Fe$_3$O$_4$/Au magnetic nanoparticle amplification strategies for ultrasensitive electrochemical immunoassay of alfa-fetoprotein

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Background: The purpose of this study was to devise a novel electrochemical immunosensor for ultrasensitive detection of alfa-fetoprotein based on Fe$_3$O$_4$/Au nanoparticles as a carrier using a multienzyme amplification strategy.

Methods and results: Greatly enhanced sensitivity was achieved using bioconjugates containing horseradish peroxidase (HRP) and a secondary antibody (Ab$_2$) linked to Fe$_3$O$_4$/Au nanoparticles (Fe$_3$O$_4$/Au-HRP-Ab$_2$) at a high HRP/Ab$_2$ ratio. After a sandwich immunoreaction, the Fe$_3$O$_4$/Au-HRP-Ab$_2$ captured on the electrode surface produced an amplified electrocatalytic response by reduction of enzymatically oxidized hydroquinone in the presence of hydrogen peroxide. The high content of HRP in the Fe$_3$O$_4$/Au-HRP-Ab$_2$ could greatly amplify the electrochemical signal. Under optimal conditions, the reduction current increased with increasing alfa-fetoprotein concentration in the sample, and exhibited a dynamic range of 0.005–10 ng/mL with a detection limit of 3 pg/mL.

Conclusion: The amplified immunoassay developed in this work shows good precision, acceptable stability, and reproducibility, and can be used for detection of alfa-fetoprotein in real samples, so provides a potential alternative tool for detection of protein in the laboratory. Furthermore, this immunosensor could be regenerated by simply using an external magnetic field.

Keywords: Fe$_3$O$_4$/Au nanoparticles, alfa-fetoprotein, sandwich immunoassay, electrochemical immunosensor

Introduction
It is well known that alfa-fetoprotein (AFP), an oncofetal glycoprotein with a molecular weight of approximately 70,000 Da, is a tumor marker that occurs mainly in hepatocellular carcinoma, yolk sac tumors, and the serum of patients with other malignant tumors. The average concentration of AFP in healthy human serum is <20 ng/mL, and serum AFP levels often increase in a number of disease states. Therefore, detection of trace amounts of AFP is of great importance. Thus far, various immunosensors and immunoassays based on different measurement principles have been reported for determination of AFP, including enzyme-linked immunosorbent assay (ELISA), electrochemiluminescence, chemiluminescence, surface plasmon resonance, and quartz crystal microbalance. ELISA is the most widely used immunoassay method in the laboratory. However, concentrations of tumor-related proteins are very low in the early stages of cancer, and are beyond the detection limit of ELISA. Moreover, their lengthy analysis requires highly skilled personnel, specially equipped laboratories, and expensive reagents. Thus, new methods that can rapidly and conveniently monitor tumor-related proteins are highly desirable. Electrochemical immunosensors,
based on specificity of antigen–antibody interactions with electrochemical transducers, have attracted considerable interest because of their intrinsic advantages, such as low cost, high sensitivity, simple instrumentation, and excellent compatibility with miniaturization technologies.

Therefore, different electrochemical immunosensors, particularly amperometric immunosensors, have been developed and applied extensively for the determination of AFP.

In order to meet the increasing demand for early and ultrasensitive detection of tumor markers, three primary signal amplification strategies using nanomaterials have been developed. The first method involves the use of metal and semiconductor nanoparticles directly as electroactive labels to amplify the electrochemical detection of proteins. The second method uses nanoparticles as carriers for loading a large amount of electroactive species to amplify the detection signal. The third method is the most extensively employed, and uses enzyme-functionalized nanoparticles as labels. Enhanced sensitivity was achieved by loading a large amount of enzyme towards an individual sandwich immunological reaction event. Recently, various types of nanomaterials have been used as carriers for loading enzymes and antibodies to enhance sensitivity, including gold nanoparticles, irregularly shaped gold nanoparticles, nanosilica particles, carbon nanoparticles, carbon nanotubes, and graphene oxide. For example, Chen et al have proposed a highly sensitive electrochemical immunosensor using irregular gold nanoparticles as carriers of horseradish peroxidase (HRP)-anti-AFP for signal amplification. Similarly, Lin et al have reported use of graphene oxide, a novel tracer, to label HRP and the antibody, and developed an ultrasensitive immunnoassay method for detection of phosphorylated p53 (S392).

