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Multiplexed photoluminescent sensors: towards improved disease diagnostics

Xiao-Peng He,^{*a} Xi-Le Hu,^a Tony D. James,^{id}^{*b} Juyoung Yoon,^{id}^{*c} and He Tian^{*a}

The ability to simultaneously monitor multiple analytes in, for example, a single microplate well, is important for both basic research and clinical applications. In particular, for disease diagnosis there is a growing awareness that determination of a single disease biomarker is insufficient to pathologically confirm a disease state. Consequently, much recent literature has been directed towards the development of multiplexed photoluminescent sensors which can simultaneously detect multiple and diverse biomarkers that exist in a homogenous solution or a single cell, accelerating the progress towards precise disease diagnosis. This tutorial review highlights a selection of recent contributions towards this emerging interdisciplinary field that incorporates chemistry, chemical biology, materials sciences and medical sciences.

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Key learning points

- (1) Why there is a need for multiplexed, photoluminescent sensing of disease biomarkers?
- (2) The diverse materials used for constructing multiplexed photoluminescent sensors.
- (3) Photoluminescence detection of multiple disease biomarkers in a homogenous solution or within a single cell.
- (4) Large-scale, multicentre clinical-specimen analysis is needed to demonstrate the clinical value of multiplexed photoluminescent sensors.

1. Introduction

The early and precise diagnosis of fatal human diseases such as cancer can help significantly improve the overall therapeutic efficacy and patient prognosis. However, it has been difficult to pathologically confirm a cancer by referring to the serological test of just a single biomarker, which may either be over-expressed during other abnormal states (false positive) or, more problematically absent in a number of individuals with cancer (false negative). For example, the alpha-fetoprotein (AFP), a biomarker used clinically for the serological test of liver cancer, is also overexpressed in some patients with chronic liver diseases with a false-positive rate of up to 58%. In contrast, it is suggested that 35–65% of patients diagnosed with hepatocellular carcinoma did not show an elevated AFP expression at a cutoff of 20 ng mL⁻¹.¹ Therefore, the use of multiple biomarkers to synergistically confirm a disease state has become increasingly

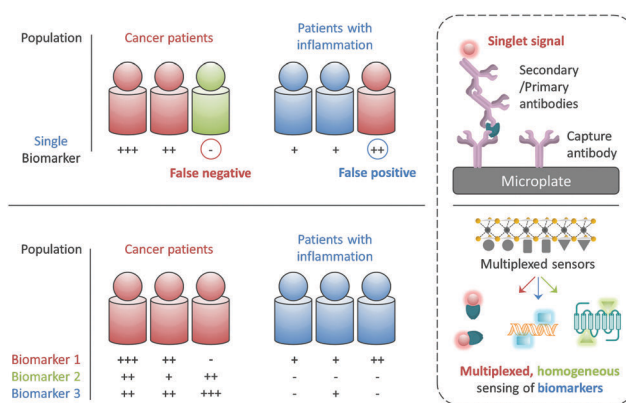


Fig. 1 Singlet sensing vs. multiplexed sensing for precise disease diagnosis.

important for the more precise and earlier identification of disease states (Fig. 1).²

While the confirmation of a set of biomarkers for a given disease requires multicentre, large-scale clinical trials, it would be ideal if these biomarkers can be simultaneously reported using a single sensing system and working with a simple blood or cell sample. The most popular analytical technique for protein biomarker detection is currently the enzyme-linked

^a Key Laboratory for Advanced Materials & Institute of Fine Chemicals, East China University of Science and Technology (ECUST), 130 Meilong Rd., Shanghai 200237, P. R. China. E-mail: xphe@ecust.edu.cn, tianhe@ecust.edu.cn

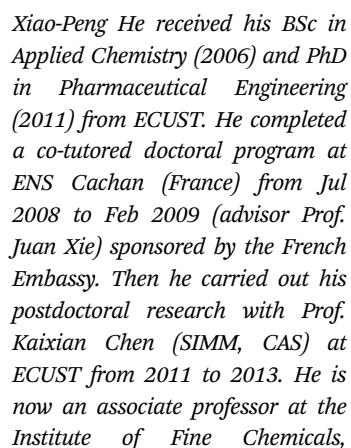
^b Department of Chemistry, University of Bath, Bath, BA2 7AY, UK. E-mail: t.d.james@bath.ac.uk

^c Department of Chemistry and Nano Science, Ewha Womans University, Seoul 03760, Korea. E-mail: jyoon@ewha.ac.kr

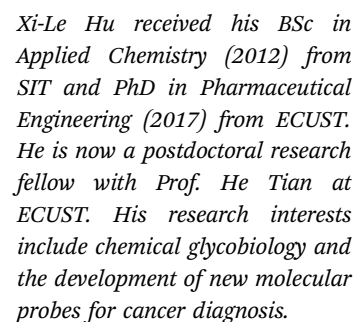


solution-based homogeneous determination of biomarkers is much simpler in manipulation and faster in signal readout since it just relies on the selective interaction of the sensor with the targets in solution to produce a sensing signal. Here we highlight the diverse tactics and materials used in developing multiplexed photoluminescent sensors for homogeneous, multiple biomarker detection.

