*Review*

# Application of aptamers in diagnostics, drug-delivery and imaging

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Aptamers are small, single-stranded oligonucleotides (DNA or RNA) that bind to their target with high specificity and affinity. Although aptamers are analogous to antibodies for a wide range of target recognition and variety of applications, they have significant advantages over antibodies. Since aptamers have recently emerged as a class of biomolecules with an application in a wide array of fields, we need to summarize the latest developments herein. In this review we will discuss about the latest developments in using aptamers in diagnostics, drug delivery and imaging. We begin with diagnostics, discussing the application of aptamers for the detection of infective agents itself, antigens/toxins (bacteria), biomarkers (cancer), or a combination. The ease of conjugation and labelling of aptamers makes them a potential tool for diagnostics. Also, due to the reduced off-target effects of aptamers, their use as a potential drug delivery tool is emerging rapidly. Hence, we discuss their use in targeted delivery in conjugation with siRNAs, nanoparticles, liposomes, drugs and antibodies. Finally, we discuss about the conjugation strategies applicable for RNA and DNA aptamers for imaging. Their stability and self-assembly after heating makes them superior over protein-based binding molecules in terms of labelling and conjugation strategies.

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## 1. Introduction

Aptamers are small, single-stranded oligonucleotides (DNA or RNA), which specifically bind to their target with high affinity. The term 'aptamers' comes from the Latin word aptus (fitting) and the Greek word meros (part). The DNA and RNA aptamers can bind to the same target with different folding patterns and sequences. Aptamers are selected from a pool of a random oligonucleotide library ($>10^{15}$ random oligonucleotides) by iterative rounds of affinity purification and amplification by a process called Systematic Evolution of Ligands by Exponential enrichment (SELEX) (figure 1). This concept of nucleic acid binding to their targets like a protein came into the light when small RNA structures were found to bind with viral or cellular proteins at high affinity and specificity during an investigation on human immunodeficiency virus (HIV) and adenovirus (Song *et al.* 2012). Initial studies on aptamers started with the report of SELEX method in 1990 by both Gold's and Szostak's groups, which was more than two decades ago (Ellington and Szostak 1990; Tuerk and Gold 1990). SELEX is a basic technique for the selection of aptamers *in vitro* against various targets, from small biomolecules to larger biomolecules like proteins and even cells. The interaction between an aptamer and its target involves different intermolecular interactions including van der Waal's forces, electrostatic interactions between charged groups, three-dimensional shape, stacking and hydrogen bonds. Aptamers can fold into a variety of secondary and tertiary structural elements, like stem loops, pseudoknots, kinks, and bulges, which can recognize multiple surfaces as target binding sites. Due to the ability of

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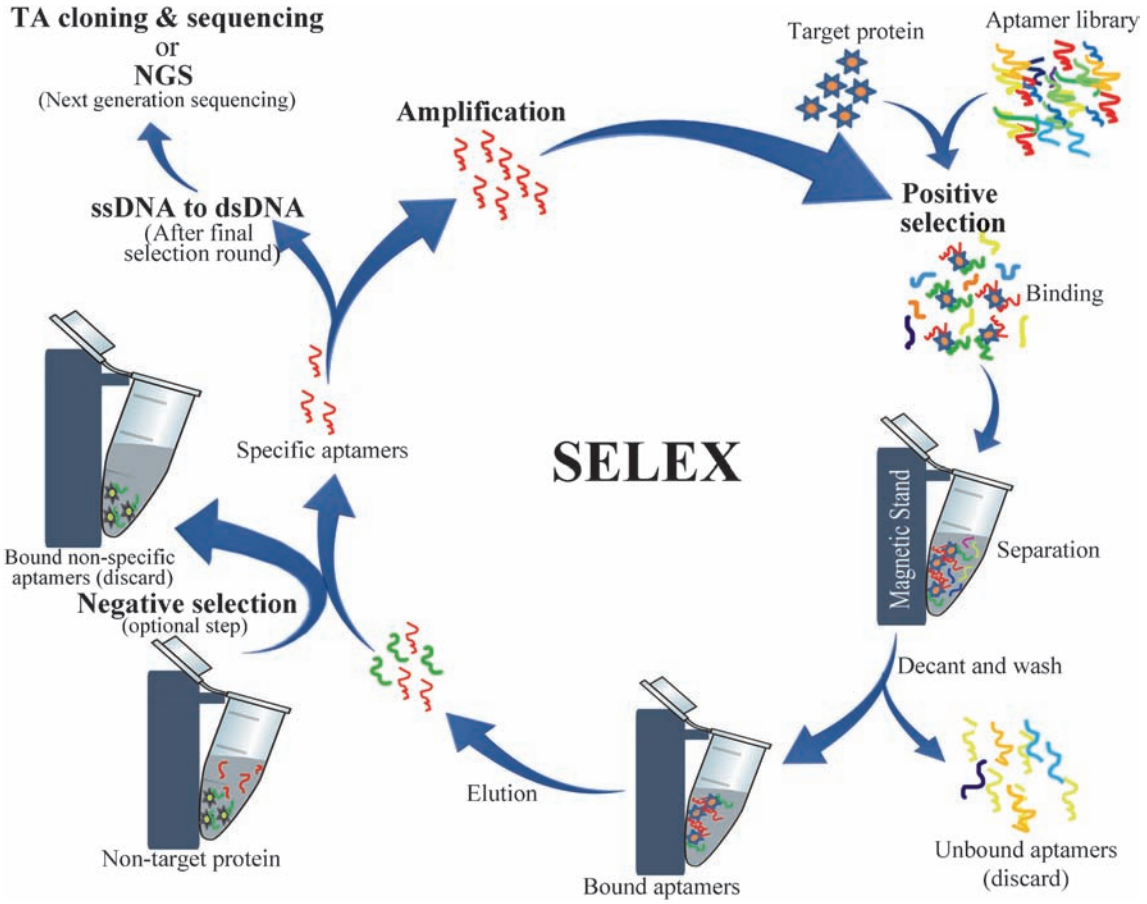


**Figure 1.** Diagrammatic representation of systematic evolution of ligands with exponantial enrichment (SELEX).

aptamers to recognize targets and binding specificity, they are often compared to antibodies. However, unlike antibodies, aptamers can be selected under non-physiological conditions like extremely high or low temperature, or pHs. Aptamers can be readily chemically synthesized with minimal batch-to-batch variations. Moreover, they are easily selected, more stable to heat and withstand organic solvents, and show low immunogenicity. Compared to antibodies, the smaller size of aptamers makes them easier to be synthesized in large quantities, and can be easily introduced with a wide range of chemical modifications, which help them to retain their binding and inhibitory behavior after immobilization on a carrier material or after delivery into animals. They are $1/10^{th}$ the molecular weight of antibodies and yet provide complex folded tertiary structures with sufficient recognition surface areas to rival and even surpass antibodies. All these properties provide a potential market for aptamers in the field of biomedical applications.

Aptamers have been studied as a biomaterial for numerous applications like diagnostics and in the development of new drugs, drug delivery systems and imaging. Today at least a dozen distinct aptamer products are being tested in several dozen trials. The first aptamer approved by Food and Drug Administration (FDA) for use in humans is Pfizer's Macugen that is administered locally to treat age related macular degeneration (AMD) by targeting vascular endothelial growth factor (VEGF) (Ruckman *et al.* 1998); however, monoclonal antibodies that are more effective clinically for this purpose have been developed (Fong and Lai 2013). The most advanced aptamer in cancer setting is AS1411, a 26-mer guanosine rich oligonucleotide against human tumor, formerly known as Agro100 (Teng *et al.* 2007). In the recent years, the aptamer technology field has evolved significantly, and is regarded as a more effective technology as the number of studies in the application of aptamers is rapidly increasing.

In this article we emphasize on applications of aptamer in the field of (a) diagnostics, (b) drug delivery and (c) imaging. This era is steering towards translational research where there is a need to move the research findings from bench-to-bedside, i.e., for clinical outcomes with commercial viability. Aptamers, because of their wide variety of

applications and the ability to undergo easy modifications are a good example to be exploited. Diagnostics, drug delivery and imaging are gaining attraction in the field of translational research because of their huge impact towards diagnosing and treating a disease. Hence, in this review article we have focused on the latest developments in the application of aptamers and how it has affected the above mentioned three fields, describing the advantages and the challenges ahead.

We begin with the role of aptamers in diagnostics where they have been a tradition in this application. As known, signal generated by a conformational change induced by the presence of a ligand is ideal for the creation of sensors for which aptamers are ideal candidates. The ease of conjugation and labelling of aptamers allows them to be combined with other advanced technologies like flow cytometry, microfluidic cell separation, endogenous nucleic acid analysis, nanoparticle based sensing and, thus, positioning them as a potential tool for diagnostics. We will cover the application of aptamers for detection of pathogenesis involving, bacteria, bacterial toxins, viruses, parasites and cancer. Then we will move towards the application of aptamers as drug delivery agents. Off-target delivery of drugs during therapeutic treatment of various diseases, especially in chemotherapy for cancer, is an important problem to be overcome. Here, we have discussed that how aptamers, due to their small size and high specificity, have been used for targeted drug delivery. They are either bound with drugs alone, or used in conjugation with nanoparticles, liposomes and antibodies for increased delivery of various therapeutic payloads. Finally, we shed light on the role of aptamers in imaging where they have been utilized in clinical and molecular imaging. We discussed how aptamers have been used in positron emission tomography (PET) scans, magnetic resonance imaging (MRI), CT, ultrasound and nuclear imaging. Also, we briefly discuss about the conjugation strategies of fluorescent probes with aptamers.

## 2. Aptamers in diagnostics

Key for the effective treatment of any disease is an early and accurate diagnosis. Early diagnosis is only possible with sensitive methods involving acute detecting agents such as aptamers. Aptamers have been used for the detection of bacterial, parasital and viral mediated diseases along with cancer (figure 2). In the field of diagnostics, aptamers are applied for the detection of infective agents itself, the detection of the antigens/toxins (bacteria), or biomarkers (cancer), or a combination. Some existing diagnostic methods are in need of high-end machinery and skilled people, which increases the cost. Currently used methods in diagnosis may take long due to the isolation of infective agents and subsequent cultivation for detection. Also, in some cases enrichment of causative agents is required for proper diagnosis because of its low titer. In order to address these points and simplify the process, aptamers can be used. In the following sections we discuss the use of aptamers as a diagnostic tool for detection of various diseases including cancer and other diseases caused by bacteria, parasites and viruses.

### 2.1 *Bacteria*

Increasing bacterial infections have triggered an unmet demand for the development of rapid and sensitive point of care diagnostic tests. In case of *Staphylococcus aureus,* infection-detection combined with culturing takes days while other methods are less cost effective. A new ultrasensitive and non-polymerase chain reaction (PCR)-based method has been developed which measures the resonance light-scattering signal of aptamer-conjugated gold nanoparticles to detect a single cell of *S. aureus* cell within 1.5 h (Chang *et al.* 2013). A sandwich luminescent bioassay was developed for the detection of *Salmonella typhimurium* and *S. aureus* simultaneously using an aptasensor with magnetic nanoparticles (MNPs). In this bioassay two different aptamers were used, and both were immobilized on magnetic nanoparticles to capture the bacteria; furthermore, these two aptamers were modified with nanoparticles making them dual color labels, and allowed to bind the captured bacteria. The luminescent signal generated by this assay showed a linear correlation with *S. typhimurium* and *S. aureus* concentrations. Detection limits for this method was found to be 5 and 8 cfu/ mL for *S. typhimurium* and *S. aureus,* respectively. This assay is highly sensitive and selective for these two different types of bacteria (Duan *et al.* 2012). Zelada-Guillén and coworkers reported label free detection of *S. aureus* in real-time. A biosensor was fabricated with aptamers against *S. aureus* and single-walled carbon nanotubes (SWCNTs) acting as potentiometric transducers. The aptamers were attached to SWCNTs in two ways: (i) drop-casted pyrenil modified aptamers were non-covalent adsorbed to the external walls of the SWCNTs, and (ii) amine-modified aptamers were covalently bound to carboxylic groups at the ends of the SWCNTs which were introduced by oxidation. Both approaches indicated a linear correlation between potential, as a function of decade, and bacteria concentration. This biosensor was tested on pig skin as a substitute for human skin (Zelada-Guillén *et al.* 2012). Recently the dos Santos team used previously screened aptamers for *S. aureus* to evaluate its use in diagnostics by scintigraphy. The aptamers were directly radiolabeled with technetium-99m (99mTc) and injected in three groups of Swiss mice. The first two groups were infected with *S. aureus* and *C. albicans* individually, whereas the third group was induced for aseptic inflammation. Aptamers were