Recently, hybrid nanomaterials consisting of two or more different nanoscale functionalities have attracted much attention due to their novel combined properties and multiple potential applications. Immunomagnetic beads in particular are widely used in enrichment and separation of particular proteins in biology samples. Among them, magnetic composite Fe$_3$O$_4$/Au nanoparticles have attracted particular attention, owing to the combined functions of Fe$_3$O$_4$ and gold. Fe$_3$O$_4$ nanoparticles have a typical superparamagnetic nature, and provide a convenient means for separation, isolation, and purification of biological samples via an external magnetic field when the functional reagents are attached onto the surface of the particles. Their unique structural, electronic, and optical properties make gold nanoparticles very attractive for several applications in biotechnology.

Further, gold nanoparticles can provide a natural environment for bimolecular immobilization and facilitate electron transfer of biosensors because of their large surface area, interesting electrochemical properties, and good biocompatibility. Therefore, magnetic composite Fe$_3$O$_4$/Au nanoparticles have had more and more applications in areas such as immunoassays, protein immobilization, cell purification, and magnetically controlled transport of anticancer drugs.

Our present work focuses on enzyme-enriched, magnetic functionalized nanoparticles in signal amplification and separation for ultrasensitive detection of AFP. Magnetic composite Fe$_3$O$_4$/Au nanoparticles were synthesized by assembling gold nanoparticles on SH-modified Fe$_3$O$_4$ and using them as nanocarriers for immobilization of HRP and a secondary antibody (Ab$_2$). Greatly amplified sensitivity is achieved using bioconjugates featuring HRP and Ab$_2$ linked to Fe$_3$O$_4$/Au at a high HRP/Ab$_2$ ratio for replacement of singly labeled secondary antibodies. A modified glass carbon electrode with porous nanostructured gold film was used to attach the primary antibody (Ab$_1$). The analytical procedure consists of immunoreaction of the antigen (AFP) with Ab$_1$, followed by binding of Fe$_3$O$_4$/Au-HRP-Ab$_2$. Electrochemical detection was performed in the presence of H$_2$O$_2$ and hydroquinone (Figure 1). The results demonstrated that an immunosensor based on this amplification strategy has a good dynamic range from 0.005 to 10 ng/mL and a low detection limit of 3 pg/mL for AFP. This simple, cost-effective, and sensitive immunosensor could find wide potential application in clinical analysis.

### Materials and methods

#### Reagents and materials

Monoclonal mouse antihuman AFP and AFP test kits were obtained from Zhengzhou Biocell Biochem Company (Zhengzhou, China). Fe$_3$O$_4$ (20 nm in diameter), 3-mercaptopropyltriethoxysilane (3-MPTES) and HRP (EC 1.11.1.7, RZ > 3.0, A > 250 U/mg) were purchased from Sigma-Aldrich, St Louis, MO. Hydrogen tetrachloroaurate (III) tetrahydrate (HAuCl$_4$·4H$_2$O), trisodium citrate, hydroquinone, H$_2$O$_2$, and bovine serum albumin were obtained from Sinopharm Group Chemical Reagent Company Ltd (Shanghai, China). All reagents used were of analytical reagent grade, and all solutions were prepared with double deionized water. Phosphate-buffered solutions 0.1 M of various pH values were prepared by mixing stock solutions of NaH$_2$PO$_4$ and Na$_2$HPO$_4$, and then the pH was adjusted with 0.1 M NaOH and H$_3$PO$_4$. 