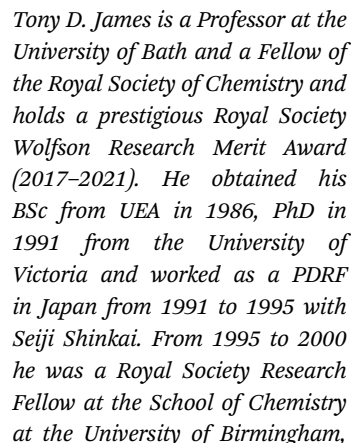
Multiplexed photoluminescent sensors for homogeneous detection of multiple analytes are constructed by the self-assembly between a range of probe-luminophores (*e.g.* fluorophores and QDs) and material substrates such as 2D materials and inorganic/organic nanoparticles for the simultaneous detection of different pathologically relevant species in an aqueous environment. Molecularly functionalised nanoparticles (*e.g.* upconversion materials and conjugated polymers) of different emission



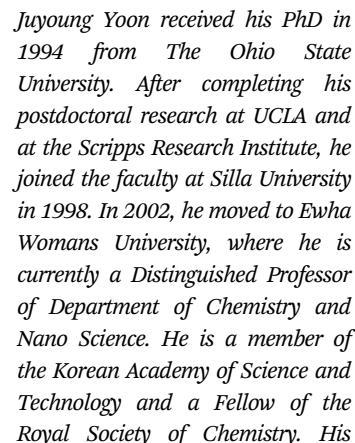
ECUST, where his research interests span chemical glycobiology to fluorescent molecular probes for disease diagnosis and theranostics. Dr He has co-authored over 100 peer-reviewed papers and is the co-inventor of 6 Chinese patents.



Xi-Le Hu



moving to the Department of Chemistry at the University of Bath in September 2000. His research interests focus on the use of boronic acid based receptors for the fluorescence sensing of saccharides.



research interests include the investigation of fluorescent probes, theranostics and organic functional materials. He is a Thomson Reuters Highly Cited Researcher in Chemistry (2014–2016). Prof. Yoon has published over 270 SCI papers.



colours for multi-colour imaging of cells, pathogens and animals are discussed. While in the perspective section we discuss other optical and electrical multiplexing strategies for clinical diagnoses. Traditional sensing strategies have focused on improving single-analyte specificity; however, this could reduce diagnostic precision (Fig. 1). With this review we suggest that rational design of multi-analyte sensors can significantly advance disease diagnosis.

2. Multiplexed sensors

2.1 Multiplexed photoluminescent sensors based on low-dimensional materials for homogeneous, photoluminescent detection of multiple analytes

Ever since the discovery of graphene – an atomic-thin carbon material with exceptional optoelectronic properties – there has been ever-increasing interest in the development of two-dimensional (2D) materials for many applications.⁴ The material substrate used for constructing fluorogenic biosensors mainly relies on water-soluble graphene oxide (GO).⁵ On the basis of the strong π -stacking between the base pairs of DNA and GO, a multi-colour GO probe for the detection of three tumour-suppressor genes (p16, p21 and p53) in homogenous solution was developed.⁶ Three different single-strand DNA (ssDNA) sequences tagged with fluorophores of different emission wavelengths were used to simultaneously assemble with GO, resulting in the fluorescence quenching of all fluorophores. The quenching was ascribed to the Förster resonance energy transfer (FRET) from the fluorophores to GO (Fig. 2a). The resulting GO/multi-DNA sensor displayed a selectively enhanced fluorescence upon hybridization with a pairing gene sequence because the double-strand DNA (dsDNA) formed resulted in a weakened interaction with the GO quenching platform (Fig. 2b). In particular, the multiplexed system has proven to only show a selective fluorescence enhancement with a given tumour-suppressor gene without interference from

