

Arginine-Engineered Gold Nanoclusters for Doxorubicin Chemiluminescence Sensing

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Abstract

The limited chemiluminescence (CL) emission intensity and efficiency of some traditional CL systems have restricted their application in practical analytical detection. Strategies such as catalysis and CL resonance energy transfer (CRET) are frequently employed to enhance CL performance. In this work, we synthesized arginine surface-engineered 6-aza-2-thiothymine gold nanoclusters (Arg/ATT-AuNCs) via host-guest assembly, which exhibit exceptional catalytic activity and intense photoluminescence. Arg/ATT-AuNCs amplified the CL intensity from $\text{NaIO}_4\text{-H}_2\text{O}_2$ system by 1200-fold. The CL Mechanistic studies revealed that Arg/ATT-AuNCs not only accelerated decay of H_2O_2 to form reactive oxygen species, but also acted as efficient energy acceptors of singlet oxygen ($^1\text{O}_2$) via a CRET pathway. It was observed that doxorubicin (DOX) quenches the enhanced CL signal through an internal filtering effect that disrupts the CRET process. Based on this, a straightforward, rapid, and highly sensitive biosensor has been developed for the detection of DOX in human serum samples, achieving a low detection limit of $0.029\text{ }\mu\text{M}$. The biosensor was applied to DOX determination in human serum samples with recoveries ranging from 91.1 to 106.2%. This study not only provides a new method for the detection of DOX, but also broadens the application scope of AuNCs in the field of CL.

1. Introduction

Doxorubicin (DOX), a prominent anthraquinone antibiotic, is widely used in the treatment of various human cancers, including malignant melanoma, soft-tissue sarcomas, and bronchogenic cancers^[1–5]. However, its clinical application is often limited by severe side effects when the plasma concentration exceeds the therapeutic threshold^[6–9]. Due to the narrow therapeutic range of DOX, accurate monitoring of its blood concentration is crucial for ensuring both treatment efficacy and patient safety. Recently, fluorescent, chemiluminescence (CL), and electrochemical sensors^[10–14] have been developed for DOX detection. Among various analytical techniques, the CL detection has the advantages such as high sensitivity, rapidity, and low background scattering, making it one of the most promising methods for drug and food analysis^[15, 16]. Nevertheless, conventional H_2O_2 -based CL systems, including $\text{NaIO}_4\text{-H}_2\text{O}_2$ ^[17], Luminol- H_2O_2 ^[18], bis(2,4,5-trichlorophenyl-6-carbopentoxypheyl)oxalate (CPPO)- H_2O_2 ^[19, 20], suffer from low CL emission efficiency, which has hindered their widespread application in practical analytical detection^[21–23]. Therefore, the development of CL systems with intensive CL emission is of significant importance.

To enhance CL performance, catalysts or CL resonance energy transfer (CRET) are frequently employed^[24, 25]. Catalysts typically accelerate the generation of free radicals in CL systems, while CRET receptors receive energy from excited-state intermediates in CL reactions, thereby improving CL efficiency. For example, our group prepared ATT-AuNCs with catalytic activity, which increased the production of reactive oxygen species (ROS), dramatically enhanced the CL intensity of the luminol- H_2O_2 reaction^[26]. Zhang et al. employed BSA-AuNCs with strong fluorescence to significantly amplify the weak CL generated from TCPO- H_2O_2 via a CRET mechanism^[20].

However, most existing methods rely on the separate introduction of catalysts and CRET acceptors, involving multiple operational steps. The integration of these dual functions into a single nanomaterial would therefore represent a significant advancement, promising enhanced efficiency and simplified procedures for CL systems.

