array as shown in FIG. 3 was constructed. The array contained three rows and each row was loaded with a different DNzyme-based sensor. Eight metal mixtures were prepared with all the possible combinations among  $Cu^{2+}$ ,  $Pb^{2+}$  and  $UO_2^{2+}$  (1  $\mu M$  each). As can be observed from FIG. 3, the wells lit up only when the cognate metals were present and the metal compositions can be read directly from the array. We can imagine that larger metal sensor arrays can be built with the isolation of more metal-specific DNzymes.<sup>5</sup>

## EXPERIMENTAL DETAILS

Sensor preparation: in a typical experiment, 1  $\mu\text{M}$  of Cu\_Sub and 2  $\mu\text{M}$  of Cu\_Enzyme (see FIG. 1A in the paper for DNA sequences and modifications) were prepared in a buffer of 200  $\mu\text{L}$  volume containing 1.5 M NaCl, 50 mM HEPES, pH 7.0. The reason for using excess amount of the enzyme strand is given in FIG. 6. The mixture was warmed to 80° C. for 1 min and allowed to cool naturally to room temperature in 1 hour to anneal the DNAzyme. For each test, the annealed DNAzyme sensor (5  $\mu\text{L}$ ) was diluted into 490  $\mu\text{L}$  of buffer (1.5 M NaCl, 50 mM HEPES, pH 7.0) in a quartz cuvette with 0.5 cm path length on each side, and 5  $\mu\text{L}$  of 5 mM ascorbate was also added. The final Cu\_Sub concentration was 10 nM, the final Cu\_Enzyme concentration was 20 nM, and the final ascorbate concentration was 50  $\mu\text{M}$ .

Detection: the above prepared cuvette was vortexed to mix all the reagents and placed into a fluorometer (SPEX Fluoromax-P, Horiba Jobin Yvon). The cuvette was allowed to incubate in the cuvette holder of the fluorometer for 1 min before taking any measurement. The temperature of the fluorometer was set at 23° C. (around room temperature). The fluorometer was set at the kinetics mode by exciting at 490 nm and monitoring emission at 520 nm with 15 sec intervals. After the first 4 readings, the cuvette was quickly taken out and a small volume (0.5 to 3  $\mu\text{L}$ ) of concentrated metal stock solutions was added. The cuvette was rapidly vortexed to mix the metal with the sensor, and was then placed back into the fluorometer to continue the kinetics monitoring. The obtained kinetics traces were normalized to the fluorescence intensity before metal addition. The slope of fluorescence increase over background from 1 min to 3 min after  $\text{Cu}^{2+}$  addition was calculated and plotted against metal concentration (FIG. 2B).

96-well plate based selectivity assays: 5.4  $\mu\text{L}$  of 100  $\mu\text{M}$  Cu\_Sub and 10.8  $\mu\text{L}$  of 100  $\mu\text{M}$  Cu\_Enzyme were annealed in 400  $\mu\text{L}$  of buffer (1.5 M NaCl, 50 mM HEPES, pH 7.0). After annealing, the solution was diluted with 5 mL of the same buffer. Ascorbate was added to a final concentration of 50  $\mu\text{M}$ . Therefore, the final Cu\_Sub and Cu\_Enzyme concentrations were 100 nM and 200 nM, respectively. The sensor solution was spotted into three rows (each row contained 8 wells) of a 96-well-plate with 200  $\mu\text{L}$  in each well. Metal solutions at 2 $\times$  of designated concentrations were prepared in the same buffer with 50  $\mu\text{L}$  volume and were spotted in the plate. The sensor solution in the wells was taken out with an 8-channel pipet (each channel transferred 50  $\mu\text{L}$  of sensor solution) and added to the metal solutions. At 12 min after mixing, the plate was imaged with a Fuji fluorescence scanner (FLA-3000G, Fuji) by exciting at 473 nm and the filter was set at 520 nm. The metal salts used include:  $\text{MgCl}_2$ ,  $\text{CaCl}_2$ ,  $\text{SrCl}_2$ ,  $\text{BaCl}_2$ ,  $\text{Mn}(\text{OAc})_2$ ,  $\text{Fe}(\text{NH}_4)_2(\text{SO}_4)_2$ ,  $\text{FeCl}_3$ ,  $\text{CoCl}_2$ ,  $\text{NiCl}_2$ ,  $\text{Cu}(\text{NO}_3)_2$ ,  $\text{ZnCl}_2$ ,  $\text{Cd}(\text{ClO}_4)_2$ ,  $\text{Hg}(\text{ClO}_4)_2$ ,  $\text{Pb}(\text{NO}_3)_2$ ,  $\text{TbCl}_3$ ,  $\text{EuCl}_3$ , and  $\text{UO}_2(\text{OAc})_2$ . Under the reaction condition (pH 7.0, 1.5 M NaCl),  $\text{Fe}(\text{NH}_4)_2(\text{SO}_4)_2$  was quickly (within 5 min) oxidized into  $\text{Fe}^{3+}$  species and the color of the well turned from colorless to yellow. The well with  $\text{Fe}(\text{NH}_4)_2(\text{SO}_4)_2$ ,  $\text{FeCl}_3$ ,  $\text{Pb}(\text{NO}_3)_2$ , and  $\text{UO}_2(\text{OAc})_2$  formed visible precipitation.