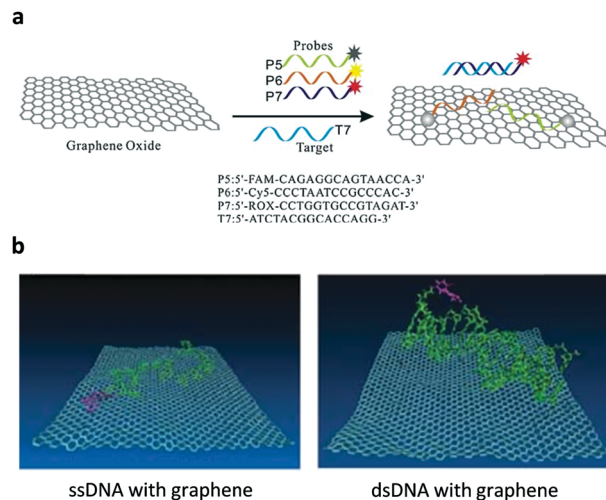


Fig. 2 (a) Schematic illustration of the co-assembly of three different ssDNA probes tagged with different fluorophores to graphene oxide and the selective hybridization of an ssDNA probe with a target ssDNA, forming a dsDNA. (b) A molecular dynamic simulation showing the different interaction modes of ssDNA and dsDNA with the graphene surface. Reproduced with permission from ref. 6. Copyright: John Wiley & Sons.

other unselective genes (Fig. 2a). This research sets the basis for the multiplexed sensing of tumour-related DNAs.

In a subsequent study, it was shown that the GO multiplexed system was also suitable for the simultaneous detection of three virus genes.⁷ Three looped DNAs tagged with different coloured fluorophores for human immunodeficiency virus (HIV), variola virus and ebola virus were coated onto GO, quenching the fluorescence. The presence of the multiple gene sequences of the viruses in the solution of the multiplexed GO sensor led to the fluorescence enhancement of all three fluorophores, similarly due to the formation of dsDNAs. Meanwhile, this multi-ssDNA-functionalized GO sensor has also been extended to the multiplexed detection of a mixture of DNAs, proteins and ions.⁸

MicroRNAs (miRNAs) are non-coding RNAs typically with 19–25 nucleotides. A number of these miRNAs have been shown to regulate cellular processes in diseases. Multiple fluorescent ssDNA probes for miRNAs were used to assemble with GO, achieving multiplexed miRNA detection in the presence of a nuclease for signal amplification.⁹ A Y-shaped DNA scaffold was then developed incorporating the cleavage sequence (each tagged with a different fluorophore) of three nucleases.¹⁰ In a homogeneous solution consisting of GO and multiple nucleases, the three different emissions of the Y-shaped DNA were quenched simultaneously, enabling a multiplexed system for nuclease analysis.

The hepatitis C virus (HCV) infection can lead to cirrhosis and ultimately hepatocarcinoma. Over 170 million people have HCV infections worldwide. Based on the DNA/GO assembly, a multifunctional system for the detection of helicase biomarkers that exist in HCV and severe acute respiratory syndrome coronavirus was developed.¹¹ Unwinding the dsDNAs of these viruses by helicases led to the simultaneous fluorescence



He Tian

Prof. He Tian was born in China in 1962. In 1999, he was appointed as the Cheung Kong Distinguished Professor by the Education Ministry of China. In 2011, he was selected as a member of the Chinese Academy of Sciences. In 2013, he became a Fellow of the TWAS – the World Academy of Science – for the advancement of science in developing countries. His current research interests include supramolecular machines and switches, synthesis of novel

functional organic dyes and development of interdisciplinary materials science that determines the electronic and optical properties of materials. He is a Thomson Reuters Highly Cited Researcher in Chemistry (2014) and Materials Science (2014 and 2015).



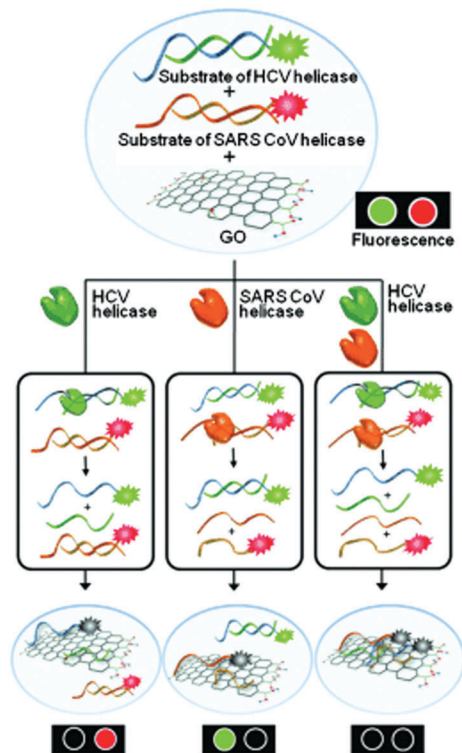


Fig. 3 Multiplexed sensing of two different helicases acting on two dsDNA probes in the presence of GO as a quenching platform. HCV and SARS CoV are hepatitis C virus and severe acute respiratory syndrome coronavirus, respectively. Reprinted from ref. 11. Copyright: John Wiley & Sons.

