Highly sensitive rapid chemiluminescent immunoassay using the DNAzyme label for signal amplification

Chen Wang,* Jie Wu,* Chen Zong,* Huangxian Ju,*a and Feng Yan*bb

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A novel trace tag for chemiluminescent (CL) immunoassay was designed by using DNAzyme to functionalize antibody-labeled Au nanoparticles (AuNPs). The trace tag showed an excellent ability to catalyze the oxidation of luminol by hydrogen peroxide, leading to strong CL emission. By coupling the trace tag with a passive mixing accelerated immunoreaction system, a highly sensitive rapid flow-through CL immunoassay method was proposed. Using carcinoembryonic antigen (CEA) as a model analyte, the capture antibody for CEA was immobilized on paramagnetic microspheres, and DNAzyme-anti-CEA antibody functionalized AuNPs were prepared as trace tag. A three-dimensional helical glass tube kept at 37 °C in a water bath was used for passively mixing immunoreagents in a two-step sandwich immunoassay, with which each immunoreaction step could be finished within 150 s. With the help of a magnet, the immunocomplex could conveniently be separated from reactants. Compared with the horseradish peroxidase-based tag, the newly designed trace tag showed obvious signal amplification due to its strong catalytic ability and high loading ratio of DNAzyme on each AuNP. The proposed method showed a linear calibration range from 0.005 to 0.5 ng mL⁻¹ for CEA detection with a detection limit of 4.1 pg mL⁻¹ at a signal-to-noise ratio of 3 and acceptable detection reproducibility. The assay results of clinical serum samples were in acceptable agreement with the reference values. The designed immunoassay system with ultrahigh sensitivity provided a programmable and low-cost approach for high-throughput clinical application.

Introduction

Highly sensitive and selective detection of biomarkers has been showing its significance in early screening of disease, evaluating the extent of disease, and monitoring the response of disease to therapy.¹ Many natural enzymes such as horseradish peroxidase (HRP) and alkaline phosphatase have been extensively used as biological catalysts to produce detection signals. By functionalizing nanoparticles with these enzymes for preparation of trace tags, various highly sensitive detection methods have been proposed.²⁻⁴ However, natural enzymes can usually lose their catalytic activity due to minor alteration in their conformation during storage. The high cost for purifying these natural enzymes also limits their application. Furthermore, the catalytic activity of some natural enzymes is often limited due to the embedding of the activity center in macromolecular peptides. Thus great effort has focused on the development of artificial enzyme mimics, which offer new opportunities to achieve catalysis with high operational stability and reusability. Several peroxidase mimics such as hemin,⁵ Fe₃O₄ nanoparticles,⁶ Au nanoparticles (AuNPs),⁷ and DNAzyme⁸⁻¹⁰ have been applied in bioanalysis. Among these mimics, hemin/G-quadruplex DNAzyme formed by embedding a hemin in a guanine-rich DNA strand has attracted considerable attention due to its high catalytic ability as HRP.⁸⁻¹⁰ Using this DNAzyme as catalytic label, several bioanalytical methods have been developed for genotyping of single nucleotide polymorphism and detection of low-molecular-weight substrates, DNA or even protein.⁹ In order to amplify the catalytic activity and achieve high detection sensitivity, AuNPs have been used as DNAzyme carrier for chemiluminescent (CL) detection of DNA and telomerase activity.¹⁰ This work designed a novel trace tag for CL immunoassay by using DNAzyme to functionalize antibody-labeled AuNPs.

Owing to the high surface-to-volume ratio and good biocompatibility, AuNPs have been extensively used as HRP carrier for preparation of trace tags. These HRP functionalized AuNPs show excellent signal amplification in both CL and electrochemical immunoassays.²⁻³ By binding hemin with a guanine-rich DNA strand, which was dissociated from DNA functionalized AuNPs linked to an immunocomplex, to form peroxidase-mimicking DNAzyme, Zhou et al.¹¹ developed an enzyme-linked immunoassay (ELISA) for tumor markers. This ultraviolet adsorption method showed a detection limit of 0.1 ng mL⁻¹ for α-fetoprotein, which was obviously insufficient for detection of low-abundant
proteins. Here, a simple CL immunoassay method was proposed by directly forming DNAzyme on signal antibody functionalized AuNPs for immunoreaction and using the attached DNAzyme to catalyze the oxidation of luminol by hydrogen peroxide for producing amplified CL emission (Scheme 1).