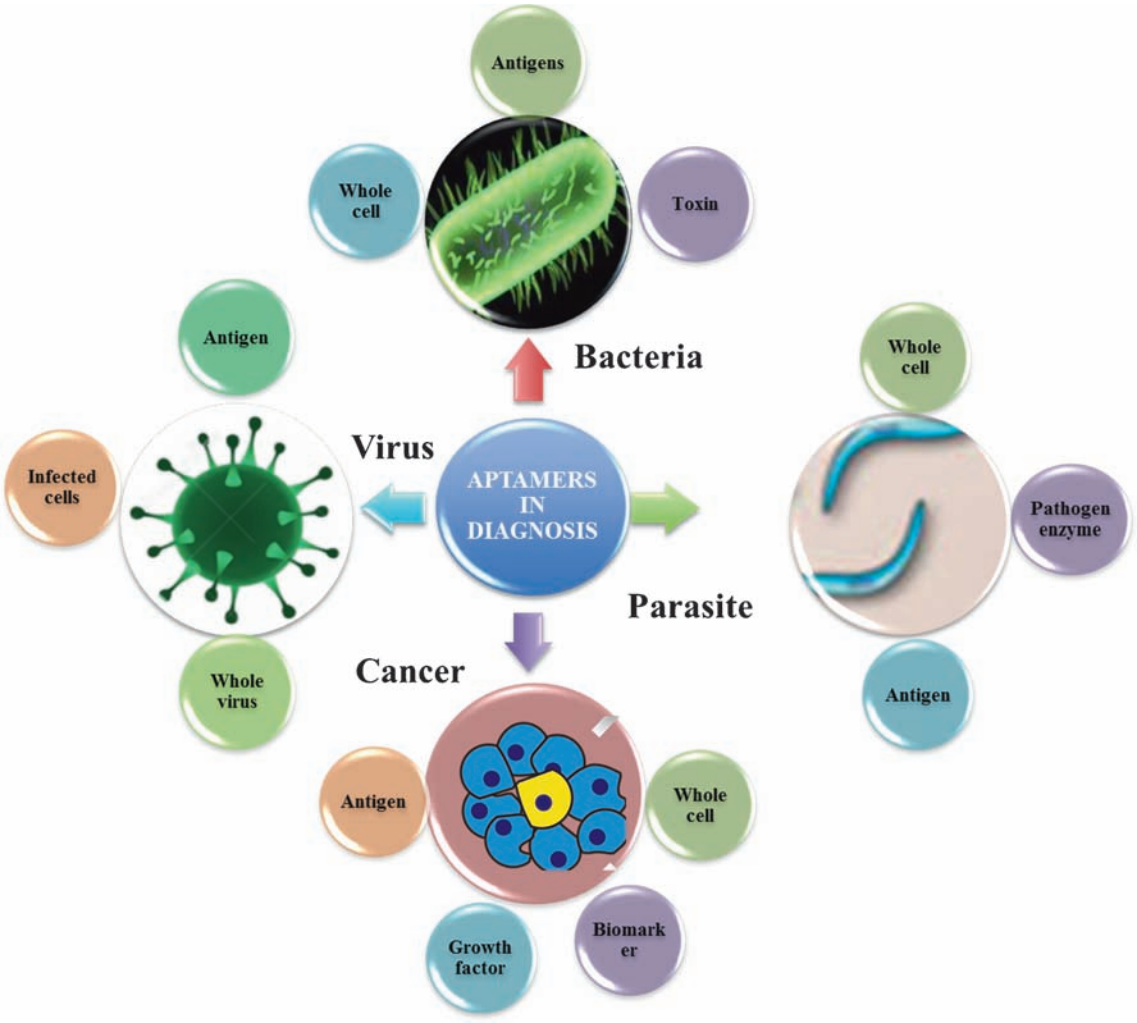


**Figure 2.** Application of aptamers in field of diagnosis.

able to detect infection foci caused by *S. aureus* and *C. albicans* with a target/non-target ratio of 4.0±0.5 and 2.0±0.4, respectively. The ratio for aseptic inflammations was 1.2±0.2. These results show the potential of 99mTc labeled aptamers for the diagnosis of bacterial infections by scintigraphy (dos Santos *et al.* 2015). Another report states development of sensor based on graphene bound to interdigital gold electrodes (IDE) connected to a series of electrode piezoelectric quartz crystals (SPQC) for the specific detection of *S. aureus*. *S. aureus* aptamers were connected to graphene via π–π stacking of DNA bases. The aptamers fall from the graphene surface in the presence of *S. aureus* resulting in a change in the electric parameters and altering the oscillator frequency of the SPQC. This sensor can detect *S. aureus* rapidly and specifically within 60 min and can be used for clinical diagnosis (Lian *et al.* 2015).

Along with early detection of a disease, it is also important to find the causative agent of the disease which helps in deciding the correct treatment plan. Here, one bottleneck is the detection limit, which is sometimes below the level of the infection dose required by the pathogen to onset a disease or because the diagnostic method is not adept to detect low levels of pathogens. Salmonellosis is one of the major food borne diseases caused by *Salmonella enterica serovar typhimurium*. Enrichment of *S. typhimurium* cells in the sample is important, which can be carried out by concentrating *S. typhimurium* using specific aptamers, followed by direct detection using qPCR. Similarly, DNA and RNA aptamers were selected against several species of Salmonella with varying dissociation constants (table 1).

*Escherichia coli* (*E. coli*) O157:H7 is an enterohemorrhagic *E. coli* strain, which secretes exotoxins known as

**Table 1.** Aptamers selected against *Salmonella* species

| Bacteria | Aptamer | Kd | Application | Reference |
|---|---|---|---|---|
| *S. typhimurium* | DNA | 1.73±0.54 μM | | Dwivedi *et al.* 2013 |
| *S. typhimurium* | RNA | 20 nM | Aptamer-immobilized ELISA and aptamer-linked precipitation experiments | Han and Lee 2013 |
| *S. typhimurium* | DNA | 3.0 nmol | | Moon *et al.* 2013 |
| *S. typhimurium* | DNA | 6.33±0.58 nM | Fluorescent bioassay | Duan *et al.* 2013 |
| *S. paratyphi A* | DNA | 47±3 nM | Biosensor based on SWNTs and DNAzyme-labeled aptamer detection probes | Yang *et al.* 2013 |

verotoxins (shiga like toxins). Currently available detection methods for this strain are time consuming as very low dose of infection causes the disease and pathogen numbers have to be increased to reach the detection level. A subtractive cell-SELEX method was employed by Lee *et al.* (2012) for selective and specific aptamer detection of *E. coli* O157:H7 related to food borne diseases. In this method the RNA aptamer library was allowed to bind with *E. coli* K12, and unbound aptamer library was further used for the selection against *E. coli* O157:H7. The specificity of the aptamers was tested using aptamer-immobilized ELISA, real-time PCR analysis, and an aptamer-linked precipitation test. These tests revealed the specificity of aptamers towards lipopolysaccharide O antigen on O157:H7. Therefore, authors suggest its application as a diagnostic ligand for the detection of *E. coli* O157:H7 (Lee *et al.* 2012). When cell SELEX is used, most of the time it is not possible to recognize the target for the selected aptamers simply because the targets for different aptamers on the cell surface could be the same or different. Thus many aptamers can be selected towards a cell with high affinity and specificity. Taking advantage of this effect by combining aptamers against same bacteria to increase the sensitivity, Kim *et al.* (2014) screened aptamers against *E. coli* using cell SELEX and compared the sensitivity of biosensors with a single aptamer and a cocktail of aptamers. A mixture of fluorescence-tagged aptamers showed an enhanced signal compared to the single aptamer. This was further evaluated by immobilizing the single aptamer and the mixture of aptamers on gold electrodes resulting in a detection limit of approximately 18 times more than that of the single aptamer. This strategy was also suggested for the detection of other bacteria, cancer cells, and tissues (Kim *et al.* 2014).

*Burkholderia pseudomallei* is a causative agent of melioidosis. The symptoms may include pain in chest, bones/joints, cough, skin infections, lung nodules and pneumonia which are noticed after high exposure to the bacteria. Lack of intensive antimicrobial treatment for a prolonged period may cause death. Hence, the need of an improved diagnostic reagent is vital for early detection. For this purpose, high affinity aptamers were selected against recombinantly expressed *B. pseudomallei* specific proteins: a putative oxidoreductase BPSL2748 and secretion pathway proteins (BipD and BopE type III), which are considered to be potential targets for applications in diagnostic assays for *B. pseudomalle* (Gnanam *et al.* 2008).

Bacterial toxins are major components of virulence factors of pathogenic bacteria and thus detecting them is an imperative for the diagnosis of a bacterial disease. For example, toxin A (TOA) is one of the lethal enterotoxins produced by *Clostridium difficile* and causes antibiotic-associated diarrhea and pseudomembranous colitis in humans. Presently available laboratory tests for the diagnosis of *C. difficile* infection are by detecting bacteria itself and TOA or Toxin B (TOB is another potent cytotoxin of *C. difficile*) in stool samples. However, the microbiological culture method is insensitive and time consuming, the cytotoxic assay is costly and requires expertise. Additionally, an enzyme immunoassay can give false positive results due to cross-reacting antibodies, and polymerase chain reaction (PCR)-based tests requires pre-treatment of sample, where small amounts of free DNA can affect the results. Here, aptamer biosensors for the detection of TOA in clinical samples provide a better alternative. Luo *et al.* (2014) developed a biosensor based on the conformational change of an aptamer for quantitative analysis of TOA in stool samples. This biosensor has thiolated ssDNA as a capture probe immobilized on a Nafion–thionine–gold nanoparticle modified screen-printed electrode (SPE), which is hybridized with a horseradish peroxidase (HRP)-labeled aptamer for detection. In the presence of TOA, there is a conformational change in the aptamer and HRP labeled aptamer is released from the complex in turn lowering the response current. However, the biosensor was not effectively able to differentiate between TOA and TOB, which directs towards finding specific aptamers in the future (Luo *et al.* 2014).

Tuberculosis (TB) is a fatal disease spread worldwide. Available diagnostic tests for TB are time consuming, expensive, or have low sensitivity, whereas aptamers with their ability to be highly sensitive and specific can be apt as an

alternative diagnostic tool. Rotherham *et al.* (2012) selected aptamers against the 10-kDa culture filtrate protein (CFP-10) and the 6-kDa early secreted antigen target (ESAT-6), which are potent T-cell antigens recognized in over 70% of TB patients. In total six aptamers were selected against these targets, which had Kd values in the nanomolar (nM) range. The study suggested that aptamers are feasible for diagnosis of active TB in human biological samples obtained from patients with and without active TB (Rotherham *et al.* 2012). Similarly, Tang *et al.* (2014) selected aptamers for CFP-10 and ESAT-6, which were able to detect these proteins in serum. The authors suggest that these aptamers have a broad range of application, as they were able to detect CFP10 and ESAT6 in active pulmonary TB patients, extrapulmonary TB patients and healthy donors by using an enzyme-linked oligonucleotide assay (Tang *et al.* 2014). Zhu and coworkers developed a sandwich ELISA based on an anti-MPT64 antibody aptamer for the diagnosis of TB. They used a combination of immunization and genetic engineering to obtain an anti-MPT64 antibody, which was further used as a target for SELEX. This method can be used for the serological diagnosis of pulmonary TB, both in sputum smear positive- and negative-patients, with a lower detection limit of 2.5 mg/L (Zhu *et al.* 2012a). Surface plasmon resonance-based SELEX (SPR-SELEX) was used to select two RNA aptamers against EsxG protein with nM affinity. This protein is a secreted substrate of the ESX-3 secretion system. The ESX-3 secretion system is one of the complexes of mycobacteria, which help the bacteria to grow in low iron environments such as macrophages. Thus, specific aptamers towards the EsxG protein can be used as molecular probes for TB diagnosis (Ngubane *et al.* 2014).

### 2.2 *Parasites*

*Trypanosoma cruzi* causes Chagas disease, estimating about 6 million to 7 million people to be infected worldwide. Nearly 30% of chronically infected people with Chagas disease develop cardiac alterations and up to 10% develop digestive, neurological or mixed alterations which may require specific treatment. The parasite has to invade the host cells in order to cause the disease. This invasion is most likely supported by the cell surface macromolecules laminin, thrombospondin, heparan sulfate, and fibronectin. Therefore, these molecules were used as targets for selection of aptamers by Ulrich *et al.* (2002). The selected nuclease resistant RNA aptamers showed specific binding affinities in the 40-400 nM range and they were shown to inhibit *T. cruzi* invasion in LLC-MK2 monkey kidney cells *in vitro* (Ulrich *et al.* 2002). The currently available detection method of *T. cruzi* in humans is PCR based and is only sensitive at the acute stage of the disease when parasite numbers are high in the blood. Thus, to improve the PCR based method Nagarkatti *et al.* (2012) utilized a whole cell SELEX method for the selection of serum stable RNA aptamers against living *T. cruzi* trypomastigotes. The high affinity aptamer Apt68 was found to be specific towards *T. cruzi* trypomastigotes and it captured living parasites when biotinylated and immobilized on solid phase. Apt68 was applied in collecting parasites from parasite-spiked blood at low concentrations to facilitate the PCR based assay for detection of *T. cruzi* (Nagarkatti *et al.* 2012). A combinatorial selection method was used to select RNA aptamers against *Trypanosoma* using living *Trypanosoma brucei* parasites, which causes African trypanosomiasis. The selected aptamers showed specificity towards a 42 kDa protein present in the flagellar pocket of the parasite (Homann and Göringer 1999). *T. brucei* escapes the host immune system by antigenic variations in surface proteins known as variant surface glycoproteins. Lorger *et al.* (2003) targeted these variant surface glycoproteins and selected a serum stable RNA aptamer with sub-nanomolar affinity. Bound with an antigenic side group the aptamer was able to direct antibodies towards the surface of the parasite *in vitro* (Lorger *et al.* 2003). Furthermore, Homann *et al.* (2006) selected a 2'-NH(2)-modified RNA aptamer towards living trypanosomes with an affinity at nanomolar range with a half-life of more than 30 hours in human serum (Homann *et al.* 2006).