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**Apparatus**

Cyclic voltammetry measurements were performed using an electrochemical analyzer CHI 660 (Shanghai Chenhua Instrumental Corp, China) connected to a personal computer. A three-compartment electrochemical cell contained a platinum wire auxiliary electrode, a saturated calomel reference electrode, and a modified glass carbon electrode (GCE, 2 mm in diameter) as working electrode. The sizes of the nanoparticles were estimated from transmission electron microscopy (H-7650, Hitachi Instruments, Tokyo, Japan). The surface topographic features and composition of variously modified electrodes were characterized using scanning electron microscopy coupled with energy dispersive spectroscopy (SEM-EDS, S3400N Hitachi). The x-ray powder diffraction images were obtained using a Bruker D8 Advance diffractometer (Bruker, Karlsruhe, Germany). Ultraviolet-visible spectra were recorded using a TU-1901 spectrophotometer (Purkinje General Instrument Co, Beijing, China). The x-ray powder diffraction spectra were taken using an AXIS UltraDLD spectrometer (Shimadzu Co, Tokyo, Japan). Vibrating sample magnetometry (Lake Shore 7410) was used to perform magnetic measurements on the dried samples to evaluate the magnetic properties of the nanoparticles.

**Preparation of Fe$_3$O$_4$/Au nanoparticles**

Figure 1A shows the procedure used to prepare the Fe$_3$O$_4$/Au. First, gold nanoparticles was prepared using the Frens method. In brief, 0.01 wt% HAuCl$_4$ (100 mL) was boiled with vigorous stirring in a flask. Trisodium citrate 1 wt% solution (2.5 mL) was added quickly to the boiling solution, resulting in a color change from pale yellow to dark red, indicating formation of gold nanoparticles. The solution was maintained for 10 minutes at boiling temperature.

Fe$_3$O$_4$/Au nanoparticles were obtained by self-assembling gold nanoparticles onto the surface of SH-modified Fe$_3$O$_4$ according to the literature with modification. Fe$_3$O$_4$ nanoparticles are commercially available. Experimentally, Fe$_3$O$_4$ 0.2 g was dispersed in 50% ethanol 90 mL by ultrasound, and then 3-MPTES 300 $\mu$L and ammonium hydroxide 500 $\mu$L were added dropwise. The mixture was stirred at 60°C for 6 hours under a nitrogen atmosphere. Uncoated Fe$_3$O$_4$ was deleted by means of washing with 0.1 M HCl (six times, for four hours each). The deposit was separated by a magnetic stirrer, which was rinsed three times with double deionized water and then ethanol to give SH-modified Fe$_3$O$_4$. Following that, the gold nanoparticles were added to the SH-modified Fe$_3$O$_4$, and shaken slightly for 4 hours at room temperature to make the gold assemble on the surface of the formed nanoparticles. After magnetic separation, the Fe$_3$O$_4$/Au obtained were rinsed with double deionized water and suspended in 10 mL water.

**Preparation of Fe$_3$O$_4$/Au-HRP-Ab$_2$ conjugates**

Figure 1B shows the procedure used to prepare the Fe$_3$O$_4$/Au-HRP-Ab$_2$ bioconjugate. Initially, 1.0 mL of a 1.0 mg/mL Fe$_3$O$_4$/Au nanoparticle suspension was adjusted to pH 8.2 with rigorous stirring in a flask. 1.0 mL of a 1.0 mg/mL Fe$_3$O$_4$/Au-HRP-Ab$_2$ bioconjugate suspension was added, and the mixture was stirred at room temperature for 6 hours. After magnetic separation, the Fe$_3$O$_4$/Au-HRP-Ab$_2$ obtained were rinsed with double deionized water and suspended in 10 mL water.

**Figure 1** Schematic representation of the preparation of (A) Fe$_3$O$_4$/Au, (B) Fe$_3$O$_4$/Au-HRP-Ab$_2$, and (C) immunosensor.

**Abbreviations:** AFP, alfa-fetoprotein; BSA, bovine serum albumin; HRP, horseradish peroxidase; Ab$_2$, secondary antibody.
using Na₂CO₃. Thereafter, 200 µL of HRP at 1 mg/mL and
200 µL of Ab₂ at 10 µg/mL were added to the dispersion,
and the mixture was stirred overnight at 4°C. After magnetic
separation and washing three times, the resulting mixture was
redispersed in 1.0 mL of pH 7.4 phosphate-buffered solution
containing 1% bovine serum albumin and stored at 4°C.