quenching of the ssDNA probes (Fig. 3). In contrast, the presence of a helicase inhibitor largely prevented the fluorescence quenching due to inhibition of helicase activity. Using this feature, a high-throughput, multiplexed assay for screening helicase inhibitors of multiple viruses was developed. This study highlights the potential of using GO multiplex systems for not only biomarker detection, but more broadly drug discovery.

Besides DNA based sensing systems, we have demonstrated that glycoligand–receptor interactions¹² can also be determined in a multiplexed manner using GO.¹³ Carbohydrate–protein interactions are involved in a number of pathological processes including cancer metastasis, virus invasion and bacterial infection. Therefore, the effective analysis of these interactions may aid the development of disease diagnosis and therapy. We assembled two glycoligands with different fluorophores to GO. The quenched fluorescence was recovered simultaneously when the receptors of both glycoligands were available.

In addition to organic dyes, quantum dots (QDs) have also been used as optical reporters for GO multiplexed sensors. A homogenous immunoassay was developed by co-assembly of two antibody-conjugated QDs (green-emitting and red-emitting) to GO, quenching the photoluminescence.¹⁴ The presence of human enterovirus 71 and Cocksackievirus simultaneously resulted in the recovery of both green and red photoluminescence as a result of antibody–virus binding. Similarly, using QDs as the reporter, the multiplexed detection of two gene markers for a human infectious pathogen, *Listeria monocytogenes*, was achieved.¹⁵

With the tremendous success of graphene, a diverse range of graphene-like 2D materials such as transition-metal dichalcogenides (TMDs) and oxides have been extensively developed for a number of applications.¹⁶ Several TMDs have been proven to possess better biocompatibility than GO, and therefore have been introduced for the development of sensors and therapeutic materials.^{17–19} It has been shown that TMDs including 2D MoS₂, TiS₂ and TaS₂ are suitable platforms to build fluorogenic multiplexed systems for sensing DNAs (Fig. 4).²⁰ Among several competing low-dimensional materials including single-walled nanotubes, gold nanoparticles and GO, TaS₂ based systems exhibited the best sensitivity towards multiplexed DNA detection. We have also shown that 2D MoS₂ can be used as a substrate to construct multiplexed sensors for influenza viruses (IVs).²¹ IVs can cause severe respiratory tract infections, and lead to seasonal epidemics. The hemagglutinin, a main surface protein of IVs, is mainly responsible for viral invasion by binding to sialyl glycans (SA) on the surface of avian or human cells. It is reported that IVs that infect birds and humans have a preference for α 2,3-SA and α 2,6-SA, respectively.²² Taking note of these facts, we have co-assembled α 2,6-SA and α 2,3-SA coupled with different fluorophores on 2D MoS₂, producing multiplexed sensors (Fig. 5). While the system showed a single emission colour with IVs containing single glycan specificity, in the presence of a virus with dual glycan specificity, both emission colours were produced. This research paves the way for the timely warning of IV mutations that can cause global epidemics.

Proteases are enzymes that catalyze the cleavage of peptide bonds. They play key roles in many diseases such as cancer, viral infection and inflammation. Carbon nanotubes (CNTs), a topical 1D material, have been used as the quenching material for constructing multiplexed sensors for proteases. Three multi-colour peptide substrates were conjugated to a CNT platform, leading to fluorescence quenching. The presence of three cancer-related proteases, matrix metalloproteinase-7, matrix metalloproteinase-2 and urokinase-type plasminogen activator, in a homogeneous solution of the sensor produced multicolour fluorescence by specific cleavage of the corresponding peptide

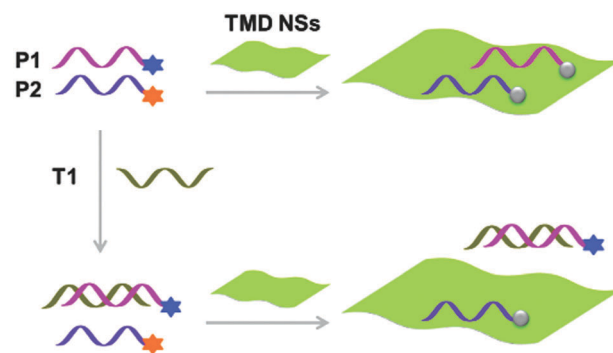


Fig. 4 Schematic illustration of the use of single-layer transition-metal dichalcogenide based multiplexed sensors for DNA detection, where P1 and P2 are different fluorophore-tagged ssDNA probes and T1 is a target ssDNA. Reprinted with permission from ref. 20. Copyright: John Wiley & Sons.