Gel-based assays: 1  $\mu\text{M}$  of Cu\_Sub and 2  $\mu\text{M}$  of Cu\_Enzyme were annealed in 750 mM NaCl, 25 mM HEPES, pH 7.0. After annealing, 50  $\mu\text{M}$  of ascorbate was also added. Before addition of  $\text{Cu}^{2+}$ , a 10  $\mu\text{L}$  aliquot was taken out as the zero time point (lane 2 in the inset of FIG. 5). After adding  $\text{Cu}^{2+}$ , 10  $\mu\text{L}$  aliquots were taken out at designated time points and were quenched in a stop buffer containing 8 M urea, 50 mM EDTA, 0.05% xylene cyanol, and 50 mM Tris acetate, pH 8.2. A sample with only 1  $\mu\text{M}$  Cu\_Sub (no Cu\_Enzyme), 20  $\mu\text{M}$   $\text{Cu}^{2+}$ , and 50  $\mu\text{M}$  ascorbate was also prepared (lane 1

in the inset of FIG. 1C, incubated at room temperature for 1 hour before adding the stop buffer). The samples were loaded into 20% polyacrylamide gel electrophoresis to separate cleaved and uncleaved substrate. The gel was imaged with a fluorescence scanner (FLA-3000G, Fuji) by exciting at 473 nm and setting the emission filter at 520 nm.

Test of  $\text{Cu}^{2+}$ ,  $\text{Pb}^{2+}$ , and  $\text{UO}_2^{2+}$  DNAzymes: the design of the  $\text{Pb}^{2+}$  and  $\text{UO}_2^{2+}$  sensors have been described elsewhere and are also presented here in FIG. 4.<sup>7,8,13</sup> The  $\text{Cu}^{2+}$  sensor was prepared with a final Cu\_Sub concentration of 12 nM and Cu\_Enzyme of 24 nM in 1.5 M NaCl, 50 mM HEPES, pH 7.0, 50  $\mu\text{M}$  ascorbate. The  $\text{Pb}^{2+}$  sensor was prepared with a final substrate concentration of 6 nM and enzyme concentration of 6 nM in 100 mM NaCl, 25 mM Tris acetate, pH 8.2. The  $\text{UO}_2^{2+}$  sensor was prepared with a final substrate concentration of 200 nM and enzyme concentration of 400 nM in 300 mM NaCl, 50 mM MES, pH 5.5. The three sensors were spotted into three rows of a 96-well plate, respectively, with each row containing 8 wells. Eight metal mixtures were prepared with all the eight possible combinations among  $\text{Cu}^{2+}$ ,  $\text{Pb}^{2+}$  and  $\text{UO}_2^{2+}$ . The metal concentrations in each mixture were either 0 or 20  $\mu\text{M}$ . 5  $\mu\text{L}$  of each metal mixture was spotted into three wells along the same column but in different rows. 95  $\mu\text{L}$  of sensor was transferred into the wells containing the metal mixture and the reaction was allowed for 10 min at room temperature. The final metal concentration for each metal after mixing with the sensor was either 0 or 1  $\mu\text{M}$ . The plate was imaged with the Fuji fluorescence scanner.