Fabrication of the immunosensor
The procedure followed to prepare the proposed immunosen-
sor is schematized in Figure 1C. The GCE was polished with
0.3 µm and 0.05 µm alumina, followed by successive sonica-
tion in distilled water and ethanol for 5 minutes and dried
in air. A porous nanostructure gold film was then deposited
at a voltage of −0.5 V for 50 seconds on the clean GCE that
was immersed in 5 mL 0.08 M HAuCl₄ solution containing
0.004 M lead acetate. After thorough washing with water,
the electrode was immediately followed by incubation
with 20 µL 0.5 mg/mL Ab₁ for one hour. After washing
with 0.05% Tween-20 and phosphate-buffered solution,
Ab₁/Au/GCE was incubated in 3% bovine serum albumin
and phosphate-buffered solution at 37°C for one hour to
block excess active groups and nonspecific binding sites
on the surface. The electrode was then washed with 0.05%
Twee-20 and phosphate-buffered solution before use.

Immunooassay procedure for detection
of AFP
A sandwich immunoassay was used for determination of
AFP. The immunosensor, Ab₁/Au/GCE, was incubated
with 20 µL of a different concentration of standard AFP
antigen for 30 minutes at 25°C, followed by washing with
0.05% Tween-20 and phosphate-buffered solution. Next, the
electrode was incubated with 20 µL of Fe₃O₄/Au-HRP-Ab₂
for 30 minutes at 25°C, followed by washing with 0.05%
Twee-20 and phosphate-buffered solution to remove the
nonspecific adsorption of conjugate. Electrochemical detect-
tion was performed in 5 mL of pH 6.5 phosphate-buffered
solution containing 2 mM hydroquinone and 5 mM H₂O₂,
and from −0.6 to 0.6 V (versus saturated calomel reference
electrode) with a scan rate of 100 mV/second.

Results and discussion
Characterization of Fe₃O₄/Au-HRP-Ab₂
conjugation
In this work, Fe₃O₄/Au was as an excellent carrier for HRP and
Ab₂ because of its good biocompatibility, large surface area,
and superparamagnetic properties. Transmission electron
microscope images provide more detailed morphological
information on the prepared nanoparticles (Figure 2). They
demonstrated that both Fe₃O₄ and Fe₃O₄/Au nanoparticles
were spherical in structure, monodispersed, and of appropri-
ate size. The average diameter of the Fe₃O₄/Au nanoparticles
was about 40 nm (Figure 2C). Upon deposition of gold
onto the Fe₃O₄ nanoparticles, the diameter of the particles
increased by about 20 nm, demonstrating that the thickness
of the gold was about 10 nm.

Figure 3A compares the x-ray powder diffraction pattern
for the Fe₃O₄ nanoparticles and Fe₃O₄/Au nanoparticles.
In Figure 3A (curve a), the diffraction peak positions at
2θ = 30.0°, 35.3°, 42.6°, 53.4°, and 62.5° can be attributed
to the (220), (311), (400), (422), (511), and (440) planes of
Fe₃O₄ in a cubic phase (space group Fd₃m), respectively.
In Figure 3A (curve b), the diffraction peak positions at
2θ = 38.1°, 44.2°, 64.5°, 77.5°, and 81.6° can be attributed
to the (111), (200), (220), (311), and (222) planes, respectively.
Other peaks can be attributed to Fe₃O₄, and the simultaneous
observation of both Fe₃O₄ and gold peaks verified successful
assembly of Fe₃O₄/Au nanoparticles.

The surface composition of elements such as iron and
gold in the Fe₃O₄/Au nanoparticles were determined by x-ray
photoelectron spectra as shown in Figure 3B. Figure 3B shows gold peaks including Au 4s, Au 4p, Au 4d, and Au 4f appearing on the surface of the Fe₃O₄ nanoparticles. The Au 4f appearing at 80–90 eV can be assigned to the Au⁰. The Fe₃O₄ showed Fe 2p at 700–720 eV. The x-ray photoelectron spectra result was in agreement with a report by Cui et al indicating that gold had been successfully assembled on the surface of the magnetic Fe₃O₄ nanoparticles.⁴⁸

The magnetic properties of the nanoparticles are illustrated in Figure 4. It can be seen that a small coercivity or remanence existed around room temperature, indicating the Fe₃O₄ and Fe₃O₄/Au have superparamagnetic properties. As a result, the Fe₃O₄/Au could be isolated from solution by an adscititious magnet. It can also be seen that the saturation magnetization for Fe₃O₄/Au is much smaller than that for Fe₃O₄. The saturation magnetization values were 76.8 emu/g and 54.9 emu/g for Fe₃O₄ and Fe₃O₄/Au nanoparticles, respectively.