CL immunoassay, which combines good specificity of immunoreaction with high sensitivity of CL detection, has been well known as a powerful and important technique. However, due to the low diffusive rate of macromolecular immunoreagents, the detection procedure generally needs long incubation time, which may lead to absorption of immunoreagents on the channel inner wall and thus cross talk among the tests of different samples in a one-way fluidic system. To overcome this drawback and achieve high-throughput immunoassay, different ways such as electrophoretic flow, micro-bubble, and magnetic stirring have been employed to accelerate the immunoreaction. Previously, we proposed a dual acceleration strategy using infrared heating and electrokinetic flow, which cannot form DNAzyme (Scheme 1B) and amplified the CL signal with the attached DNAzyme on signal antibody functionalized PMs and antigen, (TT) DNAzyme and antibody functionalized PMs of CEA, including standard solutions of CEA, and HRP substrate solutions (luminol-iodophenol and H2O2) were obtained from Autobio Diagnostics Co., Ltd. (China). Electrochemiluminescent immunoassay (ECLIA) reagent kits used for reference detection of CEA were supplied by Roche Diagnostics GmbH (Germany). HRP was obtained from Beijing Biosynthesis Biotechnology Co., Ltd. (China). Bovine serum albumin (BSA) was purchased from Nanjing Sunshine Bio Co., Ltd. (China). The aqueous suspension of paramagnetic silicon dioxide microspheres (PMs) coated with epoxy groups (diameter 0.5–1 µm and concentration 5 g L–1) was obtained from Tianjin BaseLine Chromtech Research Centre (China). Ultrapure water obtained from a Milliapore water purification system (≥18 MΩ, Milli-Q, Millipore) was used in all runs. The clinical serum samples were obtained from Jiangsu Institute of Cancer Prevention and Cure. All other reagents were of the best grade available and used as received.

The coupling buffer for antibody immobilization was 0.01 M phosphate buffer solution (PBS, pH 7.4). The stock buffer was PBS containing 0.1% BSA. The blocking buffer was PBS containing 1% BSA. To minimize nonspecific adsorption, 0.05% Tween-20 was spiked into PBS (PBST) as the washing buffer. The regeneration buffer was 0.1 M glycine–HCl at pH 2.2.

**Instrumentation**

The Teflon tubes (0.8 mm i.d.) and silicon rubber tubes (1.0 mm i.d.) were used to connect all components in this system. All solutions were delivered with a multichannel bidirectional peristaltic pump of an IFFM-D Luminescent Analyzer (Remax, China). The introduction of different solutions into the one-way channel was performed using a multiposition valve of four inlets and one outlet. A heat concentrating magnetic mixer (DF101S, Jintan Medical Instrument Plant, China) was used for water bath incubation at 37 °C. The three-dimensional helical glass tube for incubation had an inner diameter of about 1 mm and 10 turns, and was coiled at a radius of about 12 mm, while the distance between two turns (the pitch) was about 8 mm. A permanent magnet provided the magnetic field to capture the PMs in a glass tube of 30 µL (length 4.0 cm, i.d. 1 mm), which was positioned in front of the helical glass tube followed by a quartz tube. The quartz tube was positioned in front of a photomultiplier (PMT) biased at −800 V to record the CL emission. The Instrument control and data record were performed using the IFFM software package run under Windows 2000.