Leishmaniasis caused by *Leishmania* is another important disease which severely affects millions of people worldwide. Martín *et al.* (2013) used *L. infantum* KMP-11, LiH2A and LiH3 proteins from Leishmania as targets. The two selected aptamers had different secondary structures, but were able to recognize the same peptides located on the side of the LiH2A. These aptamers were able to detect the parasite on ELONA platforms and were able to purify o LiH2A from complex mixtures (Martín *et al.* 2013). Kinetoplastid membrane protein-11 (KMP-11) is a widely distributed, conserved kinetoplastid and a major cell membrane component of kinetoplastid parasites like *Leishmania infantum*. DNA aptamers were selected against KMP-11 bound to colloidal gold during SELEX processes intended for diagnostic purpose. The use of colloidal gold added a higher mass to the protein in order to be purified by centrifugation during the partition phase of the SELEX process (Moreno *et al.* 2003).

The aptamer's secondary structure plays an important role in determining its specificity and high affinity towards the target. Aptamers selected against lactate dehydrogenase of *Plasmodium falciparum,* a causative agent of malaria, had a dissociation constant of 42 nM. The crystal structure of the protein-aptamer complex revealed two aptamers binding one tetramer of the protein, where both of them displayed a distinct hairpin loop structure involved in the binding with a *Plasmodium* lactate dehydrogenase loop that is absent in human lactate dehydrogenase. Furthermore, gold nanoparticles were

conjugated to this aptamer for a colorimetric application to detect malaria (Cheung *et al.* 2013).

### 2.3 *Viruses*

The usual methods for the detection of viruses are time consuming so a need for more efficient, specific and faster technique is evident. Aptamers are a good solution in all these aspects. For example, Parekh *et al.* (2010) used cell SELEX to select aptamers against *Vaccinia* virus, since it is closely related to smallpox virus *Variola*. The selected aptamer was highly specific towards virus-encoded hemagglutinin expressed on the surface of infected cells. Thus, aptamers can be generated against a given specific infectious agent like virus and can also be used for diagnostic purposes (Parekh *et al.* 2010). For early detection of hepatitis C virus (HCV) from patient's sera a protein chip-based assay was developed. Here, RNA aptamers specific for HCV core antigen were immobilized on a sol-gel based material to form a biosensor, and then patient sera along with Cy3-labeled human antibody was applied for the detection of HCV infection. The RNA aptamers showed stronger signals with the infected sera compared to negative controls (Lee *et al.* 2007). Furthermore, a functional ssDNA aptamer specific towards HCV envelope surface glycoprotein E2 was screened by cell surface-SELEX. The selected ZE2 aptamer showed highest specificity and affinity to E2-positive cells from patient sera when tested with the E2 antigen-aptamer assay, and assays for HCV RNA quantification or HCV antibody detection. Sandwich ELISA was used for virus capture assays using ZE2, indicating that ZE2 aptamer can also bind to HCV and thus can be used for capture and diagnosis of HCV (Chen *et al.* 2009a). After treatment against HCV it is important to monitor efficacies of potential anti-HCV drugs, for example by quantification of HCV infectious units. The conventional foci counting method is laborious and time-consuming, while other methods including quantitative reverse transcriptase-PCR (RT-PCR) and immunological measurement of core proteins are not ideal either. The viral RNA, which is measured by real-time RT-PCR cannot correlate with the infectivity of a HCV sample, moreover, immunological measurement of core proteins also fails since core proteins exist in both infectious and noninfectious HCV particles. A recently developed assay called 'Enzyme Linked Apto-Sorbent Assay (ELASA) for the quantification of infectious HCV particles uses aptamers against the HCV E2 envelope protein (Park *et al.* 2013). ELASA utilizes two different aptamers recognizing two different regions of HCV E2, where one capture aptamer is attached directly to the surface of a microtiter plate well and binds to E2 proteins on the virus surface, while the other detection aptamer is biotinylated. In the presences of HCV the biotinylated aptamer will react with streptavidin conjugated with HRP correlating proportionally to the amounts of HCV E2. This assay can also monitor the activities of anti-HCV drugs. Liu and coworkers were the first to report a RNA aptamer, which could bind to a surface antigen (HBsAg) of Hepatitis B virus (HBV for the diagnosis of the virus. They selected aptamer HBs-A22, which binds specifically to the HBsAg expressing hepatoma cell line HepG2.2.15, but did not bind to HBsAg-devoid HepG2 cells (Liu *et al.* 2010).

*Avian influenza viruses* (AIV) have caused devastating outbreaks worldwide with high mortality rates in both poultry and humans. To contain spreading of the disease, quick and sensitive diagnosis of H5N1 infections is essential. Currently available laboratory methods use conventional virus cultures followed by serological differentiation, RT-PCR and real- time RT-PCR, which are time consuming and demand technical expertise as described earlier. As an alternative an aptamer hydrogel based quartz crystal microbalance (QCM) biosensor was developed by Wang and Li (2013) for the detection of AIV H5N1. Specifically selected aptamer against AIV H5N1 surface protein was hybridized with ssDNA to form the cross linker in the polymer hydrogel. Furthermore, the hydrogel was immobilized on the gold surface of the QCM sensor, where the hydrogel is in a shrunken state in the absence of the H5N1 virus due to the crosslinking between the aptamer and ssDNA in the polymer network. Presence of H5N1 virus causes the dissolution of the linkage between the aptamer and ssDNA resulting in subsequent swelling of the hydrogel. The swelling of the hydrogel is observed in terms of a decreased frequency by the QCM sensor. The hydrogel QCM aptasensor has lowered the detection time twofold when compared with the anti-H5 antibody coated QCM immunosensor, which takes an hour (Wang and Li 2013). The influenza virus acquires new antigenicity with every outbreak, leading to the emergence of new virus strains, for which new diagnostic tools must be developed rapidly to detect novel influenza strains. Shiratori *et al.* (2014) developed DNA aptamers that bind to HA1 proteins of multiple influenza A virus subtypes. A novel aptamer-based assay for evaluating the binding properties of the selected aptamers was developed. A microtiter plate well coated with viral protein and flooded with HA1 specific biotinylated aptamers is followed by the addition of streptavidin-HRP. In this approach H5N1, H1N1, and H3N2 subtypes of influenza A virus were detected (Shiratori *et al.* 2014). Bruno and coworkers screened DNA aptamers against various virulent arboviruses like Chikungunya, Crimean-Congo hemorrhagic fever (CCHF), dengue, tick borne encephalitis and West Nile viruses using recombinant envelope proteins or synthetic peptides and/or whole inactivated viruses. They showed the diagnostic utility of some aptamers for arbovirus detection on the surface of magnetic micro-beads, lateral flow chromatographic assays and in fluorescent-based sandwich assay (Bruno *et al.* 2012). Park *et al.* (2011) screened an aptamers against Hemagglutinin (HA) which is present in the virus envelope. Antiviral efficacy of the selected RNA aptamer HAS15-5, binding to HA1, was

determined by a hemagglutination inhibition assay using egg allantoic fluids harboring the virus. This lead to blocking and inhibition of viral HA, and thus can further be developed as a diagnostic tool as well as a novel antiviral agent against type H5 avian influenza virus (Park *et al.* 2011).

Drug-resistant variants of HIV-1 are also known to be resistant to anti RT-RNA aptamers. Li *et al.* (2008) isolated two aptamers against Mutant 3 (M3) from the multidrug-resistant HIV-1 RT panel. These aptamers were able to bind a new RNA-binding epitope on the surface of HIV-1 RT. Using these aptamers, M3 and wild type HIV-1 RTs could be distinguished using an aptamer based microarray which can help in determining HIV-1 drug resistance. By probing protein conformation as a correlation to drug resistance an additional and useful measure has been introduced (Li *et al.* 2008).

Current diagnostic tools for the isolation of viruses during an outbreak rely on serotyping. Several aptamers were selected against the recombinant HA protein from swine Influenza A virus (IAV) H3 cluster IV for a more rapid approach. From the selected aptamers the HA68 aptamer was able to bind and detect H3N2v isolated from recent human cases. This aptamer can be used as a subtype-specific aptamer against Swine H3N2 IAVs for fast detection and virus sero-typing (Wongphatcharachai *et al.* 2013). Dengue fever is one of the prominent arthropod-borne viral diseases and it can be detected by ELISA-based and reverse transcriptase polymerase chain reaction methods. A biosensor for the detection of the Dengue virus genome was developed by Fletcher and co-workers which consists of three modules: (a) detection of target the nucleic acid, (b) signal transduction and (c) signal detection module. In the detection module the target-of-interest is detected by a stem/loop linker oligonucleotide. The loop portion is complementary to the target-of-interest, while one of the strands of the stem duplex (i.e. the trigger) is complementary to a portion of the aptamer within the transducer module. The signal transducer comprises an *EcoRI* inhibitory-aptamer complex. In the signal detection module an oligonucleotide like molecular break-light (MBL) is used. It consists of a stem/loop-forming unit with a 5′ fluorophore and 3′ quencher with an *EcoRI* recognition sequence in the stem duplex. When the dengue virus genome is present the linker interacts with the signal transducer module and liberates the restriction endonuclease *EcoRI* from aptamer-mediated inhibition. The active *EcoRI* molecule then cleaves multiple signaling molecules by dissociation of the fluorophore and the quencher resulting in a detectable signal. In this modular system the linker can be changed for the target-of-interest, e.g. for the detection of the four Dengue genome serotypes (DEN1-DEN4) without modifying the signal transduction module (Fletcher *et al.* 2010). Dengue virus enters the host cell through receptor-mediated endocytosis with the help of envelope (E) protein, cell surface receptors. The 395 residue E ectodomain has three domains, namely EDI, EDII and EDIII (residues 295–394), and the EDIII is possibly involved in host cell receptor binding. A thioaptamers targeting this EDIII protein of dengue-2 virus was developed by Gandham *et al.* (2014). This aptamer DENTA-1 was able to bound DENV-2 EDIII which is adjacent to a known neutralizing antibody binding site with a kd of 154 nM. Thus, can be used as potential candidate for diagnosis as well as for antiviral drug discovery (Gandham *et al.* 2014).

DNA aptamers can also be used as a replacement of antibodies to characterize the subtle conformational changes in therapeutic proteins which might occur during pasteurization step of manufacturing. Early detection of these subtle conformational changes is important for safety, stability and efficacy of the therapeutic protein. It has been previously shown that heat treatment does not affect the protein activity; however, the resulting conformational changes cannot be detected by antibodies. To address this issue, Zichel *et al.* (2012) developed a panel of aptamers for the detection of conformational changes in thrombin after heat treatment. These aptamers were also used in both ELISA and label-free platform type assay to characterize different thrombin products (Zichel *et al.* 2012).

### 2.4 *Cancer*

Biomarkers for specific diseases are an important tool for the timely and effective management of pathological conditions, including determination of susceptibility, diagnosis, and monitoring efficacy of preventive or therapeutic strategies. Early detection of cancer is crucial in oncology. In this aspect, aptamers play a crucial role in screening against particular cancer cell biomarkers. When biomarkers and efficient tools like specific aptamers with high affinity are merged, an effective tool to detect their interaction using a sensor is needed, e.g. an aptasensor. Thus, numerous aptasensors were developed recently which facilitate the detection of various cancers at an early stage. In this section, we discuss about the aptamer mediated diagnostic tools for cancer detection, categorized according to the cancer subtype:

2.4.1 *Breast cancer detection:* Human mucin-1 (MUC1) and vascular endothelial growth factor-165 (VEGF-165) are important biomarkers for the diagnosis of breast cancer. Elevated levels of MUC1 in breast cancer is associated with its recurrence and increased lymph node metastases (Mukhopadhyay *et al.* 2011), while overexpression of VEGF is related to increased mortality in lymph node-negative and lymph node-positive breast cancer patients (Ghosh *et al.* 2008). Many aptasensors have been developed using these two biomarkers for the assessment of breast cancer. Previously discovered aptamers for MUC1 and VEGF165 were used by Zhao *et al.* (2012a) for the development of so called 'signal-on' electrochemical aptasensors. This aptasensor has a Fc-labeled cDNA-

fragment, immobilized on a gold electrode, with a complementary binding site for MUC1 and VEGF165 aptamers. In absence of MUC1 and VEGF165 biomarkers the aptamers are hybridized with the cDNA-fragment to form a long double strand that keeps Fc-molecules away from the electrode surface, resulting in no signal. In the presence of only one of these biomarkers, one of the aptamers will be detached from the cDNA-fragment, thus, reducing the distance between electrode surface and the Fc-molecule, resulting in a minor signal. However, in the presence of MUC1 and VEGF165, both, the aptamers bind to their respective targets, triggering the reduction of distance between the electrode and the Fc-molecule due to stem loop formation by the ss-cDNA-fragment, resulting in a stronger signal. The method of using two tumor markers over only one can be expanded to other types of tumors by changing the aptamers for their respective targets (Zhao *et al.* 2012a).