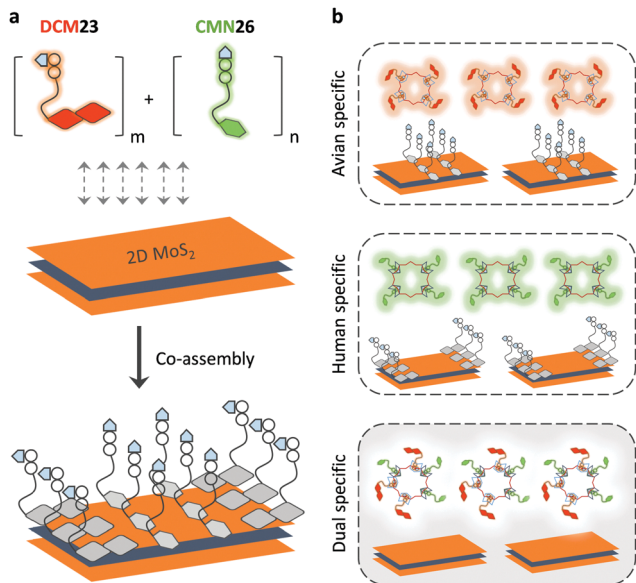


Fig. 5 Schematic illustration of (a) the co-assembly of two sialyl glycan probes tagged with different fluorophores to 2D MoS₂ and (b) the use of a multiplexed system for the detection of influenza viruses with single or dual glycan specificities, where DCM23 and CMN26 are dicyanomethylene 4*H*-pyran-tagged Neu5Ac α 2,3Gal- β 1,4Glc and coumarin-tagged Neu5Ac α 2,6Gal- β 1,4Glc probes, respectively. Reprinted with permission from ref. 21. Copyright: The Royal Society of Chemistry.

substrates.²³ In addition, tube-like silicon nanowires have also been proven to be a suitable quenching platform for multiplexed sensing of cancer-related DNA biomarkers.²⁴

2.2 Multiplexed photoluminescent sensors based on nanoparticles for homogeneous, photoluminogenic detection of multiple analytes and multi-colour cell imaging

Inorganic nanoparticles have been the material of choice in advancing modern nanotechnology, owing to their unique optical features at the nanoscale. Of the nanoparticles available, gold nanoparticles (AuNPs) are among the most frequently used for sensing and cell imaging. With the aim of simultaneously probing three tumour-suppressor genes, a molecular beacon (*i.e.* a dual-labelled stem-loop-structured oligonucleotide with a quenched fluorescence) sensor was developed using the Au-thiol assembly of three multicolour DNA sequences onto a single AuNP core (Fig. 6).²⁵ The universal quenching ability of AuNPs precluded the need to optimise the fluorophore-quencher pair for each DNA probe. This beacon sensor simultaneously displayed a multicolour fluorescence enhancement in the presence of multiple tumour-related DNA markers (p16, p21 and p53).

Subsequently, this strategy was extended to the multicolour detection of tumour-related mRNA markers.²⁶ A nanoprobe that consists of AuNPs coated with a dense shell of recognition sequences hybridised with different dye-labelled reporter sequences was developed (Fig. 7a). A competitive hybridisation with three tumour-related mRNAs (c-myc mRNA, TK1 mRNA and GalNAc-T mRNA) caused the multicolour fluorescence emission to recover as a result of the formation of more stable