In recent years, gold nanoclusters (AuNCs) with sizes below 3 nm have drawn considerable interest due to their high specific surface area, excellent catalytic performance, and unique photoluminescence (PL) properties^[27–31]. In this study, arginine surface-engineered 6-aza-2-thiothymine-gold nanoclusters (Arg/ATT-AuNCs) integrating both exceptional catalytic activity and strong PL were synthesized through host-guest assemblages. The as-synthesized Arg/ATT-AuNCs elicited an approximately 1200-fold enhancement in the CL intensity of the $\text{NaIO}_4\text{-H}_2\text{O}_2$ system compared to the pristine ATT-AuNCs. It is postulated that Arg/ATT-AuNCs function dually as both a catalyst and a CRET acceptor, thereby substantially improving the CL efficiency. Leveraging the inhibitory effect of doxorubicin (DOX) on the Arg/ATT-AuNCs- $\text{NaIO}_4\text{-H}_2\text{O}_2$ CL system, a highly sensitive method for the detection of DOX in human serum samples was developed (Scheme 1). This work not only provides a novel strategy for DOX sensing but also proposes a general concept for further amplification of CL signals.

2. Materials and methods

2.1 Chemicals and Materials

6-Aza-2-thiothymine (ATT) was from Xiya Chemical Co. Ltd (Shandong, China). Tetrachloroaurate III trihydrate ($\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$), L-arginine (L-Arg), L-lysine (L-Lys), L-alanine (L-Ala), L-tryptophan (L-Trp), L-histidine (L-His), L-phenylalanine (L-Phe), Glycine (Gly), L-isoleucine (L-Ile), L-Cysteine (L-Cys), sodium chloride (NaCl), potassium chloride (KCl), Iron(II) chloride (FeCl_2), calcium chloride (CaCl_2), glucose, uric acid, glutathione (GSH), ascorbic acid (AA), nitrotetrazolium blue chloride (NBT), thiourea, and doxorubicin (DOX) were obtained from the Aladdin Reagent Co., Ltd (Shanghai, China) (<http://www.aladdin-e.com/>). Luminol, hydrogen peroxide (H_2O_2 , 30%), sodium periodate (NaIO_4), and sodium hydroxide (NaOH) were from Sinopharm Chemical Reagent Co., Ltd. All commercial chemicals were of analytical grade. Hence, they were used without any further purification.

2.2 Apparatus

The CL signal was recorded by MPI-A/B multifunctional chemical detector (Xi'an Remai Electronic Technology Co., Ltd.). Fluorescence spectrum was obtained by Cary Eclipse fluorescence spectrometer (Agilent Technologies Co., Ltd.). UV-vis spectrum was measured by UV-2600 UV-Visible spectrometer (Shimadzu, Japan). The ESR spectrum was collected by JES-FA200 spectrometer (JEOL, Tokyo, Japan). The dynamic light scattering (DLS) and ζ potential were performed on Zetasizer Nano ZS90 (Malvern Instruments Ltd., UK). Transmission electron microscope (TEM) was taken on JEM-2100 microscope (JEOL). CL spectrum was conducted on Cary Eclipse fluorescence spectrometer (Agilent Technologies, USA).

2.3 Preparation of Arg/ATT-AuNCs

The synthesis of Arg/ATT-AuNCs was carried out as described in our earlier reports^[32]. 15 mL of ATT (80 mM, with 0.2 M NaOH) was mixed with 15 mL of HAuCl₄·3H₂O (10 mg/mL), and the mixture was incubated at 30°C in the dark for 1 h, yielding a yellow solution. The as-synthesized ATT-AuNCs was then dialyzed overnight using a 3.5-kDa cut-off dialysis bag with deionized water to remove the impurities. Following that, two milliliters of 40 mM Arg (pH 10) was thrown into 18 mL of an as-prepared ATT-AuNCs solution (pH 10) and the mixed solution was allowed to react at 37°C for 24 h. The resulting ATT-AuNC solutions were stored at 4°C in the dark prior to use.

2.4 CL measurement

Briefly, 100 µL NaIO₄ (25 mM, pH 7) and 100 µL Arg/ATT-AuNCs (2 mg/mL) were premixed in a quartz vial. Subsequently, 100 µL H₂O₂ (0.1 M) was injected into the above vials with a microliter syringe under dark conditions. The CL signal was detected by a photo multiplier tube (PMT) adjacent to the quartz vial (Figure S1).