Another sensing platform developed by Zhao *et al.* (2012) uses aptamers and RNA polymerase-based amplification for the detection of Michigan cancer foundation-7 (MCF-7) breast cancer cells. In this assay, a biotinylated aptamer specific to MUC1 was immobilized on a microtiter plate well using streptavidin that captures tumor cells (i.e. recognition probe). To this, a complex oligonucleotide, composed of a MUC1 aptamer region and single-stranded T7 RNA polymerase promoter (ssPr), is added to form a sandwich structure. A template probe comprised of complimentary ssPr and a template sequence hybridizes with the ssPr region of the recognition probe forming a double-stranded T7 RNA polymerase promoter site (dsPr). Finally, T7 RNA polymerase can attach and generate multiple copies of RNA strands which in turn are detected by the addition of SYBR Green II dye. The cell concentration is determined by the fluorescence intensity with 500 cells/mL limit of detection (LOD) (Zhao *et al.* 2012b).

Furthermore, a signal-on fluorescence aptasensor was developed for label-free detection of MCF-7 breast cancer cells. This sensor uses a MUC1 specific aptamer which binds MCF-7 cells and is then removed by centrifugation. A signal probe complementary to anti-MUC1 aptamer is added to the supernatant along with terbium (III) ($Tb^{3+}$), as ssDNA subsequently enhances the emission of $Tb^{3+}$. However, the lack of MCF-7 cells results in hybridization of the signal probe with aptamer forming ds-DNA. The ds-DNA cannot increase the emission intensity of $Tb^{3+}$ compared to ssDNA. This signal-on aptasensor has a LOD of 70 cells/mL (Cai *et al.* 2015).

A label-free and electrical detection of vascular VEGF using anti-VEGF aptamer-modified Si nanowire field-effect transistors (SiNW-FETs) was developed for breast cancer diagnosis. SiNW-FET biosensors were prepared by immobilization of anti-VEGF aptamers on the surface of modified single-crystalline SiNWs (n-type and p-type). Since the VEGF molecules are positively charged under experimental conditions at pH 5.4 (the iso-electric point of VEGF is 8.5), they are effectively screened against RNA aptamers due to their negative charge. The resulting charge depletion in the nanowire channel and the decrease in conductance in case of the p-type Si nanowire biosensors were observed. However, this positive gate voltage by VEGF had the opposite effect on the device in case of n-type Si nanowire biosensors. The LOD of the VEGF biosensor was ~1 nM for n-type and 100 pM for p-type SiNW-FETs (Lee *et al.* 2009). In addition, for detection of breast cancer, a new quantitative immunohistochemistry (QIHC) microfluidic polydimethylsiloxane (PDMS) platform was developed with aptamer as a reporting probe specific to the Fc region of IgG antibodies. The microfluidic PDMS platform harbors breast cancer cells in paraffin block-slides to form a micro-reaction chamber. Primary antibodies specific to breast cancer marker proteins were loaded followed by the aptamer. The marker proteins were quantified by real time amplification of the aptamers using quantitative nucleic acid sequence based amplification, resulting in detection of cancer proportional to the concentration of different primary antibodies for marker proteins. This microfluidic platform was also used for aptamer-assisted IHC for breast cancer cell lines and showed good correlation with conventional IHC (Yeong Won *et al.* 2013).

Another electrochemical technique based on the aptamer–cell–aptamer sandwich architecture for the detection of MCF-7 human breast cancer cells was based on immobilized MUC1 aptamer on a gold electrode. In the presence of target cells and after incubation with the HRP-labeled MUC1 aptamer, the electrochemical response is catalysed by HRP, with the help of thionine, an electron mediator. The LOD for this technique was 100 cells/mL (Zhu *et al.* 2013a).

A selective electrochemical diagnosis of breast cancer was developed by Zhu and coworkers based on a hydrazine–Au nanoparticle–aptamer bioconjugate (Hyd–AuNP–Apt), where the aptamer is specific toward human epidermal growth factor receptor 2 (HER2), which is overexpressed in breast cancers. Here, hydrazine, capable of reducing silver ions to silver metal is attached to AuNPs and aptamer to form Hyd–AuNP–Apt. The sensor probe has a monoclonal anti-HER2 antibody immobilized on electrode, which is the nanocomposite surface with self-assembled DPB (2, 5-bis (2-thienyl)-1H-pyrrole-1-(p-benzoic acid)) and AuNPs attached to indium tin oxide coated glass. During the detection of HER2-overexpressing SK-BR-3 breast cancer cells, a sandwich is formed between the sensor probe, HER2 expressing cells and Hyd–AuNP–Apt, which is then treated with silver nitrate solution where silver ions are reduced by hydrazine and deposits onto the breast cancer cells. This deposited silver on breast cancer cells can be observed under a microscope and analysed using square wave stripping voltammetry to determine the

amount of HER2 cells with a LOD of 26 cells/mL in human serum samples (Zhu *et al.* 2013b).

2.4.2 *Cervical cancer:* In case of cervical cancer, most of the carcinogenesis is caused by human papillomavirus (HPV) infection, which may or may not lead to carcinogenesis and, hence, there is need to find biomarkers that differentiates the two. For this purpose, Graham and Zarbl screened a panel of aptamers against cell surface epitopes of human cervical cancer using a HeLa cell line for whole cell SELEX and isogenic HeLa cells for negative selection. The aptamers had a high affinity for epitopes specific to the cell surface of non-tumorigenic revertants derived from the human cervical cancer HeLa cell line, but did not bind to the HPV transformed cervical cancer cell line. This indicated that the aptamers are specific for epitopes that were lost during HPV induced transformation of the cervical cells and can be used to identify new biomarkers that are related to carcinogenesis and for diagnosis (Graham and Zarbl 2012).

2.4.3 *Burkitt lymphoma detection:* Burkitt lymphoma diagnosis is challenging due to its morphologic overlap with diffuse large B cell lymphoma and the person's level of experience performing diagnosis (Rane *et al.* 2014). Shi *et al.* (2010) were the first to report molecular engineered aptamers with signaling molecules for fluorescence imaging of specific tumor cells in a mouse, for which, a known aptamer, TD05, specific against Ramos cells – a human Burkitt's lymphoma cell line – was used. The specificity of the TD05 aptamer was tested via labelling with Cy5 dye. Cy5-TD05 aptamer along with control Cy5-Sgc8a and Cy5 dye alone were injected into mice harboring a Ramos tumor. The authors observed that Cy5-TD05 accumulated in the Ramos tumor while Cy5 dye and the control probe Cy5-Sgc8a were gradually cleared from mice (Shi *et al.* 2010). For visualized detection of Ramos tumor cells a chemiluminescence imaging array (CLIA) strategy alongwith a combination of tumor cell aptamer recognition and amplification of bio-bar-code nanotechnology with rolling circle amplification (RCA) for signal amplification was used. The aptamers TD05 and TE02 bind specifically to Ramos cells and were used in the CLIA. Biotinylated TE02 was attached to a streptavidin-coated 96-well microtiter plate as a capture aptamer, and thiol-TD05 was immobilized on the AuNPs along with circular DNA templates as bio-barcodes hybridized with primer for recognition of cells and to avoid cross-reactions. Upon addition of Ramos cells on the CLIA a sandwich assay format is formed to give a AuNP-TD05aptamer-cell-TE02 aptamer complex. When Klenow DNA polymerase and dNTPs are added to this complex a RCA is initiated on the AuNPs which produces a long ssDNA with tandem-repeat sequences, which bind to biotinylated detection probes. This biotinylated probe further binds to streptavidin–HRP to which luminol–$H_2O_2$–PIP is added for 10 min and visual detection is performed by observing the chemiluminescence intensity. Quantitative analysis was done by using analysis software for reading the optical intensity, and 3 σ was used to detect LOD at 163 Ramos cells/mL. Even with the complexity of the method, the authors claim it to be an operationally robust, easy and cost-effective strategy (Bi *et al.* 2013).

2.4.4 *Multiplexed cancer cell detection:* Chen *et al.* (2009b) developed an aptamer-conjugated fluorescence resonance energy transfer (FRET)-nanoparticles (NPs) assay for the detection of simultaneous multiplexed monitoring of cancer cells. They used the sgc8 aptamer for CEM cells (human acute lymphoblastic leukemia cells) conjugated to a NP (FAM-R6G), the TDO5 aptamer against Ramos cells (human Burkitt's lymphoma cells) coupled with a NP (FAM-R6G-ROX), and the T1 aptamer for Toledo cells (human diffuse large cell lymphoma) coupled to a NP (FAM). These conjugated aptamers when added to cancer cells were able to bind specifically to the respective cells (Chen *et al.* 2009b).

Viraka Nellore *et al.* (2015) reported for the first time an efficient capture and accurate identification of multiple types of circulating tumor cells (CTCs) from infected blood using aptamer-modified porous graphene oxide membranes. They used Cy2-modified S6 aptamer that binds specifically to HER2 biomarker for breast cancer CTCs, Cy5-modified A9 aptamer that binds to prostate-specific membrane antigen (PSMA), a biomarker for prostate cancer CTCs, and the Alexa Fluor 488 dye modified YJ-1 aptamer specific towards CEA biomarker for colon cancer CTCs. These three aptamers were conjugated to porous graphene oxide membranes, where graphene oxide is an efficient quencher and, thus, when dye conjugated aptamers are attached to graphene oxide, fluorescence from dye gets quenched by graphene oxide. In principle, when the dye-conjugated aptamer binds to targeted cancer cells the distance between the dye and graphene oxide increases resulting in fluorescence. This graphene oxide membrane conjugated with aptamers was able to capture multiple types of tumor cells selectively and simultaneously from infected blood and was also able to identify captured cancer cells via multicolor fluorescence imaging (Viraka Nellore *et al.* 2015).

2.4.5 *Cancer detection using common biomarkers:* Many cell surface cancer biomarkers are common in a variety of cancers, e.g., nucleolin, carcinoembryonic antigen (CEA), HER-2, epithelial cell adhesion molecule (EpCAM) etc. Taking advantage of this information many aptamers have been developed against these biomarkers, which serve as a diagnostic tool for the generic detection of these cancer types. We have discussed some of these recently developed aptamers and aptasensors below.

The cancer biomarker nucleolin is overexpressed on the plasma membrane of tumor cells as compared to normal cells. To detect cancer cells Feng *et al.* (2011) used aptamer AS1411, specific for nucleolin, to develop a label-free detection method based on a graphene electrochemical-aptasensor, which was utilized in the phase II clinical trial. Perylene tetracarboxylic acid (PTCA) was used to functionalize chemically converted graphene, and the $NH_2$-modified aptamer strand was linked to it by a carbodiimide-mediated wet-chemistry approach. These aptamer-PTCA nanocomposites were used as nanoscale anchorage substrates to capture tumor cells on the electrode surface. Electrochemical impedance spectroscopy (EIS) was then used to monitor change in electron transfer resistance. Addition of AS1411 complementary DNA (cDNA) hybridized with the aptamer and disrupted aptamer-tumor cell binding, regenerating the sensors. The LOD for HeLa cells was calculated to be 794 cells/mL at 3 σ (Feng *et al.* 2011).

Highly glycosylated CEA is another over-expressed protein in a large number of tumors. An electrochemical aptamer biosensor was designed by Shu and coworkers based on the signal amplification of AuNPs for the detection of a CEA. In this biosensor CEA is sandwiched between an Au electrode with thiol-terminated CEA aptamer-1 and the AuNPs with thiol-terminated CEA aptamer-2 and 6-ferrocenyl hexanethiol (Fe). The concentration of CEA was determined by the detection of Fe by differential pulse voltammetry with a LOD of 0.5 ng/mL (Shu *et al.* 2013). Recently, a new method was developed for radiolabelling aptamers with $^{99m}$Tc where the two aptamers - Apt3 and Apt3-amine - selected against the well characterized human tumor associated antigen CEA were used. In binding assay the radiolabeled aptamer showed high specificity and affinity to T84 cells making the aptamer a promising agent for the identification of CEA present in tumor cells (Correa *et al.* 2014). One more method was developed for the detection of CEA by capillary electrophoresis (CE) which is based on the combination of graphene oxide (GO) and quantum dots labeled with aptamer (QD–aptamer). Addition of CEA to the QD–aptamer forms QD–aptamer-CEA complex. Since the CE peaks for the QD–aptamer are close to the QD–aptamer–CEA, to reduce this, GO is first added to the QD–aptamer, which quenches its fluorescence. The QD–aptamer–CEA complex could not bind to GO stably, hence, gets separated by CE, which in turn improves the fluorescence. The LOD for this method was approximately 5 pg/mL (Zhou *et al.* 2014).