The saturation magnetization value of the magnetic nanoparticles declined after coating with a layer of gold. This lower saturation magnetization value is due to the presence of nonmagnetic gold.

The Fe₃O₄/Au-HRP-Ab₂ obtained was characterized by ultraviolet-visible spectroscopy and, as shown in Figure 5, the Fe₃O₄ nanoparticles did not show any obvious absorbance peaks in ultraviolet-visible spectroscopy (curve a). However, the Fe₃O₄/Au nanoparticles showed a clear absorption band containing a maximum centered at 540 nm (curve c). This band showed a red shift in comparison with pure gold nanoparticles (curve b, 520 nm). This finding suggests that a combination of Fe₃O₄ nanoparticles and gold nanocomposites leads to a red shift of resonant wavelength. After Ab₂ and HRP were conjugated onto the Fe₃O₄/Au, two absorption peaks around 280 nm and 404 nm were observed (curve f), which can be ascribed to the typical absorption of Ab₂ (curve d) and HRP (curve e).

**SEM-EDS characterization of gold nanoparticles modified electrode with direct electroposition**

SEM-EDS were used to investigate the successful fabrication of the immunosensor. Figure 6A shows the energy dispersive spectroscopy analysis of Au/GCE showing Au-M (2.0 keV), Au-Lα (9.7 keV), and Au-Lβ (11.4 keV), which indicates successful electrodeposition of gold on the GCE. Furthermore, scanning electron microscopy was used to investigate the Au/GCE before and after modification with Ab₁. As shown in Figure 6B, many small porous gold nanoparticles were obtained on the Au/GCE. Obviously, the
A porous gold film-modified electrode had a larger surface compared with the ordinary glassy carbon electrode, which could provide a larger surface area for the immobilization of Ab₁. Upon immobilization of Ab₁, obvious aggregation of the trapped biomolecules could be observed on the surface (Figure 6C), indicating successful immobilization of Ab₁.

Electrochemical characterization of the immunosensor

As shown in Figure 7, the cyclic voltammograms of Ab₁/Au/GCE did not show any detectable signal in pH 6.5 phosphate-buffered solution (curve a). Upon adding 2 mM hydroquinone and 5 mM H₂O₂ to the phosphate-buffered solution, Ab₁/Au/GCE exhibited a pair of stable and well-defined redox peaks at −145 mV and 345 mV (curve b), corresponding to the electrochemical redox response of hydroquinone on the electrode surface. When incubating the immunosensor with 5 ng/mL AFP antigen, no obvious change in signal was observed. However, after incubation with Fe₃O₄/Au-HRP-Ab₂, the resulting sandwich immunocomplex displayed an obvious increase in electrocatalytic reduction current (curve c) because of the introduction of HRP onto the electrode surface by the immunoreaction.

Comparison of detection antibodies with various labels

To investigate further the effect of the synthesized Fe₃O₄/Au on the sensitivity of the electrochemical immunosensors,
three types of detection antibodies were used, i.e., HRP-anti-Ab₂, Au-HRP-Ab₂, and Fe₃O₄/Au-HRP-Ab₂ (Figure 8). As shown in Figure 8A–C, upon addition of H₂O₂ to the substrate solution, an obvious catalytic characteristic appeared, with a distinct increase in the reduction current and a decrease in the oxidation current. The catalytic current is mainly due to the labeled HRP toward the reduction of H₂O₂ with the help of hydroquinone as an electron mediator. As shown in Figure 8, we found that the electrochemical immunosensor exhibited a larger current shift using Au-HRP-Ab₂ (Figure 8B) as the detection antibody than when using HRP-anti-Ab₂ (Figure 8A). The reason for this might be that the gold nanoparticles with a high surface-to-volume ratio and good biocompatibility can load more HRP and Ab₂. Moreover, gold nanoparticles have good conductivity, which can enhance enzyme activity.⁴⁹ More significantly, the electrochemical responses could be improved by using Fe₃O₄/Au-HRP-Ab₂ (Figure 8C) rather than Au-HRP-Ab₂ (Figure 8B). A possible reason is that Fe₃O₄ can allow more room for attachment of gold nanoparticles, which indirectly increases the amount of bound Ab₂ and HRP. When one antibody molecule on the surface of Fe₃O₄/Au-HRP-Ab₂ is reacted with the corresponding antigen, other HRP molecules can enter and participate in the electrochemical reaction. At the same time, Fe₃O₄/Au can enhance the electron transfer rate between the enzyme and the electrode.⁵⁰,⁵¹