Results of gel-based assays: Gel-based assays were carried out to confirm the cleavage reaction (FIG. 5). Lane 1 contained the substrate alone and  $\text{Cu}^{2+}$ . Lane 2 had the DNAzyme complex but no  $\text{Cu}^{2+}$ . Cleavage was observed only after addition of  $\text{Cu}^{2+}$  to the DNAzyme complex (lanes 3-5).

The enzyme to substrate ratio in the  $\text{Cu}^{2+}$  sensor. The structure of the  $\text{Cu}^{2+}$ -specific DNAzyme is different from the  $\text{UO}_2^{2+}$  and  $\text{Pb}^{2+}$  DNAzymes shown above. One of the substrate binding arms of the  $\text{Cu}^{2+}$  DNAzyme contained a DNA triplex. Therefore, the stability of the DNAzyme complex is not as high as that with normal Watson-Crick base pairs. To form stable DNAzyme complex at room temperature, high ionic strength conditions (1.5 M NaCl) were used. With the 1:1 enzyme to substrate ratio, the fluorescence enhancement was only 7-fold in 4 min (FIG. 6, red curve). With a 2:1 enzyme to substrate ratio, the enhancement was ~10-fold in 4 min, which was attributed to more complete substrate hybridization. Therefore, we chose a ratio of 2:1 for the  $\text{Cu}^{2+}$  sensing experiment. Considering the consumption of materials, further increase of the enzyme was not tested.

Gel-based assay of the  $\text{Cu}^{2+}$  sensor in the presence of  $\text{Fe}^{2+}$  and  $\text{UO}_2^{2+}$ : Since fluorescence enhancement was observed in the presence of 1 mM of  $\text{Fe}^{2+}$  or  $\text{UO}_2^{2+}$ , gel-based assays were carried out to test whether the fluorescence increase was due to cleavage or due to DNA denature in the presence of high level of metal ions (FIG. 7). All the lanes contained the sensor DNAzyme complex shown in FIG. 1A with 1  $\mu\text{M}$  Cu\_Sub and 2  $\mu\text{M}$  Cu\_Enzyme. Lane 1 did not have any added metal ion. Lane 2 contained 1  $\mu\text{M}$   $\text{Cu}^{2+}$ , lane 3 contained 10  $\mu\text{M}$   $\text{Cu}^{2+}$ . Lane 4-6 contained 10, 100, and 1000  $\mu\text{M}$   $\text{Fe}^{2+}$ , respectively. Lane 7-9 contained 10, 100, and 1000  $\mu\text{M}$   $\text{UO}_2^{2+}$ , respectively. 1 mM  $\text{Fe}^{2+}$  produced clear cleavage products; while no well-defined cleavage bands were observed with 1 mM  $\text{UO}_2^{2+}$ . Ascorbate (50  $\mu\text{M}$ ) was included in all the lanes.

Quantitative measurement of sensor response to  $\text{Fe}^{2+}$ : The  $\text{Cu}^{2+}$  sensor was titrated with varying concentrations of  $\text{Fe}^{2+}$  and the results are presented in FIG. 8. The assay conditions

were the same as that used for  $\text{Cu}^{2+}$  titration described previously. Only 1 mM  $\text{Fe}^{2+}$  showed enhanced fluorescence, which is consistent with the results in 96-well plate based measurements. The sensor response to 1  $\mu\text{M}$  of  $\text{Cu}^{2+}$  is also measured for comparison. Based on this data, the selectivity for  $\text{Cu}^{2+}$  over  $\text{Fe}^{2+}$  is  $\sim 3000$ -fold.