The UV-vis spectroscopic experiment was performed with a UV-3600 UV-vis spectrophotometer (Shimadzu, Japan) to demonstrate the binding of monoclonal anti-CEA and thiolated DNA to AuNPs. An ESCALAB 250 spectrometer working in ultrahigh vacuum with an Al K-X-ray source was employed for X-ray photoelectron spectroscopic (XPS) analysis of PMs before and after the immobilization of capture antibody. CL
The mixture flowed back and forth at an optimal flow rate in the glass tube to mix with CEA-anti-CEA antibody immobilized PMs. After the mixture was incubated in the helical glass tube for another 2.5 min using the same method, the formed sandwich immunocomplex was separated from free hemin and free DNAzyme-antibody functionalized AuNPs and washed in the glass tube with the help of a permanent magnet. Then the magnet was withdrawn, and 80 μL of CL substrate solution flowed fast into the tube to wash away the PMs and fully mix. Afterwards, the mixture flowed through the helical glass tube and was delivered into the quartz tube for recording the CL signal. This process takes 30 s to achieve complete reaction of the CL reagents. The whole procedure from sample injection to signal detection could be finished within 8 min. Finally, the one way detection channel was washed with 1 M HCl solution and washing buffer for 30 and 60 s, respectively, to avoid potential cross talk. After the detection, the sandwich immunocomplex immobilized PMs were expelled and collected, which could be regenerated by washing in regeneration buffer for 10 min and blocking buffer three times, respectively.

**Results and discussion**

**Characterization of DNAzyme-anti-CEA antibody functionalized AuNPs and antibody immobilized PMs**

UV-vis spectra were used to demonstrate the binding of the monoclonal anti-CEA and guanine-rich DNA strand to AuNPs (Fig. 1A). The size of AuNPs could be estimated to be 13 nm from the absorption peak at 519 nm (curve a). Compared with AuNPs, the UV-vis spectrum of antibody functionalized AuNPs showed a red shift of the absorption peak to 522 nm (curve b), indicating that a slight aggregation of the nanoparticles occurred after the binding of anti-CEA antibody onto AuNPs. After the guanine-rich DNA strand was attached on the surface of AuNPs, a strong absorption peak occurred at about 260 nm (curve c), which was obviously stronger than the absorption peak of anti-CEA antibody functionalized AuNPs at 280 nm (curve d) due to the adsorption of the guanine-rich DNA strand, indicating the successful binding of DNA to the surface of AuNPs.

PMs have been extensively used in immunoassays due to their advantages in separation and collection of the immunocomplex from free immunoreagents, which provides easy handling for automation analysis. This work used epoxy group modified...
PMs with a diameter of 0.5–1 μm to immobilize the capture antibody. The XPS spectrum of the PMs showed an N (1s) peak at 399 eV (Fig. 1B, curve a), indicating the existence of nitrogen on the PM surface. After the capture antibody was covalently linked to the PMs, the height of the N (1s) peak at 399 eV increased by 2.2 times (curve b), which was obviously due to the covalent binding of the antibody on the surface of PMs.

Kinetics and mechanism of CL reaction

The kinetic behavior of the CL reaction catalyzed by DNAzyme labeled to the sandwich immunocomplex of CEA on PMs was studied with a static method. The CL reaction on PMs occurred immediately upon injection of the CL substrates. The intensity of CL emission increased quickly and reached its maximum value within 30 s. The CL kinetic of the DNAzyme system was obviously faster than the HRP system that reached the maximum value at 4 min. This was in favor of the fast and high-throughput immunoassay. In order to acquire high detection sensitivity, 80 μL of CL substrate solutions flowed fast into the glass tube to fully mix up with the PMs, then the mixture flowed through the helical glass tube and was delivered into the quartz tube for recording the CL signal. This process from mixing to recording costs exactly 30 s, which matched the time reaching the maximum CL emission and thus helped the reagents to react completely for obtaining the sensitive CL signal.

A further inspection of CL spectra was performed on a spectrophotometer (Fig. 2A). In the absence of hemin, the guanine-rich DNA could not fold to form a G-quadruplex structure, thus the CL intensity gave a very low response in the wavelength range from 370 to 500 nm (curve a). After addition of hemin into the guanine-rich DNA-antibody functionalized AuNPs, the formed G-quadruplex structure as DNAzyme led to a maximum emission peak at about 430 nm (curve b), which was at the same wavelength as that of the HRP-based tag (curve c), indicating the DNAzyme catalyzed CL process had the same CL reaction mechanism as the HRP catalyzed CL emission, in which the DNAzyme catalyzed the oxidation of luminol by hydrogen peroxide. It was interesting that at the same amounts of the functionalized AuNPs and CL substrates the CL intensity of the DNAzyme catalyzed system (curve b) was much stronger than those of HRP-antibody functionalized AuNPs (curve c) and free hemin (curve d) systems, indicating the stronger catalytic ability of the DNAzyme-antibody functionalized AuNPs. The strong ability resulted from both the high catalytic activity of DNAzyme due to less embedding of the activity center in the G-quadruplex structure than in macromolecular peptides of HRP and the higher loading amount of DNAzyme on AuNPs due to its smaller size than HRP. The signal amplification phenomenon was further confined in the proposed FTCLIA with the CEA concentration of 0.05 ng mL⁻¹ (Fig. 2B). These results suggested that the high catalytic ability of the DNAzyme-antibody functionalized AuNPs trace tag could lead to excellent signal amplification for highly sensitive immunoassay.