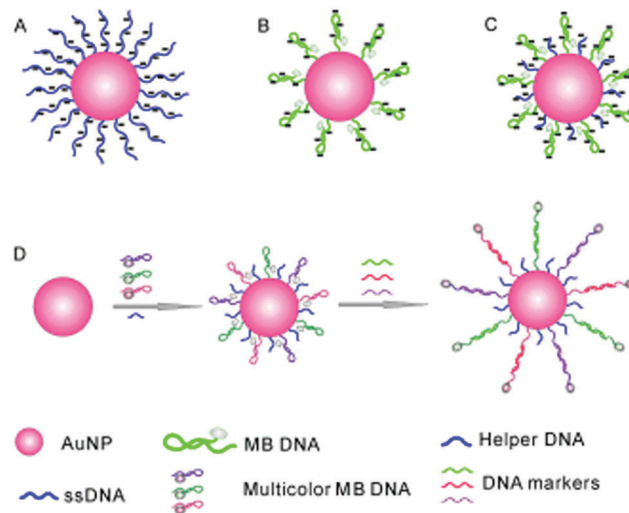


Fig. 6 Schematic illustration of a gold nanoparticle based multiplexed sensor for the simultaneous detection of multiple DNA targets. Unlike AuNPs densely assembled with linear ssDNA probes (A, stable but without the ability to form stem-loop structures) and those with sparsely assembled stem-loop structures (B, easy to aggregate), the co-assembly of a helper DNA with ssDNA probes (C) facilitates the formation of stable nanoparticles without affecting the formation of stem-loop structures for multiplexed sensing (D). Reprinted with permission from ref. 25. Copyright: John Wiley & Sons.

duplexes. This nanoprobe has also shown the ability to simultaneously image three mRNAs in a set of cancer cells (Fig. 7b). In addition to AuNPs, silver nanoclusters are also used for multiplexed DNA detection.²⁷ Label-free molecular beacons were developed based on DNA-templated silver nanoclusters with different emissions, achieving simultaneous detection of influenza A subtype H1N1 and H5N1 genes.

QDs represent another class of widely used nanoparticles for bioimaging because of their emission brightness, large Stokes shift and photostability.²⁸ Using sophisticated bioconjugation methods, multicolour immunohistochemistry was achieved in order to simultaneously image a range of different biomarkers on cancer cells and tissues.²⁹ Five QD bioconjugates were synthesised with antibodies against five different biomarkers of breast cancer with multicolour emission.³⁰ These bioconjugates have been used to simultaneously quantify the expression level of the different biomarkers in both cultured breast cancer cells and single paraffin embedded tissue sections. More importantly, the QD-antibody conjugates have been successfully used for endoscopy-guided multicolour cancer diagnosis.³¹ Conventional diagnosis of colon cancer using endoscopy relies on the clinician's naked eye, which is subjective and may lead to false detection. Multicolour QD bioconjugates coated with matrix metalloproteinase (MMP) 9, MMP 14 and carcinoembryonic antigen were used to help diagnose tumours on sectioned mouse tissue, fresh mouse colons and human colon adenoma. This multiplexed approach imaged using endoscopy provides a rapid and accurate molecular fluorescence imaging technique for colon cancer diagnostics.

In addition to antibody conjugation, peptide-functionalised QDs and QD-based nanocomposite emulsions have been

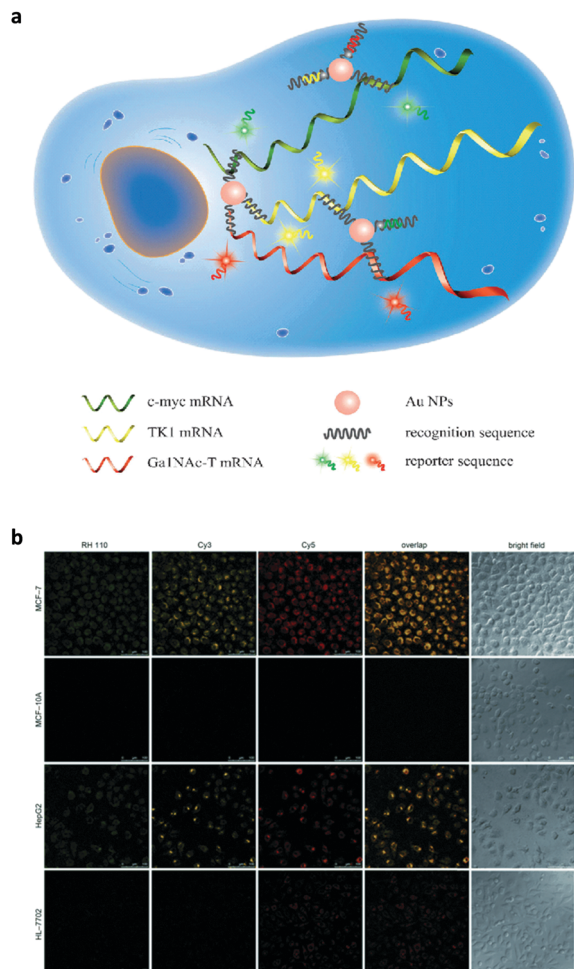


Fig. 7 (a) Schematic illustration of a gold nanoparticle based multiplexed sensor for the simultaneous detection of multiple mRNA targets. (b) Multiplexed fluorescence imaging of the multiple mRNA targets in different cells. Reprinted with permission from ref. 26. Copyright: John Wiley & Sons.

developed for *in vivo* imaging of therapeutic cells³² and spatio-temporal multicolour labelling of distinct subcellular compartments,³³ respectively. DNA-functionalised liposome-QD complex (with a reporter DNA sequence), in combination with magnetic beads (with a capture DNA sequence), has been developed for the multiplexed detection of low-abundance DNA.³⁴ The presence of a target DNA facilitated the formation of a sandwich structure with both the reporter and capture DNA sequences. Subsequently the sandwich ensemble was separated by an external magnetic field and the QDs released an optical signal. This research enables the simultaneous detection of HIV-1 and HIV-2 genes with attomolar sensitivity.