**Optimization of immunoassay conditions**

Because of the coimmobilization of enzymes and antibodies on the Fe₃O₄/Au nanocarrier, the ratio of HRP and Ab₂ is the most important factor in the response signal. As shown in Figure 9A, one can see that the electrocatalytic current increases with an increasing ratio of HRP/Ab₂, and the maximum response is achieved at a ratio of 100:1. An increase in the HRP/Ab₂ ratio could increase the total amount of HRP loaded per Fe₃O₄/Au nanocarrier, which would be expected to increase the response amplification for this sandwich immunoassay. However, reducing the amount of Ab₂ in the immunoassay may decrease the efficiency of the immune reaction to the AFP antigen captured at the electrode surface, which may result in a decreased response. Therefore, an HRP/Ab₂ ratio of 100:1 was selected as the optimal condition in which to prepare the Fe₃O₄/Au-HRP-Ab₂ conjugate. To determine the amount of active HRP in the Fe₃O₄/Au-HRP-Ab₂ conjugate dispersion, the mixture was reacted with the TMB substrate for HRP. The reaction product was read at 650 nm. These results were compared with a standard curve constructed using pure HRP as part of an enzyme activity experiment. The concentration of active HRP in the Fe₃O₄/Au-HRP-Ab₂ conjugate dispersion was determined to be 7.14 µg/mL.

The pH of the detection solution is an important parameter because the acidity of the solution is greatly affected by the activity of immobilized proteins. The effect of pH
of the solution on the amperometric response for AFP is shown in Figure 9B. The current response was increased by increments in pH from 4.0 to 6.5 and then decreased when pH exceeded 6.5. Therefore, a 0.1 M solution of pH 6.5 was selected as the optimum solution for AFP detection.

The temperature and time taken for the antigen-antibody interaction to occur greatly influenced the sensitivity of the sandwich-type immunoassay developed. Considering the practical applications of the proposed system in clinical immunoassays, all experiments were carried out at room temperature (25°C ± 1.0°C). Under this condition, the effect of various incubation times (10–45 minutes) on the immunosensor current was investigated at 1 mg/mL of AFP. As shown in Figure 9C, the reduction current increased with increasing incubation time and tended to level off after 30 minutes, indicating optimal formation of the sandwich-type immunocomplexes. A longer incubation time could not improve the response. Therefore, 30 minutes of incubation time was used for the detection of AFP in this study.

Analytical performance

The cyclic voltammograms of the immunosensor was investigated by assaying various AFP standards using Fe3O4/Au-HRP-Ab2 as trace labels and H2O2 as the enzyme substrate. The reduction current increased with incremental AFP concentration in the incubation solution. As shown by curve a in Figure 10, the increase in reduction current was proportional to AFP concentration in the range of 0.005–10 ng/mL; the linear regression equation is $\Delta i_p (\mu A) = 13.3 \times \log C_{\text{AFP}} (\text{ng/mL}) + 42.2$ with a detection limit of 3 pg/mL ($R^2 = 0.988$). For comparison, we also investigated the analytical performance of the immunosensor using Au-HRP-Ab2 and HRP-anti-AFP as detection antibodies, respectively. The regression equations, linear ranges, and detection limits are as follows:

Using Au-HRP-Ab2 (Figure 9 curve b):

$\Delta i_p (\mu A) = 5.88 \times \log C_{\text{AFP}} (\text{ng/mL}) + 13.0$,

$R^2 = 0.990$, 0.01–10 ng/mL, 6 pg/mL AFP (i)