2.5 Detection of DOX

The quantification of DOX was performed using the developed flow injection analysis chemiluminescence (FIA-CL) system (Figure S2). In this setup, a solution of Arg/ATT-AuNCs (2 mg/mL) premixed with varying concentrations of DOX was introduced into the system via one channel of a peristaltic pump (P1). Simultaneously, a second channel of another peristaltic pump (P2) delivered the CL reagents, comprising 25 mmol/L NaIO₄ (pH 7) and 0.1 mol/L H₂O₂. These streams merged at the reaction cell, where the ensuing CL emission was monitored and recorded by a photomultiplier tube (PMT). The concentration of DOX was quantified based on the degree of CL signal suppression.

2.6 Analysis of DOX in human serum sample

To evaluate the practical applicability of the proposed method, the detection of DOX was conducted in human serum samples. The fresh serum was initially subjected to a 5-fold dilution with ultrapure water, followed by ultrafiltration at 10,000 rpm for 30 min to remove interfering proteins. The resulting filtrate was subsequently diluted 25-fold with the dilution buffer prior to analysis. The processed samples were analyzed following the standard DOX detection protocol described above. Recovery studies were performed to assess accuracy by spiking the original serum samples with known concentrations of DOX at 250, 500, and 1000 nM prior to the sample preparation steps.

3. Results and discussion

3.1 Characterization of ATT-AuNCs and Arg/ATT-AuNCs:

The multifunctional Arg/ATT-AuNCs nanocomposite was successfully constructed via a supramolecular host-guest assembly strategy between arginine (Arg) and the precursor ATT-AuNCs. As depicted in Fig.

1A-C, high-resolution TEM (HRTEM) images confirmed the formation of uniform, spherical nanoparticles with an average diameter of 2.0 nm and a well-resolved lattice spacing of 0.23 nm. The excellent colloidal stability of the nanocomposite in aqueous solution was verified by dynamic light scattering (DLS), which showed a hydrodynamic diameter of 8.01 nm and indicated the absence of significant aggregation post-functionalization (Figure S3). The optical properties crucial for its role as a CRET acceptor were thoroughly characterized. The UV-vis absorption spectrum (Fig. 1D) exhibited three distinct peaks at 505, 465, and 405 nm, attributable to ligand-to-metal charge transfer^[33, 34]. Furthermore, the photoluminescence spectrum (Fig. 1E) revealed strong fluorescence with excitation and emission maxima at 405 nm and 528 nm, respectively. The elemental composition and surface chemistry were probed by X-ray photoelectron spectroscopy (XPS). The full survey spectrum (Fig. 1F) displayed characteristic peaks for S 2p (162.5 eV), C 1s (284.8 eV), N 1s (399.4 eV), O 1s (530.8 eV), and Au 4f (84.1 eV), collectively affirming the successful integration of Arg into the nanocomposite structure.

3.2 CL from Arg/ATT-AuNCs in NaIO₄-H₂O₂ system

The CL kinetic profiles were recorded using a static injection system. As illustrated in Fig. 2A, a negligible CL emission (intensity ≈ 14) was observed from the NaIO₄-H₂O₂ reaction system alone. The introduction of ATT-AuNCs alone resulted in only a marginal increase in the CL signal (intensity ≈ 35). In contrast, the incorporation of the Arg/ATT-AuNCs nanocomposite led to a dramatic amplification of the CL intensity, reaching a value of 17,128, which corresponds to an enhancement of approximately 1200-fold compared to the pristine NaIO₄-H₂O₂ system. Control experiments confirmed that no detectable CL signal was generated when Arg/ATT-AuNCs were individually mixed with either NaIO₄ or H₂O₂. This critical observation indicates that the strong CL emission originates from the specific interaction between the nanocomposite and the reactive intermediates generated in situ from the reaction between NaIO₄ and H₂O₂.

To elucidate the underlying CL mechanism, the effect of reagent mixing sequence was systematically investigated. As depicted in Fig. 2B, the maximum CL intensity (~ 16065) was achieved when H₂O₂ was introduced into a pre-mixed solution of NaIO₄ and Arg/ATT-AuNCs. This optimal signal can be attributed to the absence of any pre-reaction between NaIO₄ and the nanocomposite, thereby ensuring that the full catalytic and energy-accepting capacity of Arg/ATT-AuNCs is available upon the introduction of H₂O₂. Furthermore, the CL enhancement factor achieved by the Arg/ATT-AuNCs system exceeds those of other recently reported nanomaterials (including N-CDs, Co-MOF, AuNSs, and SN-GQD) for the NaIO₄-H₂O₂ reaction, as detailed in Table S1.