Incubation time and flow rate

To obtain high analytical performance, some important detection parameters, such as incubation time and flow rate, were optimized (Fig. 3). With the increasing incubation time, the CL signal increased and trended to the maximum value at 5 min (Fig. 3A), indicating the maximum formation of the sandwich immunocomplex. At an incubation time of 2.5 min, the CL signal was 80% of the maximum value, which was sufficient for obtaining high sensitivity. Considering the optimal analytical performance, 2.5 min was chosen as the optimal incubation time.

At the optimal incubation time the flow rate was further examined. With the increasing flow rate, the CL response increased and then quickly decreased, the maximum CL emission occurred at a flow rate of 10 μL s⁻¹ (Fig. 3B). At the flow rates higher than 10 μL s⁻¹, the constantly increasing variance and skewness led to less transversal mixing, thus the CL response decreased. This work selected the flow rate of 10 μL s⁻¹ for immunoassay, with which the mixture of immunoreagents could flow back and forth in the helical tube ten times to match the optimal incubation time.

Regeneration of antibody immobilized PMs

Because of the covalent binding of the antibody to the PMs, the antibody immobilized PMs could be regenerated. By a simple and short-period dissociation of the sandwich immunocomplex, antibody immobilized PMs could be reused with little breaking of covalent bonds and little activity loss of immobilized antibody. The most efficient dissociating reagent was found to be
immunoreactivity is very important for the development of the proposed method in low-cost application.

Detection of CEA in serum samples

Under the optimum conditions, the analytical reliability and application potential of the proposed immunoassay system were evaluated by assaying clinical serum samples using the proposed method as well as the reference ECLIA method. The results are shown in Table 1, which indicate an acceptable agreement between the two methods, and the relative errors were less than 9.6%.

Conclusions

A novel DNAzyme amplified strategy coupled with a passive mixing accelerated FTCLIA system is proposed for ultrasensitive and rapid immunoassay. Compared with the HRP-based tag, the proposed DNAzyme-antibody functionalized AuNPs trace tag exhibits stronger catalytic ability and faster CL reaction kinetics, which result from both the high catalytic activity of DNAzyme due to less embedding of the activity center in the G-quadruplex structure than in macromolecular peptides of HRP and the higher loading amount of DNAzyme on AuNPs due to its smaller size than HRP. The DNAzyme-based signal amplification produces a much stronger CL response than HRP-based immunoassay at low analyte concentrations, thus leading to an ultrahigh sensitivity of CL immunoassay. During the incubation process the mixture can flow back and forth in the helical tube to maintain the passive mixing for accelerating the immunoreaction, so the whole assay including the incubation, washing and detection steps can be accomplished within 8 min. The immunosensing system shows a promising practicality in automated rapid screening and clinical diagnosis.

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Notes and references


Table 1 Assay results of CEA in serum samples using the proposed and reference methods (in ng mL\(^{-1}\))

<table>
<thead>
<tr>
<th>Sample</th>
<th>Proposed method(^a)</th>
<th>Reference method</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.5</td>
<td>5.3</td>
<td>3.4</td>
</tr>
<tr>
<td>2</td>
<td>8.1</td>
<td>8.8</td>
<td>-8.2</td>
</tr>
<tr>
<td>3</td>
<td>62.0</td>
<td>56.6</td>
<td>9.6</td>
</tr>
<tr>
<td>4</td>
<td>226.7</td>
<td>218.7</td>
<td>3.7</td>
</tr>
<tr>
<td>5</td>
<td>259.2</td>
<td>251.4</td>
<td>3.1</td>
</tr>
</tbody>
</table>

\(^a\) The serum samples were diluted by 1 : 1000.