Reaction of the  $\text{Cu}^{2+}$  sensor in the presence of  $\text{Fe}^{3+}$ :  $\text{Fe}^{3+}$  with ascorbate is commonly used to generate reduced iron species. Therefore, it is surprising that there was no response from this combination in the selectivity experiment (FIG. 2C). To understand the reason behind it, a gel-based assay was carried out as shown in FIG. 9. Lane 1 and 2 contained 50  $\mu\text{M}$  ascorbate. Lane 1 did not contain  $\text{Cu}^{2+}$  while lane 2 contained 10  $\mu\text{M}$   $\text{Cu}^{2+}$ . These two lanes served as negative and positive controls, respectively. Lanes 3-5 contained 1 mM  $\text{FeCl}_3$  and 0, 50  $\mu\text{M}$ , and 1 mM ascorbate, respectively. Lanes 6-8 contained 1 mM  $\text{Fe}(\text{NO}_3)_3$  and 0, 50  $\mu\text{M}$ , and 1 mM ascorbate, respectively. Cleavage products were observed in lanes 4, 5, 7, and 8. Therefore,  $\text{Fe}^{3+}$  with ascorbate can indeed induce cleavage. The reason for the failure to generate fluorescence increase in the selectivity experiment was attributed to the following two reasons. First, the cleavage even with 1 mM  $\text{Fe}^{3+}$  in the presence of 50  $\mu\text{M}$  ascorbate (lanes 4 and 7) was very slow. Because only 50  $\mu\text{M}$  ascorbate was used in the sensing experiment, such slow cleavage may give limited cleavage products. Second,  $\text{Fe}^{3+}$  is a strong quencher and even fluorescence did increase, the overall fluorescence intensity may still below background. To further confirm the effect of  $\text{Fe}^{3+}$ , solution based fluorescence kinetics experiments were performed and the results are shown in FIG. 10. At all the three tested  $\text{Fe}^{3+}$  concentrations, quenched fluorescence was observed. There was slight recovery of fluorescence for the 100  $\mu\text{M}$   $\text{Fe}^{3+}$  sample. Even based on this enhancement, the selectivity for  $\text{Cu}^{2+}$  was still  $\sim 4200$ -fold higher for  $\text{Cu}^{2+}$  than for  $\text{Fe}^{3+}$ .

$\text{Cu}^{2+}$ -induced FAM quenching: FAM was chosen as the signaling fluorophore to detect  $\text{Cu}^{2+}$  in this work. Although the  $\text{Cu}^{2+}$  recognition part of the sensor was spatially separated from FAM,  $\text{Cu}^{2+}$  could still induce quenching due to non-specific fluorophore/metal interactions. A FAM-labeled double stranded DNA was employed to quantitative measure the quenching effect of  $\text{Cu}^{2+}$  to FAM, and a Stern-Volmer plot was made as shown in FIG. 11 (red curve), the remaining fluorescence was less than 10% when  $\text{Cu}^{2+}$  concentration was higher than 100  $\mu\text{M}$  (quenching efficiency  $>90\%$ ). In the current system, 50  $\mu\text{M}$  of ascorbate was included, which significantly suppressed the quenching effect (blue curve). When  $\text{Cu}^{2+}$  concentration was lower than 50  $\mu\text{M}$ , the quenching was less than 15%. This experiment was carried out under the identical conditions as the  $\text{Cu}^{2+}$  detection: 1.5 M NaCl, 50 mM HEPES, pH 7.0 at 23° C.

Test of  $\text{Cu}^+$  and the effect of ascorbate on the rate of cleavage: To test the effect of ascorbate on the rate of signal enhancement of the sensor, the sensor response in the absence of ascorbate was also carried out. As shown in FIG. 12 (pink curve), even though fluorescence did increase, the rate was much slower compared to that with 50  $\mu\text{M}$  ascorbate (red curve). This result is consistent with literature reports that this DNzyme can operate independent of ascorbate.<sup>10,11</sup> The reaction of  $\text{Cu}^+$  with this DNzyme has never been reported before and we also studied this effect.  $\text{Cu}^+$  was tested using  $[\text{Cu}(\text{MeCN})_4](\text{PF}_6)_2$  in acetonitrile as the metal source (blue curve). With ascorbate, the rate of fluorescence increase was as fast as that with  $\text{Cu}^{2+}$ . In the absence of ascorbate,  $\text{Cu}^+$  also can induce fast fluorescence increase (green curve), which was faster than that of  $\text{Cu}^{2+}$  in the absence of ascorbate (pink

curve). Therefore, it is likely that  $\text{Cu}^{2+}$  was reduced by ascorbate to  $\text{Cu}^+$ , which subsequently reacted with oxygen to oxidatively cleave DNA.

The effect of anions is shown in FIG. 13.