3.3 The mechanism of NaIO₄-Arg/ATT-AuNCs-H₂O₂ system

To identify the reactive oxygen species (ROS) involved in the NaIO₄-Arg/ATT-AuNCs-H₂O₂ CL system, radical scavenging experiments and electron paramagnetic resonance (EPR) spectroscopy were employed. As illustrated in Figure S4, scavengers, including ascorbic acid (AA, for total ROS), thiourea

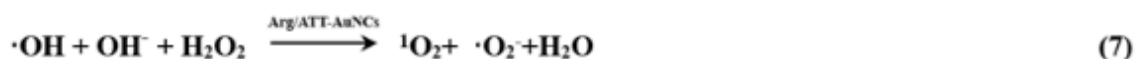
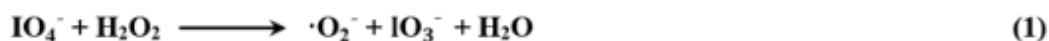
(for $\cdot\text{OH}$), nitrotetrazolium blue chloride (NBT, for $\text{O}_2^{\cdot-}$), and histidine (for $^1\text{O}_2$), were introduced into the system at 1 mM. The corresponding CL inhibition rates were 86.50%, 83.46%, 100%, and 94.76%, respectively, indicating the involvement of all these ROS in the emission process. EPR analysis further confirmed the generation of $\cdot\text{OH}$ and $^1\text{O}_2$. Characteristic adduct signals of DMPO- $\cdot\text{OH}$ (with a 1:2:2:1 quartet) and TEMP- $^1\text{O}_2$ (with a 1:1:1 triplet) were observed in the $\text{NaIO}_4\text{-H}_2\text{O}_2$ system (Fig. 3A, 3B). Notably, the signal intensities increased markedly upon the addition of Arg/ATT-AuNCs, demonstrating the catalytic role of the nanocomposite in promoting ROS formation. Furthermore, purging the system with N_2 for 20 min led to a 7.59% decrease in CL intensity (Fig. 3C), confirming that dissolved oxygen also participates in the reaction. These results verify that Arg/ATT-AuNCs enhance the CL emission by facilitating the generation of $\cdot\text{OH}$, $\text{O}_2^{\cdot-}$, and $^1\text{O}_2$ in the $\text{NaIO}_4\text{-H}_2\text{O}_2$ system.

UV-vis absorption and photoluminescence (PL) spectroscopy were utilized to investigate the potential role and stability of Arg/ATT-AuNCs during the CL process. As shown in Figure S5, the characteristic absorption profile of Arg/ATT-AuNCs, featuring peaks at 405, 470, and 505 nm, remained virtually unaltered upon completion of the CL reaction. This spectral stability suggests the stability of the nanocomposite. In parallel, NaIO_4 exhibited a characteristic absorption peak at 223 nm, the intensity of which diminished significantly following the introduction of H_2O_2 . This observation corroborates the expected redox reaction between periodate and H_2O_2 , resulting in the reduction of IO_4^- to IO_3^- . Furthermore, the PL emission spectrum of Arg/ATT-AuNCs was not quenched or shifted after the CL reaction. The invariance of both the absorption and emission spectra provides strong evidence that Arg/ATT-AuNCs maintain their structural integrity and function as a stable catalyst or energy acceptor, rather than being consumed as a reactant, in the $\text{NaIO}_4\text{-H}_2\text{O}_2$ CL system.