A label-free and turn-on aptamer strategy for cancer cell detection was developed by Yin and colleagues. This strategy involves two probes; a signal probe (S-Probe) tailored with DNA template with dark silver nanoclusters (Ag-NCs) and a link sequence complementary to the arm segment of the recognition probe (R-Probe). The R-Probe includes a central target-specific aptamer sequence at the 3'-end, a guanine-rich DNA sequence and an arm segment at the 5'-end forming a hairpin structure due to hybridization of the arm segment with its complementary part of the aptamer sequence in absence of target cells. In the presence of target cancer cells, aptamer binds to the protein receptors on the cancer cells enforcing conformational changes in R-Probe and causing the arm segment dissociation, followed by hybridization between the arm segment and the link sequence in the S-Probe. This brings S-Probe templated dark Ag-NCs close to the guanine-rich DNA sequences of the R-probe resulting in enhanced fluorescence. In particular, this strategy was used for the detection of CCRF-CEM cancer cells using sgc8c aptamer and, in general, it has the potential for being a simple, sensitive, universal and specific cancer cell detection method (Yin *et al.* 2013).

EpCAM is overexpressed in most adenocarcinomas, cancer stem cell and metastases CTCs (Bellone *et al.* 2009). Song and coworkers screened DNA aptamers that selectively bind human recombinant EpCAM protein and these aptamers were able to detect live human cancer cells derived from breast, colorectal, and gastric cancers expressing EpCAM. One of the selected SYL3 aptamer was optimized in length to improve its binding ability which was also able to detect target cancer cells from mixed cells in cell media (Song *et al.* 2013).

A single-step single aptamer-based surface-enhanced fluorescent optical sensor was developed for the detection of a biomarker of cancer angiogenesis i.e., VEGF165. The aptasensor uses a combination of an aptamer-target interaction and nanoplasmonic-fluorophore interaction for target recognition and for signal enhancement respectively. When clinical samples of serum and saliva were tested, the aptasensor results for VEGF165 were in agreement with the limits of the ELISA kit (Cho *et al.* 2013).

2.4.6 *Circulating tumor cell detection:* For the detection, diagnosis, and monitoring of CTCs a method based on aptamer-functionalized hydrogels and restriction endonucleases was proposed by Li and coworkers. CCRF-CEM cells (CL-119, human T lymphocytic leukemia cell line) were used as a model cell line for this assay method. Here, hydrogel functionalized with aptamer was able to capture target cancer cells with a density over 1000 cells/mm. The hydrogel coating was regenerated by treatment with restriction endonucleases due to sequence-specific hydrolysis of the aptamer. Moreover, 98% of the released cells were viable with release efficiency reaching 99% (Li *et al.* 2013).

2.4.7 *Metastatic hepatocellular carcinoma detection:* Hepatocellular carcinoma (HCC) has the tendency for metastasis and, hence, to arrest it, an early prediction of metastasis is necessary. To address this issue Wang *et al.* selected aptamers against HCC

cell line HCCLM9 with high metastatic potential and used MHCC97-L cell line with low metastatic potential as a control. When labeled with FITC, selected aptamer LY-1 was able to detect HCC cells in simulated peripheral blood environment. They also successfully used biotinylated LY-1 aptamer to capture CTCs using streptavidin coated magnetic beads in peripheral blood environment (Wang *et al.* 2013).

2.4.8 *Colon cancer metastasis at lymph node:* Colon cancer leads to metastasis most of the time. Utmost the tumor progression to metastasis is through entry of tumor cells into the circulatory system like lymphatic channels. Li *et al.* (2015a) developed DNA aptamers that specifically bind to SW620 colon cancer cells derived from metastatic site-lymph node. Selected DNA aptamer XL-33-1 was truncated to 45 nt and showed specificity towards SW620 with the binding target proposed to be a membrane protein on the cell surface. To specifically recognize lymph node tissue with colon cancer metastasis XL-33-1 aptamer was FAM-labeled which showed bright green fluorescence after incubating with the colon cancer tissue with metastasis in regional lymph nodes, and lymph node tissue with colon cancer metastasis (Li *et al.* 2015a).

2.4.9 *Gastric carcinoma detection:* Human gastric carcinoma is the most common malignant cancer due to lack of premature state detection methods. To overcome this, aptamers were selected against human gastric cancer cell line SGC7901 for high affinity and specificity using cell-SELEX. The specificity of selected S1a and S4a aptamers labeled with Cy5- fluorophore at the 5′ end and the quencher group BHQ2 at 3′ was verified by detecting clinical samples of human gastric tumor tissues and normal human gastric tissues, where tumor tissue gave bright red fluorescence with negligible signal from normal tissue. Furthermore, for the CTCs capture of SGC7901 cells a fluorescent-magnetic multifunctional nanospheres (FMNS) were prepared by mixing Nano-γ-$Fe_2O_3$ particles, QDs and ethanol-dehydrated nanospheres which were conjugated with streptavidin and subsequently, selected S4a biotinylated aptamers were functionalized with the streptavidin-FMNS. This assay showed a capture efficiency of 93% for SGC7901 cells compared to 7% of control cells. The aptamers also showed potential for *in vivo* testing as confirmed by the *in vivo* study in mice (Ding *et al.* 2015).

2.4.10 *Lung cancer detection:* Late diagnosis of lung cancer has become a major cause of cancer death since in the advanced stage the curative treatment is no longer possible (Detterbeck *et al.* 2013). Hence, there is an urgent need to develop tools for diagnosis of this cancer at an early stage. In this regard, Kunii *et al.* (2011) selected aptamers against small cell lung cancer adherent SBC3 cell line. The aptamers were evaluated and identified by fluorescent confocal microscopy and flow cytometry. The selected aptamers preferentially bound to intercellular junctions of SBC3 cells with the ability to be used as a detection probe (Kunii *et al.* 2011).

In another study, Zhao and coworkers performed cell-SELEX to obtain four aptamer probes against a subtype of non-small cell lung cancer (NSCLC), i.e., adenocarcinoma. They used A549 cell line (NSCLC, adenocarcinoma) for the positive selection and HLAMP (NSCLC, large cell carcinoma) cell line for counter selection by cell-SELEX. When the aptamers were tested with clinical tissue sections representing various subtypes of lung cancer, three of them showed a significantly stronger fluorescence with adenocarcinoma tissue sections compared to other lung cancer sections (Zhao *et al.* 2009). Hence, these aptamers have paved a way for early detection and treatment of adenocarcinoma subtype of NSCLC.

2.4.11 *Leukemia detection:* Sefah *et al.* (2009) selected aptamers against acute myeloid leukemia (AML) cells using cell-SELEX. One of the selected aptamers, KH1C12, showed selectivity towards AML cell line (HL60) compared to control cell lines K562 and NB4, and was able to recognize the target cells within a complex mixture of normal bone marrow aspirates (Sefah *et al.* 2009).

2.4.12 *Prostate cancer detection:* Prostate cancer occurrence has been increasing recently. The early diagnosis of this cancer involves a prostate biopsy test, a microscopic examining process, but is not used in all cases as it may cause acute pain for patients. Other tests, digital rectal examination (DRE), blood test for prostate specific antigen (PSA) and trans rectal ultrasonography (TRUS), are prone to errors due to the indirect process. To overcome these limitations Min and coworkers designed a dual-aptamer probe, conjugating A10 RNA aptamer to DUP-1 peptide aptamer for detection by an electrochemical impedance spectroscopy (EIS) sensor. Biotin-A10 aptamer with 2'-F modified pyrimidines for the PSMA (+) cell line and a biotin-DUP-1 peptide aptamer for the PSMA (-) cell line were immobilized to streptavidin to form a dual-aptamer probe. These aptamers were conjugated to a Au electrode, to which, samples containing prostate cancer cells were added. Due to difficulty of charge transfer through physical blocking by bound cells to the aptamer probe on the electrode surface, impedance increases. The authors expect this sensitive electrochemical approach to be used for preliminary diagnosis of prostate cancer with an advantage of being a non-painful biopsy test (Min *et al.* 2010).

2.4.13 *Glioblastoma detection:* Glioblastoma is the most common and malignant brain tumor with short survival and fatal outcome even after treatment, and is associated with morphologic, genetic, and gene-expression heterogeneity (Olar and Aldape 2012). Two aptamers named GBM128 and GBM131 were selected against cultured human glioblastoma

cell line U118-MG using cell-SELEX. These aptamers were also able to differentiate between clinical glioma tissues and normal brain tissues. The binding affinity and selectivity of these two aptamers were also retained in biological environment and, thus, can be used for early detection of glioblastoma (Kang *et al.* 2012).

## 3. Aptamers for drug delivery

There are various methods for delivering drugs or biomolecules in cells for the therapeutic purposes. Historically, payloads have been delivered to the target cells using liposomes, microspheres, nanofibers, antibodies or peptides. However, these drug delivery carriers have their own limitations, most commonly non-specificity, or sometimes lower tissue penetration in case of antibodies and peptides. In this regard, aptamers have emerged as a new class of drug delivery tools that carry very high specificity, lacking immunogenicity, and have higher tissue penetration, which are imperative prerequisites for a good drug delivery vehicle. Also, less challenging process of industrial synthesis gives them an advantage over antibodies or peptides in terms of being more economical to synthesize. Aptamers are easy to synthesize, and it takes a short time, i.e., 3 months on average to obtain a novel aptamer through the process of SELEX (Sefah *et al.* 2010), with less batch to batch variability than existing tools.

There are some challenges in using aptamers for therapeutic purposes as well. Aptamers are susceptible to nuclease degradation, especially RNA aptamers, because the nucleases are present in serum. However, this problem can be overcome by chemical modifications in the sugar unit of the phospho-sugar backbone of aptamers either post-selectively or during the synthesis step of SELEX. Modifications include replacement of the 2′-OH group of ribose sugar with 2′-fluoro, 2′-O-methyl or locked nucleic acids (LNAs) (Behlke. 2008). Also, the phosphate backbone of nucleotides can be replaced with phosphorothioate (Green *et al.* 1995) or boranophosphate (Keefe and Cload 2008) to reduce the nuclease affinity. Additionally, binding PEG (polyethylene glycol) to the aptamers can increase the half-life of the aptamer in physiological environment (Tucker *et al.* 1999). In the last decade there has been a significant growth in the efforts towards using aptamers as a tool for drug delivery, using various payloads. Below, we have discussed some significant works where aptamers have been used with different conjugates, or alone, to increase their efficiency for targeted delivery (figure 3). A table (table 2) shows recent work from the last five years where aptamers have been used as a drug delivery tool.

### 3.1 *siRNA and other oligonucleotide conjugated aptamers*

The use of oligos such as siRNAs, miRNAs, shRNA as an effective tool to inhibit the expression of complementary RNA transcripts is being used as a new class of therapeutics for diseases including cancer and HIV. However, the successful intracellular delivery of the oligos to a specific cell type is one of the stumbling blocks towards their use as a therapeutic agent. Also, their anionic charge is an impediment to their entry into the cells, and hence, various transporters, viz., liposomes, cationic nanoparticles, antibodies and cholesterol conjugates are used for their trans-membrane movement.

Aptamers have been used with oligos recently for their specific delivery. The advantage of using aptamers with oligos is their relative ease of synthesis because they can be attached to the aptamer by extension of the RNA aptamer, thus, circumventing the need of conjugation or purification steps. Such constructs are called as aptamer-siRNA chimeras (AsiCs) as they represent the combination of two noncoding nucleic acids with different functions. The first si-RNA-aptamer conjugates were produced by Ellington *et al.* (Chu *et al.* 2006) and Sullenger *et al.* (McNamara *et al.* 2006) using two different approaches. Since then, many works have been done showing the role of aptamer-siRNA conjugates as therapeutic agents.

In one such example, an aptamer against CTLA4 surface antigen in both tumor associated T-cells and tumor cells helped in the successful internalization of siRNA against STAT3 gene resulting in an inhibition of tumor growth and metastasis (Herrmann *et al.* 2014). Also, AS1411 aptamer has been used along with PEGylated liposomes to target nucleolin protein for the delivery of siRNA targeting BRAF gene to prevent melanoma. This *in vitro* study was extended to *in vivo*, where A375 tumor xenograft mice showed inhibition of melanoma growth on using siRNA conjugated AS1411 aptamer (Li *et al.* 2014b).

Controlled delivery of a drug to target cells has been a challenge since long. To overcome this problem, a group used an anticancer drug, doxorubicin (Dox), bound nanocarriers capped with a programmable DNA hybrid. This DNA hybrid consisted of an aptamer against nucleolin and an antisense oligonucleotide for miR-21 both of which are overexpressed in cancer cells. Here, after the nanocarriers undergo aptamer mediated endocytosis, the overexpressed endogenous miR-21 unlocks the nanocarriers by competitive hybridization with the DNA hybrid leading to a sustained lethality of cancer cells with maximum therapeutic efficacy and minimal side effects (Zhang *et al.* 2014b).