## REFERENCES

- (1) (a) Tsien, R. Y., In *Fluorescent Chemosensors for Ion and Molecule Recognition*, Czarnik, A. W., Ed. ACS Symposium Series 538: Washington, D.C., 1993, pp 130-146.
- (b) Jiang, P.; Guo, Z., *Coord. Chem. Rev.* 2004, 248, 205-229.
- (c) Lim, M. H.; Lippard, S. J., *Acc. Chem. Res.* 2007, 40, 41.
- (2) (a) Burdette, S. C.; Walkup, G. K.; Spingler, B.; Tsien, R. Y.; Lippard, S. J., *J. Am. Chem. Soc.* 2001, 123, 7831-7841.
- (b) Yoon, S.; Albers, A. E.; Wong, A. P.; Chang, C. J., *J. Am. Chem. Soc.* 2005, 127, 16030-16031.
- (c) Yang, L.; McRae, R.; Henary, M. M.; Patel, R.; Lai, B.; Vogt, S.; Fahrni, C. J., *Proc. Natl. Acad. Sci. U.S.A.* 2005, 102, 11179.
- (d) He, Q.; Miller, E. W.; Wong, A. P.; Chang, C. J., *J. Am. Chem. Soc.* 2006, 128, 9316-9317.
- (e) Zeng, L.; Miller, E. W.; Pralle, A.; Isacoff, E. Y.; Chang, C. J., *J. Am. Chem. Soc.* 2006, 128, 10.
- (f) Wegner, S. V.; Okesli, A.; Chen, P.; He, C., *J. Am. Chem. Soc.* 2007, 129, 3474.
- (g) Nolan, E. M.; Lippard, S. J., *J. Am. Chem. Soc.* 2007, 129, 5910.
- (3) (a) Sasaki, D. Y.; Shnek, D. R.; Pack, D. W.; Arnold, F. H., *Angew. Chem. Int. Ed.* 1995, 34, 905-907.
- (b) Torrado, A.; Walkup, G. K.; Imperiali, B., *J. Am. Chem. Soc.* 1998, 120, 609-610.
- (c) Bolletta, F.; Costa, I.; Fabbri, L.; Licchelli, M.; Montalti, M.; Pallavicini, P.; Prodi, L.; Zaccheroni, N., *J. Chem. Soc., Dalton Trans.* 1999, 1381-1386.
- (d) Grandini, P.; Mancin, F.; Tecilla, P.; Scrimin, P.; Tonelato, U., *Angew. Chem., Int. Ed.* 1999, 38, 3061-3064.
- (e) Klein, G.; Kaufmann, D.; Schurch, S.; Raymond, J. L., *Chem. Comm.* 2001, 561-562.
- (f) Zheng, Y.; Huo, Q.; Kele, P.; Andreopoulos, F. M.; Pham, S. M.; Leblanc, R. M., *Org. Lett.* 2001, 3, 3277-3280.
- (g) Boiocchi, M.; Fabbri, L.; Licchelli, M.; Sacchi, D.; Vazquez, M.; Zampa, C., *Chem. Comm.* 2003, 1812.
- (h) Zheng, Y.; Cao, X.; Orbulescu, J.; Konka, V.; Andreopoulos, F. M.; Pham, S. M.; Leblanc, R. M., *Anal. Chem.* 2003, 75, 1706-1712.
- (i) Zheng, Y.; Orbulescu, J.; Ji, X.; Andreopoulos, F. M.; Pham, S. M.; Leblanc, R. M., *J. Am. Chem. Soc.* 2003, 125, 2680-2686.
- (j) Roy, B. C.; Chandra, B.; Hromas, D.; Mallik, S., *Org. Lett.* 2003, 5, 11-14.
- (k) Kaur, S.; Kumar, S., *Tetrahedron Lett.* 2004, 45, 5081.
- (l) Mei, Y.; Bentley, P. A.; Wang, W., *Tetrahedron Lett.* 2006, 47, 2447-2449.
- (m) Zhang, X.-B.; Peng, J.; He, C.-L.; Shen, G.-L.; Yu, R.-Q., *Anal. Chim. Acta* 2006, 567, 189-195.
- (n) Comba, P.; Kraemer, R.; Mokhir, A.; Naing, K.; Schatz, E., *Eur. J. Inorg. Chem.* 2006, 4442-4448.
- (o) Kim, S. H.; Kim, J. S.; Park, S. M.; Chang, S.-K., *Org. Lett.* 2006, 8, 371-374.
- (p) White, B. R.; Holcombe, J. A., *Talanta* 2007, 71, 2015-2020.
- (q) Oter, O.; Ertekin, K.; Kirilmis, C.; Koca, M., *Anal. Chim. Acta* 2007, 584, 308-314.