To address the inability of conventional biochemical techniques such as western blotting and single-colour immunohistochemical methods for multiplexed detection of cancer, antibody-conjugated single-band upconversion nanoparticles (UCNPs) with different colours were developed (Fig. 8).³⁵ Compared to QDs, which may suffer from the autofluorescence background of biological samples with blue or ultraviolet emission wavelengths, UCNPs use tissue-transparent near-infrared

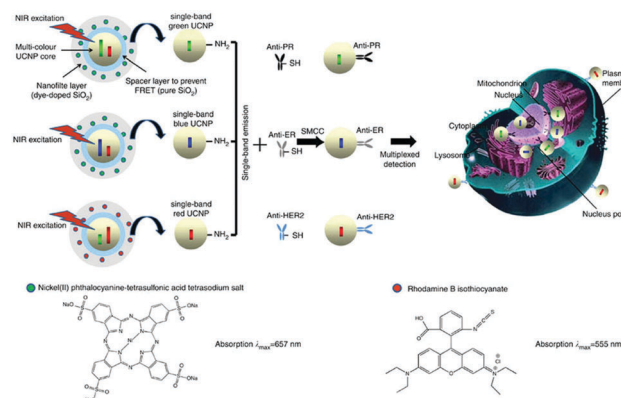


Fig. 8 Schematic illustration of the synthesis of multiplexed upconversion nanoparticles for the simultaneous imaging of three biomarkers in breast cancer cells and tissues. Reprinted with permission from ref. 35. Copyright: Nature publishing group.

irradiation to produce photoluminescence. It was shown that the expression of three typical breast cancer biomarkers, estrogen receptor, progesterone receptor and human epidermal growth factor receptor 2, could be simultaneously quantified in cancer cells and tissue specimens, even in triple-negative breast cancer cells that poorly express these biomarkers (Fig. 8).

2.3 Multiplexed photoluminescent sensors based on organic materials for *in vitro* and *in vivo* multi-colour imaging

Due to tuneable emission wavelengths (colour) and high quantum yields, emissive conjugated polymers (CPs) have been widely used in biosensing and bioimaging.^{36,37} An interesting approach based on a simple mixture of bacteria and emissive CPs has been developed.³⁸ Four CPs with different emission colours were synthesised and self-assembled with *E. coli* cells to produce microparticles where multicolour emissions are achieved by tuning the FRET efficiencies among the CPs (Fig. 9). The use of a FRET mechanism to modulate multicolour emissions of these materials is advantageous since a single wavelength excitation is required and the emission can be modulated using the CPs with different colours. These microparticles have been shown to be well-suited for multiplexed cell detection and identification using flow cytometry.

CPs have also been used to construct surface-functionalised nanoparticles for the identification of two different kinds of cancer cells.³⁹ A green-emitting CP grafted with an affibody (*i.e.* small proteins engineered to strongly bind to target proteins and peptides) for human epidermal growth factor receptor 2 (which is overexpressed on breast cancer cells) and a red-emitting CP grafted with a peptide ligand for integrin (which is overexpressed on colon cancer cells) were produced. These CPs were successfully used to discriminate a breast cancer cell line from a colon cancer cell line in live cell mixtures, using single laser excitation (Fig. 10). Polymer-based nanoparticles can also be loaded with a set of different organic fluorophores using a FRET cascade for multiplexed imaging.⁴⁰ Multiplexed single excitation *in vivo* imaging was achieved using the subcutaneous injection of three differently coloured



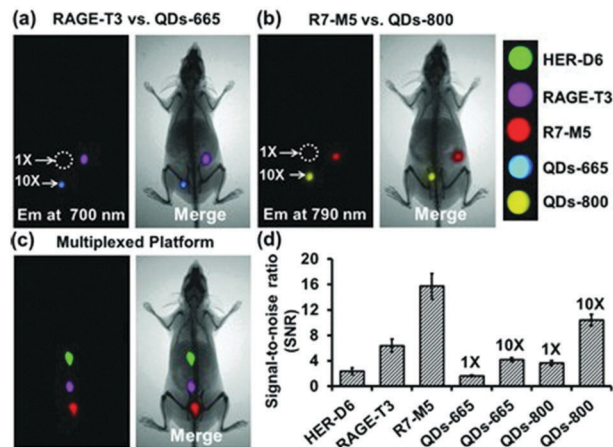


Fig. 11 Multiplexed *in vivo* imaging using multicolour polymer-based nanoparticles in comparison with quantum dots (QDs). Reproduced with permission from ref. 40. Copyright: John Wiley & Sons.