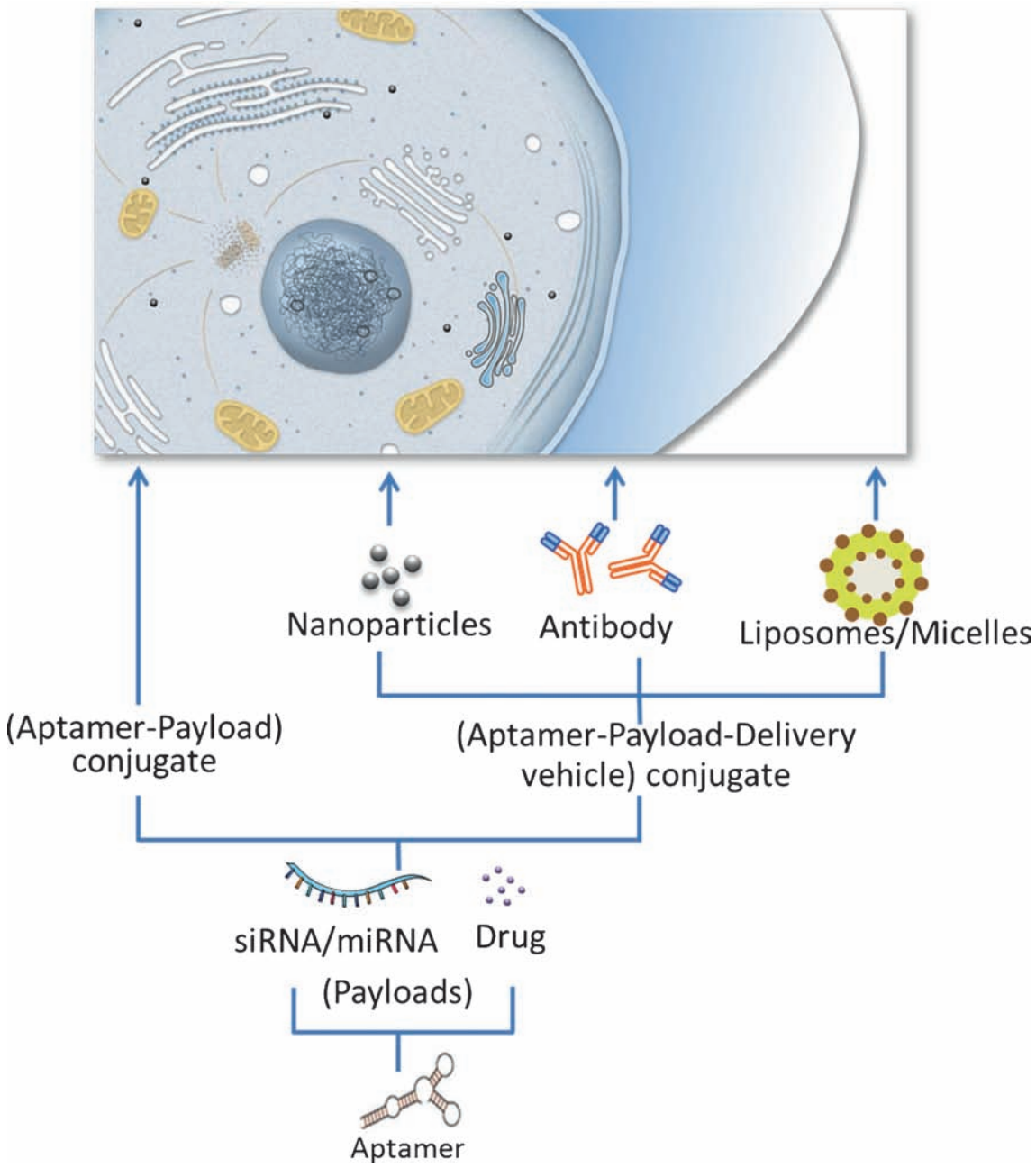


**Figure 3.** Aptamers are either used alone or in conjugation with nanoparticles, liposomes/micelles and antibodies to increase their specificity for targeted delivery of various payloads, viz. drugs, siRNAs or miRNAs.

In addition to cancer, siRNA-aptamer conjugates have also been used in countering AIDS. A chimera of DNA aptamer and siRNA has been used to efficiently knock down the expression of exogenously expressed HIV1 protease gene (HIV-PR) in CD4+ T cells (Zhu *et al.* 2012b). In another study, a group was successfully able to conjugate and deliver a siRNA conjugated to a RNA aptamer into the HIV1 infected cells. They tagged an aptamer against gp120, a protein that is present on HIV-1 envelope and helps in the entry of HIV-1 into the CD4 cells, to the si-RNA. This gp120 aptamer-siRNA conjugate acted as a dual function chimera, where both the aptamer and the siRNA had potent anti-HIV activity that prevented HIV-1 infectivity (Zhou *et al.* 2011).

### 3.2 *Nanoparticle conjugated aptamers*

Use of aptamers along with nanoparticles has seen a substantial growth in the last decade. Aptamer functionalized nanoparticles have been used in recent years for better targeting and increased delivery of drugs for various diseases, especially cancer. As a result of multivalent binding, aptamer-nanoparticle conjugates have higher binding affinities to targeted cells as compared to free aptamers (up to 1,70,000 fold) (Zhou *et al.* 2015).

During a targeted delivery, the aptamer binds to a specific cell surface protein, thereby increasing the specificity of the therapy. Thus, the drug is delivered only to the specific set of cells bearing the aptamer specific target protein, increasing the potency of localized delivery. Therefore, in contrast to a systemic therapy, the local concentration of the drug can be increased while side-effects to the healthy cells can be reduced.

Drug release, in addition to specific targeting by a delivery vehicle, is an important aspect of drug therapeutics. To this aim, a group used aptamers along with nanotechnology in the field of cancer therapeutics. This group synthesized a hollow gold nanosphere (HAuNS) that was bound with a biomarker specific aptamer and the drug doxorubicin for internalization and cytotoxicity in tumor cells respectively. This conjugate (Apt-HAuNS-Dox) was stable at the biological pH7.4 but at the low pH 5.0 in lysosomes, after internalization, aptamer releases Dox that selectively kills tumor cells (Zhao *et al.* 2013). On the same principle, aptamer-functionalized calcium carbonate ($CaCO_3$) nanostructure (Apt-CCN) resulted in pH dependent release of drug doxorubicin, i.e., at low pH on entering lysosomes of target cells (Zhou *et al.* 2015). In addition, photodynamic therapy (PDT) (Shiao *et al.* 2014), miRNA (Zhang *et al.* 2014b) and ATP (Mo *et al.* 2014) have also been used as an alternative for the controlled release of a drug to the cancer cells.

In another work, EpCAM targeted aptamers conjugated with Dox loaded PEG-PLGA polymerosomes were used against adenocarcinoma cell lines successfully. Since EpCAM is a cancer stem cell marker, this conjugate can improve the specificity to EpCAM positive cancer cells (Alibolandi *et al.* 2015). The overexpression of EpCAM has been capitalized for the targeting and delivery of many other drug-aptamer-nanoparticle conjugates for cancer therapeutics, e.g., retinoblastoma (Subramanian *et al.* 2012) and hepatocellular carcinoma (Pilapong *et al.* 2014). Also, a targeting supported by aptamers along with nanoparticles has been utilized for the nuclear uptake of an anticancer drug, specifically for the treatment of multidrug resistant cancers (Qiu *et al.* 2015).

In some studies, success has been observed also at the *in vivo* level. In one such study, Balb/c mice were injected with CD26 cells for colon cancer tumor progression. After a sizeable tumor formation they were treated with epirubicin loaded 5TR1 aptamer functionalized super paramagnetic iron oxide nanoparticles (SPION), which was able to significantly reduce the tumor growth *in vivo* (Jalalian *et al.* 2013). Similarly, Yu *et al.* were also able to show selective drug delivery in LNCaP xenograft mouse model. They used a doxorubicin conjugated PSMA aptamer functionalized thermally cross-linked superparamagnetic iron oxide nanoparticles (TCL-SPIONs). The advantage of this Dox-Apt-hybr-TCL-SPION conjugate was that super paramagnetic iron oxide nanoparticles facilitated the MRI of the target tumor tissue while Dox conjugated aptamer resulted in tumor cytotoxicity *in vivo* (Yu *et al.* 2011).

### 3.3 *Micelles and liposomes conjugated aptamers*

Though there has been significant development in the field of nanotechnology in the last decade, some challenges in their clinical application still persist. Firstly, nanoparticles do not have very satisfactory physico-chemical properties, mainly because of tedious preparation process, low drug loading, and poor stability. Secondly, although NPs reach the target cells by enhanced permeability and retention (EPR) effect, their non-specific uptake by the mononuclear phagocytic cells of liver, spleen and lungs may cause severe side effects.

Among all nanoparticle based drug delivery systems, liposomes are the most suitable to be used for clinical purpose. They are biocompatible, stable, easy to synthesize, have a low batch-to-batch variation, stable, high drug payload and could carry one or more therapeutic molecules. Liposomes have earlier been used in cancer cell targeting with chemotherapeutic payloads based on the principle of enhanced permeability and retention. However, this principle has a drawback that liposomes cannot differentiate between normal and diseased cells, and can be taken up by non-target cells causing serious side effects. Hence, aptamers have been used to functionalize liposomes for the targeted delivery of drugs to the diseased cells causing higher cytotoxicity and minimize the off-target side effects.

In one of the studies, doxorubicin loaded AS1411 aptamer (Ap) functionalized pluronic F127/cyclodextrin linked polymer composite micelles (CM) were used and studied both *in vitro* and *in vivo*. *In vitro*, CM-Ap showed higher cellular uptake and reduced proliferation due to the nucleolin-mediated endocytosis as compared to the control. In the *in vivo* study involving MCF-7 tumor bearing mice the CM-Ap showed extended circulation time in blood, improved antitumor activity, decreased cardiotoxicity and better accumulation in tumor. Thus, aptamer-conjugated composite micelles could be used as potential anticancer targeting vehicles (Li *et al.* 2015b).

**Table 2.** List of aptamer mediated drug delivery systems for therapeutic purposes

**a. siRNA and other oligonucleotide conjugated aptamers**

| Aptamer type | Aptamer target | Cargo | Vehicle | siRNA/miRNA target |
|---|---|---|---|---|
| RNA | gp120 | siRNA | None | tat/rev |
| RNA | CTLA4 | siRNA | None | STAT3 |
| DNA | Nucleolin | siRNA | PEGylated Liposome | BRAF |
| DNA | Nucleolin | anti miR-21 and Doxorubicin | Mesoporous silica coated quantum dots (MSQD) | miR-21 |
| DNA | CD4 | siRNA | None | HIV1 protease |
| DNA | MUC1 | let-7i miRNA | None | Cyclin D1, cyclin D2, Dicer1, PGRMC1 |
| RNA | PSMA | miR-15a & miR-16-1 | PAMAM-PEG | Bcl-2, Cyclin D1, Wnt3a |
| RNA | gp120 | siRNA | None | tat/rev |

**b. Nanoparticle conjugated aptamers**

| Aptamer type | Aptamer target | Cargo | Vehicle | - |
|---|---|---|---|---|
| RNA | CD30 | Doxorubicin | Gold nanosphere (AuNS) | - |
| DNA | PTK7 | Doxorubicin | Calcium carbonate nanostructure (CCN) | - |
| DNA | Nucleolin | Doxorubicin | UCNP-MOF nanocomposites | - |
| DNA | PTK7 | Doxorubicin | Nanoparticle (Gold)/Nanorod (Gold-Silver) assembly | - |
| DNA | HER2 | Doxorubicin | Mesporous silica-carbon nanoparticles | - |
| RNA | EpCAM | Nutlin-3a | PLGA nanoparticle | - |
| DNA | EpCAM | Doxorubicin | CMC-MNPs (Carboxymethyl cellulose-modified magnetic nanoparticles) | - |
| RNA | EpCAM | Doxorubicin | PEG-PLGA nanopolymersom-es | - |
| DNA | Nucleolin | Doxorubicin | Au NP | - |
| DNA | MUC1 | SN38 | Chitosan NP | - |
| DNA | PTK7 | Doxorubicin | Gold coated $Fe_3O_4$ nanoroses | - |
| RNA | EpCAM | Curcumin | PLGA-Lecithin-PEG NPs | - |
| DNA | Nucleolin | Doxorubicin | pPEGMA-PCL-pPEGMA | - |
| DNA | Nucleolin | Doxorubicin | Single walled carbon nanotubes | - |
| DNA | Mucin-1 | Epirubicin | Super paramagnetic iron oxide nanoparticles (SPION) | - |
| RNA | PSMA | Doxorubicin | Super paramagnetic iron oxide nanoparticles (SPION) | - |

**c. Micelles/liposome conjugated aptamers**

| Aptamer type | Aptamer target | Cargo | Vehicle | - |
|---|---|---|---|---|
| DNA | Nucleolin | Doxorubicin | Composite micelle (Pluronic F127 and beta-CD-PELA) | - |
| RNA | CD44 | None | PEGylated liposome | - |
| DNA | Nucleolin | Doxorubicin | Liposome | - |
| RNA | PSMA | Doxorubicin | H40-PLA-PEG micelle | - |