## 11

- (4) (a) Dujols, V.; Ford, F.; Czarnik, A. W., *J. Am. Chem. Soc.* 1997, 119, 7386.  
 (b) Yang, J.-S.; Lin, C.-S.; Hwang, C.-Y., *Org. Lett.* 2001, 3, 889.  
 (c) Kaur, S.; Kumar, S., *Chem. Comm.* 2002, 2840-2841.  
 (d) Wu, Q.; Anslyn, E. V., *J. Am. Chem. Soc.* 2004, 126, 14682.  
 (e) Royzen, M.; Dai, Z.; Canary, J. W., *J. Am. Chem. Soc.* 2005, 127, 1612.  
 (f) Xu, Z.; Xiao, Y.; Qian, X.; Cui, J.; Cui, D., *Org. Lett.* 2005, 7, 889-892.  
 (g) Wen, Z.-C.; Yang, R.; He, H.; Jiang, Y.-B., *Chem. Comm.* 2006, 106-108.  
 (h) Yang, H.; Liu, Z.-Q.; Zhou, Z.-G.; Shi, E.-X.; Li, F.-Y.; Du, Y.-K.; Yi, T.; Huang, C.-H., *Tetrahedron Lett.* 2006, 47, 2911.  
 (i) Martinez, R.; Zapata, F.; Caballero, A.; Espinosa, A.; Tarraga, A.; Molina, P., *Org. Lett.* 2006, 8, 3235.  
 (5) Lu, Y., *Chem. Eur. J.* 2002, 8, 4588-4596.  
 (6) Navani, N. K.; Li, Y., *Curr. Opin. Chem. Biol.* 2006, 10, 272-281.  
 (7) Li, J.; Lu, Y., *J. Am. Chem. Soc.* 2000, 122, 10466-10467.  
 (8) Liu, J.; Brown, A. K.; Meng, X.; Crokek, D. M.; Istok, J. D.; Watson, D. B.; Lu, Y., *Proc. Natl. Acad. Sci. U.S.A.* 2007, 104, 2056.

## 12

- (9) Georgopoulos, P. G.; Roy, A.; Yonone-Lioy, M. J.; Opiekun, R. E.; Lioy, P. J., *J. Toxicol. Env. Health, B.* 2001, 4, 341.  
 (10) Carmi, N.; Breaker, R. R., *Bioorg. Med. Chem.* 2001, 9, 2589-2600.  
 (11) Carmi, N.; Balkhi, H. R.; Breaker, R. R., *Proc. Natl. Acad. Sci. U.S.A.* 1998, 95, 2233-2237.  
 (12) Carmi, N.; Shultz, L. A.; Breaker, R. R., *Chem. Biol.* 1996, 3, 1039-1046.  
 (13) Liu, J.; Lu, Y., *Anal. Chem.* 2003, 75, 6666-6672.  
 (14) Hertzberg, R. P.; Dervan, P. B., *Biochemistry* 1984, 23, 3934-3945.  
 (15) Yazzie, M.; Gamble, S. L.; Civitello, E. R.; Stearns, D. M., *Chem. Res. Toxicol.* 2003, 16, 524.  
 (16) Fluorescent and Luminescent Probes for Biological Activity. A Practical Guide to Technology for Quantitative Real-Time Analysis, Second Ed. W. T. Mason, ed. Academic Press (1999).  
 (17) WO 99/27351.  
 (18) Lakowicz, J. R. In Principles of Fluorescence Spectroscopy; 2nd ed.; Kluwer Academic/Plenum: New York, 1999.

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<210> SEQ ID NO 8
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<212> TYPE: DNA
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<220> FEATURE:
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<400> SEQUENCE: 8

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<210> SEQ ID NO 10
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<210> SEQ ID NO 11
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<213> ORGANISM: Artificial Sequence
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actcactata rggaagagat gtctgt                            26

<210> SEQ ID NO 12
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<213> ORGANISM: Artificial Sequence
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<400> SEQUENCE: 12

acagacatct cttctccgag ccggtcgaaa tagtgagt                38

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What is claimed is:

1. An isolated nucleic acid enzyme activated in the presence of copper, comprising an oligonucleotide comprising a nucleotide sequence shown in SEQ ID NO: 1, wherein the nucleic acid enzyme is not self-cleaving.