Using HRP-anti-AFP (Figure 9 curve c):

$\Delta i_p (\mu A) = 3.51 \times \log C_{\text{AFP}} (\text{ng/mL}) + 3.88$,

$R^2 = 0.962$, 1.0–10 ng/mL, 0.6 ng/mL AFP (ii)

These results suggest that Fe3O4/Au could greatly improve the sensitivity and work range of the immunosensor. Although the threshold of human serum AFP is 10 ng/mL, actual serum samples should be diluted during the clinical diagnostic process, so the concentrations detected are usually <10 ng/mL. Small volume samples are preferable. Thus, the sensitivity of this immunoassay was adequate for practical application.

Regeneration of immunosensors is of great interest to immunoanalysts. Traditional regeneration of the immunosensor usually requires a different regeneration solution, such as an
acid, alkali, or electrolyte solution at a high concentration to break the linkage between the antigen and antibody. In the present work, the immunosensor could be regenerated by simply using an external magnetic field to remove the Fe$_3$O$_4$/Au-HRP-Ab$_2$-bonded antigen. Experimental results indicated that the immunosensor could retain 90.7% of the initial current response for 18 applications once regenerated.

**Immunosensor specificity, reproducibility, and stability**

Specificity is an important feature of the immunosensor. To investigate this, the immunosensor was incubated with 1 ng/mL AFP containing a different interference substance, such as carcinoma antigen 125, carcinoembryonic antigen, human IgG, prostate-specific antigen, and bovine serum albumin. No remarkable change of currents was observed in comparison with the results obtained in the presence of AFP only, indicating good selectivity of the proposed AFP immunosensor.

The reproducibility of the proposed immunosensor was evaluated by intra-assay and interassay coefficients of variation. The intra-assay precision of the analytical method was evaluated by analyzing one immunosensor for six replicate determinations. Coefficients of variation for the intra-assay were 3.6% and 4.7% at 0.1 ng/mL and 1.0 ng/mL AFP, respectively. Similarly, the interassay coefficients of variation for six immunosensor determinations were 3.9% and 5.5% at 0.1 ng/mL and 1.0 ng/mL AFP, respectively. These results demonstrate the acceptable reproducibility and precision of the proposed immunosensor.

We also examined the stability of the developed immunosensor. When not in use, the immunosensor could be stored in pH 7.0 phosphate-buffered solution at 4°C for at least 3 weeks without any obvious signal change. Moreover, the immunosensor retained 89.4% of its initial response after a storage period of 4 weeks. The slow decrease in current response may be attributed to gradual deactivation of biomolecules immobilized on the nanoparticle surface.

**Application of the immunosensor in human serum**

The electrochemical immunosensor was further validated by assaying six serum specimens gifted from the Nanfang Medical Hospital, China. The serum was prepared by collecting whole blood, leaving it undisturbed for 15–30 minutes at room temperature to clot, and then removing the clot by centrifugation at 1000–2000 rpm for 10 minutes in a refrigerated centrifuge, and collecting the supernatant serum. Table 1 describes the correlation between the partial results obtained by the
proposed immunoassay and the ELISA method, indicating no significant difference between the two methods, ie, the proposed immunoassay could be used for satisfactory clinical determination of AFP levels in human serum.

**Conclusion**

We have successfully designed a multi-enzyme labeling Fe₃O₄/Au strategy as part of a signal amplification procedure and demonstrated its use in the ultrasensitive, selective, and accurate quantification of AFP by electrochemical immunoassay. Highlights of the developed immunoassay are: Fe₃O₄/Au as the enzyme-loading carrier can load many enzyme molecules on each Fe₃O₄/Au nanoparticle, thus enhancing the sensitivity of the immunoassay; using Fe₃O₄/Au as signal enhancers favors rapid separation and purification of the signal antibody on an external magnetic field; after each detection, the immunoassay can be easily regenerated by applying an external magnetic field. The proposed immunoassay has high sensitivity, good reproducibility, stability, and accuracy. We anticipate that this method can be extended for determination of other proteins and have promising potential in clinical applications.

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**Disclosure**

The authors report no conflicts of interest in this work.

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