To identify the emitting species, the CL spectra of the systems were recorded using a fluorescence spectrometer. As presented in Fig. 4A, the $\text{NaIO}_4\text{-H}_2\text{O}_2$ system exhibited a CL emission maximum at 455 nm, which is characteristic of singlet oxygen ($^1\text{O}_2$) emission. Critically, a significant spectral overlap was observed between this $^1\text{O}_2$ CL emission and the absorption profile of Arg/ATT-AuNCs (Fig. 4A), fulfilling a fundamental prerequisite for CL resonance energy transfer (CRET). Upon incorporation of Arg/ATT-AuNCs into the system, the CL emission maximum underwent a distinct redshift to 528 nm (Fig. 4B). This resultant wavelength aligns precisely with the intrinsic photoluminescence maximum of Arg/ATT-AuNCs ($\lambda_{\text{em}} = 525$ nm under $\lambda_{\text{ex}} = 405$ nm). The congruence between the CL emission of the enhanced system and the PL of the nanoclusters provides definitive evidence for the occurrence of CRET from the $^1\text{O}_2$ (energy donor) generated in the $\text{NaIO}_4\text{-H}_2\text{O}_2$ reaction to the Arg/ATT-AuNCs (energy acceptor).

Based on the above discussion, the processes of catalysis and CRET simultaneously occurred in $\text{NaIO}_4\text{-Arg/ATT-AuNCs-H}_2\text{O}_2$ system. First, IO_4^- and H_2O_2 react to form $\text{O}_2^{\cdot-}$ and IO_3^- under alkaline conditions (Eqs. (1)). Subsequently, the generated $\text{O}_2^{\cdot-}$ reacts with H_2O_2 to produce $\text{OH}\cdot$ (Eqs. (2)). These reactive oxygen radicals can recombine to yield $^1\text{O}_2$ (Eqs. (3) and (4)). When $(^1\text{O}_2)_2^*$ returns to the ground state with weak CL emission (Eqs. (5)). Arg/ATT-AuNCs catalyze the decomposition of H_2O_2 to increase the generation of ROS, which in turn promotes the formation of $(^1\text{O}_2)_2^*$ (Eqs. (6) and (7)).

Additionally, Arg/ATT-AuNCs serve as energy acceptors, receiving energy from $(^1\text{O}_2)_2^*$ and forming excited state Arg/ATT-AuNCs (Arg/ATT-AuNCs*) (Eqs. (8)). The Arg/ATT-AuNCs* return to the ground state, with strong CL emission (Eqs. (9)).



3.4 DOX determination

Based on the synergistic catalysis-CRET effect of Arg/ATT-AuNCs, a turn-off CL biosensing platform was developed for the highly sensitive detection of DOX. As shown in Figure S6, the introduction of DOX induces a pronounced suppression of the CL signal from the NaIO_4 -Arg/ATT-AuNCs- H_2O_2 system. To elucidate the underlying quenching mechanism, we systematically investigated the interaction between DOX and the Arg/ATT-AuNCs. Fluorescence measurements revealed a substantial decrease in the PL intensity of Arg/ATT-AuNCs upon the addition of DOX (Fig. 5A). Subsequently, UV-vis absorption spectroscopy was employed to discern the nature of this interaction. The experimental absorption spectrum of the Arg/ATT-AuNCs-DOX mixture was found to be consistent with the theoretical superposition of their individual spectra (Fig. 5B), thereby precluding the formation of a ground-state complex and ruling out static quenching as a mechanism. Furthermore, time-resolved fluorescence decay analysis showed that the average fluorescence lifetime of Arg/ATT-AuNCs (3.38 ns) remained unchanged in the presence of DOX (Fig. 5C), which conclusively excludes dynamic quenching via a collisional energy transfer pathway. These spectroscopic findings indicate that the quenching mechanism is neither static nor dynamic in nature, pointing toward an alternative pathway such as an inner filter effect or a specific non-radioactive energy transfer process. the IFE between DOX and Arg/ATT-AuNCs led to a decrease in the fluorescence efficiency of Arg/ATT-AuNCs, which in turn resulted in a reduction in CRET efficiency and consequently weakened the CL intensity.