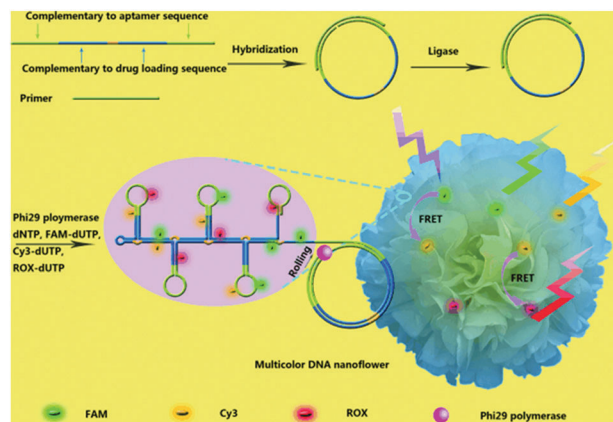


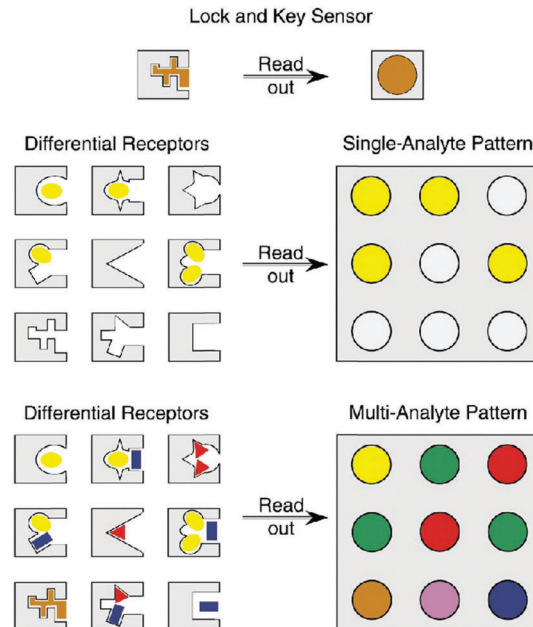
Fig. 12 Schematic illustration of the bioassisted, sequence-independent self-assembly of DNA nanoflowers covalently linked with multicolour fluorophores with FRET (Förster resonance energy transfer) cascade properties. Reproduced with permission from ref. 41. Copyright: John Wiley & Sons.

quencher-type dye, cationic perylene diimide (PDI), with fluorophore-tagged ssDNAs was also developed.⁴² The fluorescence of the ssDNA probes was quenched by PDI as a result of strong electrostatic contacts, and the presence of multiple complementary DNAs with the assistance of an exonuclease autocatalytic recycling amplification simultaneously showed multicolour fluorescence with picomolar sensitivity. A diverse range of functional materials including metal-organic framework-based molecular beacons⁴³ and lanthanide-based organometallic luminescent complexes⁴⁴ have also been developed for multiplexed detection of virus genes and enzymatic activity, respectively.

We have highlighted the recent developments in multiplexed photoluminescent sensors for the homogenous detection of multiple target mixtures and multiplexed imaging of cells and

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A particularly popular technique for developing multiplexed photoluminescent sensors is the use of ligand molecules such as carbohydrates, peptides, aptamers and other small-molecular ligands to replace antibodies, reducing the cost of reagents (obviously these ligands are much cheaper than antibodies in



Furthermore, the direct treatment of a multiplexed photoluminescent sensor with a complex human fluid may cause false-positive signals since the multicolour emissions cover the entire visible-light region. Those with relatively shorter emission wavelengths overlap biological auto-fluorescence.

In addition to the aforementioned perspectives, it should be noted that the most important hurdle for multiplexed photoluminescent sensors to clear before being widely employed in clinics is the ability to be used on a large-scale (typically >1000 specimens) in multicentre clinical trials. We are confident that this goal will be achieved and look forward to the advent of the first FDA-approved multiplexed photoluminescent sensor as a commercially available tool for precise disease diagnosis.

There are no conflicts to declare.

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