**d. Drug only conjugated aptamers**

| Aptamer type | Aptamer target | Cargo | Vehicle | - |
|---|---|---|---|---|
| DNA | Unknown | Doxorubicin | None | - |
| RNA | EGFR | Gemcitabine | None | - |
| DNA | HER2 | Doxorubicin | None | - |
| DNA | Unknown | Doxorubicin | None | - |
| DNA | MUC1 | Doxorubicin | None | - |
| RNA | EpCAM | Doxorubicin | None | - |

**e. Antibody conjugated aptamer**

| Aptamer type | Aptamer target | Cargo | Vehicle | - |
|---|---|---|---|---|
| DNA | HER2 | Doxorubicin | Anti-HER2 Ab | - |

**Table 2.** (continued)

**a. siRNA and other oligonucleotide conjugated aptamers**

| Aptamer type | Study type | Model | Disease | Reference |
|---|---|---|---|---|
| RNA | *In vitro* | CEM, PBMC | HIV-1 | Zhou *et al.* 2011 |
| RNA | *In vitro/ In vivo* | CD4+, CD8+ T cells/ Mouse | Cancer | Herrmann *et al.* 2014 |
| DNA | *In vitro/ In vivo* | A375 cells/ Mouse | Melanoma | Li *et al.* 2014b |
| DNA | *In vitro* | HeLa | Cancer | Zhang *et al.* 2014b |
| DNA | *In vitro* | CD4+ T cells | HIV-1 | Zhu *et al.* 2012b |
| DNA | *In vitro* | OVCAR-3 | Ovarian cancer | Liu *et al.* 2012a |
| RNA | *In vitro* | LNCaP | Prostate cancer | Wu *et al.* 2011 |
| RNA | *In vivo* | Humanized mice $Rag2^{-/-}\gamma c^{-/-}$ | HIV-1 | Neff *et al.* 2011 |

**b. Nanoparticle conjugated aptamers**

| Aptamer type | Study type | Model | Disease | Reference |
|---|---|---|---|---|
| RNA | *In vitro* | HDLM2, KMH2, L-428, L-540, SUDHL-1, Kapas 299 | Cancer | Zhao *et al.* 2013 |
| DNA | *In vitro* | CEM | Cancer | Zhou *et al.* 2015 |
| DNA | *In vitro* | MCF-7 | Cancer | Deng *et al.* 2015 |
| DNA | *In vitro* | CEM | Cancer | Qiu *et al.* 2015 |
| DNA | *In vitro/ In vivo* | SK-BR-3 cells/ Mouse | Breast cancer | Wang *et al.* 2015 |
| RNA | *In vitro* | MCF7, SKOVK3 & ZR751 | Cancer | Das *et al.* 2015 |
| DNA | *In vitro* | HepG2 | Hepatocellular carcinoma | Pilapong *et al.* 2014 |
| RNA | *In vitro* | MCF-7 | Cancer | Alibolandi *et al.* 2015 |
| DNA | *In vitro* | HeLa, MCF-7 | Cancer | Shiao *et al.* 2014 |
| DNA | *In vitro* | HT29 | Colon cancer | Sayari *et al.* 2014 |
| DNA | *In vitro* | CEM | Cancer | Li *et al.* 2014a |
| RNA | *In vitro* | HT29 | Colon cancer | Li *et al.* 2014c |
| DNA | *In vitro* | MCF-7, PANC-1 | Cancer | Lale *et al.* 2014 |
| DNA | *In vitro/ In vivo* | PC3 cells/ Mouse | Cancer | Zhang *et al.* 2014a |
| DNA | *In vitro/ In vivo* | C26 cells/Mouse | Colon cancer | Jalalian *et al.* 2013 |
| RNA | *In vitro/ In vivo* | LNCaP cells/ Mouse | Prostate cancer | Yu *et al.* 2011 |

**c. Micelles/liposome conjugated aptamers**

| Aptamer type | Study type | Model | Disease | Reference |
|---|---|---|---|---|
| DNA | *In vitro/ In vivo* | MCF-7 cells/ Mouse | Cancer | Li *et al.* 2015b |
| RNA | *In vitro* | A549, MDA-MB-231 | Cancer | Alshaer *et al.* 2015 |
| DNA | *In vitro/ In vivo* | MCF-7 cells/ Mouse | Cancer | Xing *et al.* 2013b |
| RNA | *In vitro/ In vivo* | CWR22Rv1 cells/ Mouse | Prostate cancer | Xu *et al.* 2013a |

**d. Drug only conjugated aptamers**

| Aptamer type | Study type | Model | Disease | Reference |
|---|---|---|---|---|
| DNA | *In vitro* | HCT116 | Cancer | Li *et al.* 2014d |
| RNA | *In vitro* | MiaPaCa-2 | Pancreatic cancer | Ray *et al.* 2012 |
| DNA | *In vitro* | SK-BR-3 | Breast cancer | Liu *et al.* 2012b |
| DNA | *In vitro/ In vivo* | LH86 cells/ Mouse | Liver cancer | Meng *et al.* 2012 |
| DNA | *In vitro* | A549 | Cancer | Hu *et al.* 2012 |
| RNA | *In vitro* | Y79, WERI-Rb1 | Retinoblastoma | Subramanian *et al.* 2012 |

**e. Antibody conjugated aptamer**

| Aptamer type | Study type | Model | Disease | Reference |
|---|---|---|---|---|
| DNA | *In vitro* | SK-BR-3 | Cancer | Kang and Hah 2014 |

In another work, CD44 specific RNA aptamer, Apt1, was bound to PEGylated liposomes using the thiol-maleimide click reaction. It was observed that the binding affinity of Apt1–liposome conjugate increased as compared to the free Apt1 to CD44, and also, Apt1-liposome had higher sensitivity and selectivity compared to the blank liposomes. In conclusion, anti-CD44 aptamer liposome conjugate (Apt1-lip) could be used as a potential system for specific drug delivery in cancer cells (Alshaer *et al.* 2015).

The majority of work in aptamer functionalized liposome drug delivery has been done i*n vitro*. However, a recent work has confirmed the efficient role of liposomes in *in vivo* as well. In this study, AS1411 aptamer functionalized liposomes carrying doxorubicin payload increased cellular internalization and cytotoxicity to MCF-7 breast cancer cells as compared to non-functionalized liposomes. Also, in the xenograft MCF-7 breast tumors in athymic nude mice, the aptamer functionalized liposomes showed enhanced tumor penetration and cytotoxicity (Xing *et al.* 2013a). Similar work, where aptamer functionalized liposomes or micelles were used for specific drug delivery *in vivo* has been performed by others as well (Baek *et al.* 2014).

### 3.4 *Aptamer–drug conjugates*

There are several anthracycline based drugs, viz., doxorubicin, daunorubicin and epirubicin that are currently being used for the treatment of cancer. However, a side effect caused by the off-target binding of these drugs is a cause of major concern. To overcome this problem aptamer-drug conjugates have been developed recently using covalent or non-covalent interactions. Compared to the drug alone these aptamer-drug conjugates are easy to make and have significantly higher specificity and cytotoxicity enabling localized targeting of the drug. Dox causes cytotoxicity by its ability to intercalate between the GC or CG base pairs in the DNA. The same concept is used to bind Dox to the oligonucleotide aptamers, and then its delivery in the cells.

In spite of the advantages of the apt-drug conjugates, there are limitations. However, work is in progress to alleviate these limitations. First, the weakly stable noncovalent aptamer-drug conjugates can be stabilized by using covalent interaction, where, the drug is bound covalently to the aptamer through a functional linker moiety. Secondly, the short half-life of aptamer-drug conjugates *in vivo* may be enhanced by the addition of PEG to the aptamer. In addition, the PEGylation of the aptamer also enhances their stability and reduces their toxic accumulation in non-target tissues (Taghdisi *et al.* 2013; Tan *et al.* 2011). Lastly, aptamers are known to have a very poor drug payload capacity because of its very simple structure, which can be overcome to some extent by synthesizing polyvalent aptamers (Zhang *et al.* 2013).

Using aptamers alone along with cancer drugs directly may help in reducing off-target effects of anti-cancer drugs and increase their potency. For this purpose a conjugate of modified aptamer TLS11a-GC with an antitumor drug doxorubicin was prepared which displayed both high potency and target specificity to liver cancer cells. Here, the non-specific uptake of membrane permeable drug Dox was prevented by its conjugation with the target specific aptamer (Meng *et al.* 2012).

In a similar example, a conjugate of RNA aptamer against EpCAM with Doxorubicin was used to deliver the chemotherapeutic drug to the retinoblastoma cells thereby preventing their proliferation (Subramanian *et al.* 2012). EpCAM, used in this study, is overexpressed in most of the solid cancers and is a cancer stem cell (CSC) marker (Shigdar *et al.* 2011). In this study, EpCAM aptamer (EpDT3-apt) conjugated with doxorubicin was able to bind specifically and internalize the nucleus of retinoblastoma cell lines Y-71 and WERI-Rb1 but not to the control Muller glial cells. The presence of EpCAM in various cancers also allows the EpCAM aptamer-Dox conjugate to be used as a therapeutic agent against all the cancers overexpressing EpCAM, viz., breast cancer, pancreatic cancer, colorectal cancer and liver cancer.

CD44 belongs to proteoglycan family of transmembrane glycoproteins and a primary receptor for hyaluronic acid which in turn plays an important role in tumor growth and metastasis. The hyaluronic acid binding domain (HABD) is conserved among the CD44 splicing variants. Hence, Somasunderam *et al.* (2010) specifically selected thioaptamer binding to the CD44's HABD with 180–295 nM affinities. These thioaptamers specifically bound to CD44 positive human ovarian cancer cell lines when compared with the CD44 negative NIH3T3 cell line. The selected thioaptamers can further be developed as a targeting or imaging agent for the delivery of therapeutic payloads for cancer tissues (Somasunderam *et al.* 2010).

### 3.5 *Aptamer–antibody conjugate*

It is known that a dimer of antibodies that recognize adjacent and non-overlapping epitopes of the same target antigen have enhanced receptor binding (Kang and Hah 2014). This increase in affinity occurs due to the increase in $k_{on}$ value and decrease in $k_{off}$ value, which ultimately leads to the increase in dissociation constant ($K_d$) value for the dimer as compared to either of the two antibodies alone. In the past both antibody homodimer, and aptamer homodimer and heterodimer have been made (Kang and Hah 2014). However, in an attempt to increase the affinities of antibodies or aptamers to their target molecule, the antibody-aptamer pincer or heterodimer was made.

Since aptamers are advantageous over antibodies due to their high binding affinity and the ability to undergo numerous chemical modifications they can be used instead of antibodies to form aptamer-antibody dimers. Kang and Hah (2014) worked in this direction and called these dimers as antibody-aptamer pincers (AAP). AAP has a higher affinity with sustained or possibly higher specificity for its target molecule. The group also observed drug delivery along with higher cytotoxicity in cancer cells. To use AAP as a platform for therapeutic delivery the anti-HER2 aptamer and anti-HER2 monoclonal antibody conjugate was loaded with doxorubicin, and the resulting AAP-HER2-Dox conjugate showed an approximately 3- and 6- fold higher cytotoxicity than drug alone and antibody alone, respectively (Kang and Hah. 2014). Thus, the conjugation of the aptamer and the antibody can significantly improve the affinities of the resulting AAPs towards their target molecules and the drug loaded AAP may be used as a platform for targeted drug delivery against many malignancies.

## 4. Aptamers in imaging

Traditional imaging techniques primarily rely on morphological evidence, to example X-rays in CAT scans, radiolabeled compounds (e.g. fluorodeoxyglucose) in PET, MRI, and sonography. These techniques are used routinely in the clinic, for example in cancer detection strategies.

Alternatively, molecular imaging uses specific molecular probes to discriminate specific biological events (Massoud *et al.* 2003). The advances of molecular imaging are: (i) the ability to detect diseases at an earlier stage, (ii) measure and characterize its pathogenesis, and (iii) use them in *in vitro* and *in vivo* assays. By using specific molecular probes particular biological processes or targets can be visualized (Wang and Farokhzad 2014). Aptamers are a very interesting class of molecular probes due to their ability to spontaneously fold into 3D scaffolds with similar binding recognition as antibodies. The great advantages of aptamers over antibodies are due to stability and relative ease of chemical modification. Another advantage is that they can be produced synthetically. Their smaller size than antibodies gives them the added advantages of higher tissue penetration and increased systemic clearance. These advantages are beneficial for diagnostics as well (Cruz-Aguado and Penner 2008).

We will highlight a few examples of molecular probes for traditional clinical imaging purposes and then briefly discuss general conjugation strategies applicable for RNA and DNA aptamers intended for imaging.