Figure 5D reveals that the absorption spectrum of DOX significantly overlaps with the fluorescence emission spectrum of the Arg/ATT-AuNCs. Consequently, it is speculated that the reduced fluorescence of Arg/ATT-AuNC is attributable to the IFE between DOX and Arg/ATT-AuNCs. The efficiency of the CRET

is related to the fluorescence efficiency of the receptor. Thus, a higher fluorescence efficiency of the receptor corresponds to a higher CRET efficiency. Therefore, it is hypothesized that the IFE between DOX and Arg/ATT-AuNCs led to a decrease in the fluorescence efficiency of Arg/ATT-AuNCs, which in turn resulted in a reduction in CRET efficiency and consequently weakened the CL intensity.

Several parameters were optimized to achieve satisfactory performance in the practical analytical detection of DOX. The results indicate that the CL signal is maximized when using 25 mmol/L of NaIO_4 (pH = 7), 0.1 mol/L of H_2O_2 , and 2 mg/mL of Arg/ATT-AuNCs (Figure S7).

Under optimal experimental conditions, the CL intensity of the NaIO_4 -Arg/ATT-AuNCs- H_2O_2 system decreased with increasing DOX concentration (Fig. 6A). The CL intensity exhibited a good linear relationship with the logarithm of the DOX concentration, ranging from 0.05 to 5 μM . The regression equation for quantifying DOX is $I_{\text{CL}} = -1093.5 \log(C) + 824.65$ with an R^2 of 0.998 (Fig. 6B). with a limit of detection of 0.029 μM . I_{CL} denotes CL intensity, while C corresponds to DOX concentration.

To verify the selectivity of this CL system, some common ions and compounds in human serum were selected to evaluate the interference effects. As shown in Fig. 7, 1 μM of L-cysteine, L-tryptophan, L-histidine, uric acid, glutathione, ascorbic acid, CaCl_2 , and FeCl_2 , and 10 μM of glycine, L-arginine, L-isoleucine, L-lysine, L-phenylalanine, L-alanine, glucose, KCl, and NaCl have negligible effects on the DOX (1 μM) detection. Therefore, the NaIO_4 -Arg/ATT-AuNCs- H_2O_2 system showed excellent potential to detect DOX in human serum.

3.5 Detection of Dox in human serum

The feasibility of this method for detecting DOX in normal human serum was further verified through recovery experiments by adding different concentrations of DOX to human serum samples. The experimental recovery was in the range of 91.12%~106.15%, and RSDs ($n = 3$) were within 4.5% (Table 1), indicating that the method has high accuracy and can be used for the detection of DOX in serum.

Table 1
Results of recovery tests of DOX added into human serum samples, $n = 3$.

Human serum sample	DOX Added (nM)	DOX Found (nM)	Recovery (%)	RSD (n = 3%)
No.1	250	244.97	97.99	4.5
	500	455.60	91.12	0.7
	1000	937.60	93.76	2.2
No.2	250	248.84	99.53	2.6
	500	481.11	96.24	3.5
	1000	932.36	93.21	2.2
No.3	250	252.13	100.85	1.3
	500	530.73	106.15	3.4
	1000	970.40	97.04	2.2

4. Conclusions

Arginine surface-engineering improved the catalytic properties and PL quantum yield of ATT-AuNCs. On the one hand, Arg/ATT-AuNCs serve as catalysts to accelerate the decomposition of H_2O_2 and promote the formation of ROS, on the other hand, Arg/ATT-AuNCs function as energy acceptors, receiving energy from the $\text{NaIO}_4\text{-H}_2\text{O}_2$ CL system and forming excited state Arg/ATT-AuNCs, which leads to strong CL emission. Based on the IFE between DOX and Arg/ATT-AuNCs- $\text{NaIO}_4\text{-H}_2\text{O}_2$ system, a sensitive CL method has been developed for DOX detection in serum samples. This study not only provides a new method for the detection of DOX, but also proves that functionalized AuNCs can improve the CL efficiency, which provides a theoretical basis for the construction of sensitive CL system.

Declarations

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CRedit authorship contribution statement:

Chuangui Cai: Data curation, Methodology, Writing-original draft. **Wensong Yao:** Methodology, Funding acquisition. **Shan Lian:** Validation. **Haohua Deng:** Formal analysis. **Kaiyuan Huang:** Investigation.