2. The nucleic acid enzyme of claim 1, wherein the oligonucleotide further comprises a first quencher at a 5'-end or a 3'-end of the nucleic acid enzyme, and optionally further comprises a spacer between the oligonucleotide and the first quencher.

3. The nucleic acid enzyme of claim 2, wherein the oligonucleotide comprises a nucleotide sequence shown in SEQ ID NO: 5.

4. An isolated nucleic acid enzyme activated in the presence of copper, comprising:

an oligonucleotide comprising a nucleotide sequence of SEQ ID NO: 1, and  
a quencher, attached at a 3' end of the nucleic acid enzyme.

50 5. The nucleic acid enzyme of claim 1, wherein the oligonucleotide further comprises a first quencher at a 3'-end of the nucleic acid enzyme, and a spacer between the oligonucleotide and the first quencher.

55 6. The nucleic acid enzyme of claim 2, wherein the oligonucleotide comprises a first quencher at a 5'-end of the nucleic acid enzyme.

7. A sensor system for determining an amount of copper in a sample, comprising:

the nucleic acid enzyme of claim 2,  
a substrate for the nucleic acid enzyme,  
a second quencher, attached to the substrate, and  
a fluorophore, attached to the substrate.

60 8. A sensor system for determining an amount of copper in a sample, comprising:

the nucleic acid enzyme of claim 5,  
a substrate for the nucleic acid enzyme,  
a second quencher, attached to the substrate, and  
a fluorophore, attached to the substrate.

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9. A sensor system for determining an amount of copper in a sample, comprising:

- the nucleic acid enzyme of claim 6,
- a substrate for the nucleic acid enzyme,
- a second quencher, attached to the substrate, and
- a fluorophore, attached to the substrate.

10. The sensor system of claim 7, wherein the substrate comprises an oligonucleotide comprising a nucleotide sequence shown in SEQ ID NO:4, wherein the second quencher is at a 5'-end of the substrate, the fluorophore is at a 3'-end of the substrate, wherein the substrate optionally further comprises a spacer between the oligonucleotide and the second quencher, and wherein the substrate optionally further comprises a spacer between the oligonucleotide and the fluorophore.

11. The sensor system of claim 8, wherein the substrate comprises an oligonucleotide comprising a nucleotide sequence shown in SEQ ID NO:4, wherein the second quencher is at a 5'-end of the substrate, the fluorophore is at a 3'-end of the substrate, wherein the substrate optionally further comprises a spacer between the oligonucleotide and the second quencher, and wherein the substrate optionally further comprises a spacer between the oligonucleotide and the fluorophore.

12. The sensor system of claim 7, wherein the substrate comprises an oligonucleotide comprising a nucleotide sequence shown in SEQ ID NO:6, wherein the second quencher is at a 5'-end of the substrate, the fluorophore is at a 3'-end of the substrate, wherein the substrate optionally further comprises a spacer between the oligonucleotide and the second quencher, and wherein the substrate optionally further comprises a spacer between the oligonucleotide and the fluorophore.

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13. A method of measuring an amount of copper in a sample, comprising:

- mixing the sample with the sensor system of claim 7; and
- detecting fluorescence, wherein detecting an increase in fluorescence indicates the presence of copper.

14. A method of measuring an amount of copper in a sample, comprising:

- mixing the sample with the sensor system of claim 8; and
- detecting fluorescence, wherein detecting an increase in fluorescence indicates the presence of copper.

15. A method of measuring an amount of copper in a sample, comprising:

- mixing the sample with the sensor system of claim 9; and
- detecting fluorescence, wherein detecting an increase in fluorescence indicates the presence of copper.

16. A method of measuring an amount of copper in a sample, comprising:

- mixing the sample with the sensor system of claim 10; and
- detecting fluorescence, wherein detecting an increase in fluorescence indicates the presence of copper.

17. A method of measuring an amount of copper in a sample, comprising:

- mixing the sample with the sensor system of claim 11; and
- detecting fluorescence, wherein detecting an increase in fluorescence indicates the presence of copper.

18. A method of measuring an amount of copper in a sample, comprising:

- mixing the sample with the sensor system of claim 12; and
- detecting fluorescence, wherein detecting an increase in fluorescence indicates the presence of copper.

19. The sensor system of claim 7, wherein the fluorophore is 6-carboxyfluorescein and the first and second quencher are Iowa Black FQ.

20. The method of claim 13, wherein the sample is further mixed with ascorbate.

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