### 4.1 *MR imaging*

Traditional gadolinium-based magnetic resonance (MR) contrast agents are mostly used to provide non-invasive two- and three-dimensional images of living specimens. Recently the need for smart contrast agents that induce detectable MRI responses in the presence of specific targets are under investigation (Lauffer 1987; Caravan *et al.* 1999). Since the first responsive $Ca^{2+}$-chelator for gadolinium, that induced changes in the longitudinal relaxation time of water protons (referred to as $T_1$) by Meade *et al.* (Li *et al.* 2002), only a few other systems have been reported (Xu and Lu. 2011). SPIONs have advantages over traditional gadolinium-based MR contrast agents due to their lower toxicity, stronger enhancement of proton relaxation, and lower detection limit. However, they are still less widely used clinically than gadolinium compounds.

Both SPIONs and responsive chelator systems for gadolinium have been combined with aptamer technology. The A10 RNA aptamer (Farokhzad *et al.* 2004) was conjugated to a TLC-SPION using standard coupling chemistry (Wang *et al.* 2008). The complex was aimed to target PSMA in prostate cancer lymph node disease. In addition, the aptamer-TLC-SPION-MR contrast agent was loaded with doxorubicin for targeted delivery. An example of a responsive system by Xu and Lu (2011) was via a NHS coupled DNA aptamer against adenosine and to gadolinium-tetraazacyclododecane tetraacetic acid (DOTA-Gd). The MRI agent increased the $T_1$ responds on binding of the aptamer to its target, thus reducing the intensity of the signal upon binding. In a follow-up study the authors demonstrated an opposite effect and increase in MRI signal upon binding with uranyl cations via a 39E DNAzyme-based smart MRI contrast agent (Xu *et al.* 2013b).

### 4.2 *CT imaging*

The A10 aptamer, targeted against PSMA (Farokhzad *et al.* 2004), was conjugated to gold nanoparticles (Kim *et al.* 2010). A thiol-modified capture probe (5′-HS-CC-$(A)_{10}$-TCGTCGTCGTCGTCGTCGTCG-3′) was covalently bound to 13 nm gold particles. The A10 aptamer was then hybridized to the capture probe. Due to the high atomic number, gold nanoparticles can act as CT imaging contrast agents (Kim *et al.* 2007; Popovtzer *et al.* 2008).

Kim *et al.* (2010) demonstrated that the A10 aptamer-nanoparticles bind specifically to PSMA-expressing prostate cancer cells and the feasibility of these particles to be used as molecular probes for the detection of PSMA-expressing cancer cells by CT imaging. In another recent example, Kuo *et al.* (2014) conjugated the AS1411 aptamer to europium-doped gadolinium oxide nanoparticles to target nucleolin, which is highly expressed in CL1-5 lung cancer cells. Due to their florescent nature, these particles can be used as a visual marker, but also act as contrast agents in MR and CT due their excellent $T_1$ contrast and strong CT signal.

### 4.3 *Ultrasound imaging*

Ultrasound is a commonly used clinical imaging technique. Advances to overcome the low resolution have resulted in the use of micro- and nano-bubbles to increase the contrast (Gramiak and Shah 1968; Ferrara *et al.* 2007). In addition, this technique has been utilized in sonodynamic therapy, ultrasound-mediated chemotherapy, ultrasound-mediated gene delivery and anti-vascular ultrasound therapy (Wood and Sehgal 2015). Specific biomarkers have been targeted via antibodies or small peptides (Chen *et al.* 2015; Huang *et al.* 2015), and recently aptamers (Wang *et al.* 2011b).

In order to overcome immunogenic side effects due to biotin-avidin conjugations an easier method for functionalize bubbles was developed by Wang *et al.* (2011b). Disulfide sgc8c aptamer was conjugated to PEG-maleimide in a lipid mixture of 1,2-Distearoyl-sn-glycero-3-phosphocholine DSPC (95%), PEG2000-1,2-Distearoyl-sn-glycero-3-phosphoethanolamine (DSPE; 2.5%), and the maleimide-functionalized PEG-DSPE. Nano-bubbles were generated by mechanical activation and the whole formulation took 2 hours. The sgc8c aptamer was linked to an imaging agent for the specific targeting of T-cell, human acute lymphoblastic leukemia (CCRF-CEM cells). Due to the strong binding of the aptamer to CEM cells and excellent hydrodynamic stability, the nanoparticles also exhibited superior behavior in local accumulation under flow conditions. Microbubbles can also act as a stimulus-responsive contrast agent. For the detection of thrombosis, or malignant blood clot formation, and *in vivo* clot activity Nakatsuka *et al.* (2012) developed aptamer-thrombin and polymer-DNA coated microbubbles where the aptamer can bind to thrombin and the DNA of the polymer-DNA coating. Microbubble shell components were prepared so that they would respond to thrombin. Poly(acrylic acid) (PAA) was coupled to the amine of DSPE via carbodiimide-mediated amidation. Subsequently two amine terminated DNA strands were attached. A DNA strand, the thrombin aptamer crosslinking strand (TACS) contained a portion complementary to the polymer-DNA to induce crosslinking, as well as two flanking 15-base DNA aptamer sequences. Both strands each possessed a half maximal inhibitory concentration (IC50) in the order of 25 nM for thrombin. Nine of the fifteen aptamer bases are left unbound at the ends of the crosslinking strand so that the binding of thrombin resulted in the complete displacement of the TACS from the polymer-DNA strands. Therefore, upon binding to thrombin the aptamer was displaced from the complex to generate an ultrasound signal. No signal was observed in normal blood conditions.

### 4.4 *Nuclear imaging*

Radionuclide-based imaging techniques, such as SPECT and PET, have excellent tissue penetration capability. Especially, pre-targeting and immunotargeting of drug carriers in combination of SPECT/CT have great potential (Lehtinen *et al.* 2012). Several radioisotopes are in use, such as $^{99m}$Tc, $^{111}$In, and $^{125}$I for SPECT, $^{11}$C, $^{18}$F, $^{76}$Br, and $^{64}$Cu for PET (Younes *et al.* 2002; Perkins and Missailidis. 2007; Lucignani 2006). A radiolabeled aptamer (NX21909-$^{99m}$Tc) against neutrophil elastase to identify inflammation was the first report of such an imaging probe (Charlton *et al.* 1997). Here the authors conjugated a peptide-$N_3S_1$-type Tc-binding via the amine linker of the NX21909 aptamer by NHS-ester reaction in dry DMSO/5% triethylamine. Compared to IgG probes the target-to-background ratio was increased 4-fold due to more rapid clearance of unbound aptamers.

Also, in the case of a radiolabeled aptamer against the extracellular matrix protein tenascin-C the rapid clearance from the blood-stream gave a 50:1 tumor to blood ratio. The TTA1 aptamer was developed in a SELEX against tumor cells and purified tenascin-C, after initial discovery of an aptamer to U251 glioblastoma cells (Daniels *et al.* 2003; Hicke *et al.* 2001). TTA1 aptamer was bioconjugated with technetium chelator $MAG_2$-uccinimidyl ester (Hilger *et al.* 1999) through the 5′ amine in dimethylformamide (Winnard *et al.* 2008). $MAG_2$ was either labeled with $^{99m}$Tc, $^{111}$In or $^{32}$P.

Other examples are $^{99m}$Tc-labeled aptamer against MUC1 protein (a tumor biomarker) (Da Pieve *et al.* 2009), the AS1411 aptamer targeted against nucleolin (a cobalt-ferrite nanoparticle) labeled with $^{67}$Ga (Hwang *et al.* 2010), and the aptamer HYNIC against tyrosine kinase-7 labeled with $^{99m}$Tc to image acute lymphoblastic leukemia CCRF-CEM cells (Calzada *et al.* 2014).

### 4.5 *Fluorescence imaging*

Fluorophores can be labeled to the 5′- or 3′-prime end or in the middle of aptamers by use of phosphoramidite chemistry. Fluorescence of this nature has been widely applied in cancer imaging (Wu *et al.* 2015). Fluorescently tagged RNA aptamer has been applied in the detection of amyloid plaques in both *ex vivo* human Alzheimer's disease brain tissue and *in vivo* APP/PS1 transgenic mice. Imaging probes were introduced in the anti-Aβ RNA aptamer, β55, by transcription of the DNA template with T7 RNA polymerase by either using biotin-labeled uracil, for *ex vivo* studies, or fluorescein-labeled uracil directly.

Alternatively, displacement of a fluorescently labeled oligo from the aptamer by the target can be detected by fluorescence polarization (FP/FA) (Cruz-Aguado and Penner 2008). Here, a small ssDNA aptamer of 36 bases bound specifically to the small molecule ochratoxin A and levels as low as 5 nM could be detected with the FP displacement assay. Fluorescence polarization or anisotropy analysis has also been applied to map aptamer-protein interactions. Zhang *et al.* (2011) studied human α-thrombin and aptamer TA29 to identify 3 thymines and the 3'-end of the aptamer as the closest contact groups.

### 4.6 *Labelling, conjugation and ligation*

Due to their synthetic nature, chemical modification of aptamers is relatively easy. For therapeutic purposes a durable performance of aptamers *in vivo* and prolonged half-lives are required (Wang et al. 2011a, b). For imaging purposes, most aptamers are conjugated or hybridized to DNA/RNA with imaging moieties. Typically, the architecture of the bioconjugate has to be adjusted to the application for which it is developed (Canalle *et al.* 2010).

In a recent review by Paredes *et al.* (2011) strategies are discussed in great detail for RNA labelling, conjugation and ligation. Summarizing, imaging labels or the introduction of moieties for later labelling can be introduced via internal handles. In addition, synthetic chemistry, enzymatic incorporation and labelling or conjugation chemistry can be applied to modify RNA. Many strategies presented can be applied to DNA as well. Incorporation of labels via solid-phase RNA synthesis has been applied for incorporation of $^{32}$P (Hilger *et al.* 1999; Paredes *et al.* 2011; Winnard *et al.* 2008) and by use of phosphoramidites for the synthesis of RNA with modifications at the 5′-end (Paredes *et al.* 2011). In post-synthetic labelling and conjugation, four general chemical strategies based on reactive species can be identified, viz. periodate chemistry (Paredes *et al.* 2011), amine chemistry, thiol chemistry, and click chemistry (Canalle *et al.* 2010; Paredes *et al.* 2011). In enzymatic incorporation of labels and reactive tags T4 polynucleotide kinase, terminal transferase, DNA polymerase I, T7 RNA polymerase, Poly (A) polymerase, and T4 RNA ligase have been used (Paredes *et al.* 2011). In chemical ligations native phosphate linkage by cyanogen bromide or a water-soluble carbodiimide and the subsequent reaction with a hydroxyl group has been utilized (Paredes *et al.* 2011). DNA splits and peptides have been used via these methods. Both protein and nucleic acid enzymes can be used to ligate two strands of RNA, or DNA. Most commonly used is T4 DNA ligase. Alternatively, T4 RNA ligase 1, T4 RNA ligase 2, and deoxyribozymes (DNAzyme) have been used for ligation and fluorescent labelling of RNA (Paredes *et al.* 2011).

## 5. Conclusion

Various aptamers have been selected to detect a wide range of targets; however, a significant number of them have not been used for diagnostic applications. These aptamers need further development to be used in biosensors to increase the efficiency and their ability to detect targets in clinical samples. Mostly the problem lies in clinical sample preparation, which is tedious, time consuming, costly and needs expertise. So aptamers must be tuned to detect the antigen at low concentration and in presence of serum impurities. Biosensors involving aptamers should have high range of sensitivity concerning the signal amplification. Some aptamers need to be more specific towards their target, mostly in case of cancer detection *in vivo*, where they have shown nonspecific signals when tested in mice. Aptamers have already proven to be a better candidate for target binding than its other counterparts and, hence, will maintain its position in diagnosis. To do so, the developed biosensors or diagnostic tests involving aptamers should be tested with human samples and should be taken from research labs to diagnostic labs. In case of drug delivery, aptamers have emerged as a new set of biomolecules that are efficient in highly specific delivery of a payload to the target cells both *in vitro* and *in vivo*. Their sturdiness and ability to undergo a range of chemical modifications gives an advantage of binding aptamers with various payloads. Also, aptamer binding and delivery to the cells can be increased by conjugation with nanoparticles, liposomes and even antibodies. Until now, an overwhelming majority of the work for targeted delivery using aptamers has been done in cancer with a very limited number of attempts on other diseases like HIV, AMD and few others. This leaves a wide possibility of using aptamers for targeted delivery of drugs in a myriad range of diseases as well. Also, a push has to be given towards taking the studies from *in vitro* to *in vivo* and clinical level, as relatively large amount of work, at present, is limited to the targeted delivery of aptamers at *in vitro* level only. Coming towards imaging applications, aptamers due to their small size, specific binding, and stability have great potential for clinical and molecular imaging. Their stability and self-assembly after heating makes them superior over protein-based binding molecules, such as antibodies (Daugherty and Mrsny 2006) or even affibodies (Feldwisch 2010) in terms of labelling and conjugation strategies.

We expect that in the near future more combinations of diagnostics, drug-delivery and imaging aptamer based tools to be combined into integrated methods to detect, visualize and treat (infectious) diseases *in vivo* at the same time.

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