Xinhua Lin: Investigation, Supervision. **Wei Chen:** Investigation, Supervision. **Zhen Lin:** Conceptualization, Methodology, Funding acquisition.

Declaration of competing interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability:

The data that has been used is confidential.

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Scheme 1

Scheme 1 is available in the Supplementary Files section.

Figures

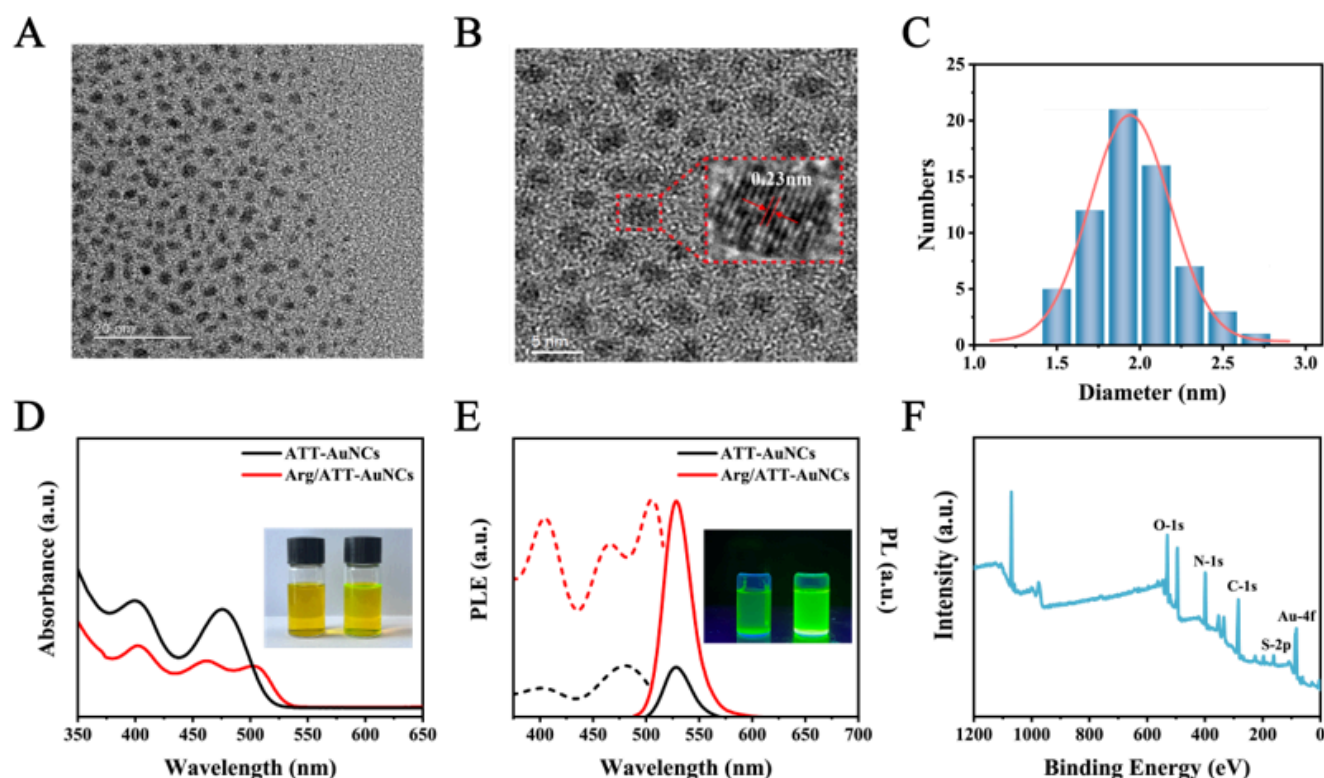


Figure 1

(A) TEM image of Arg/ATT-AuNCs (scale bar: 20 nm). (B) HRTEM image of Arg/ATT-AuNCs (scale bar: 5 nm). (C) Particle size distribution chart of Arg/ATT-AuNCs. UV-vis absorption spectrum (D) and fluorescence spectrum (E) of Arg/ATT-AuNCs. (F) XPS survey scan spectrum of Arg/ATT-AuNCs.

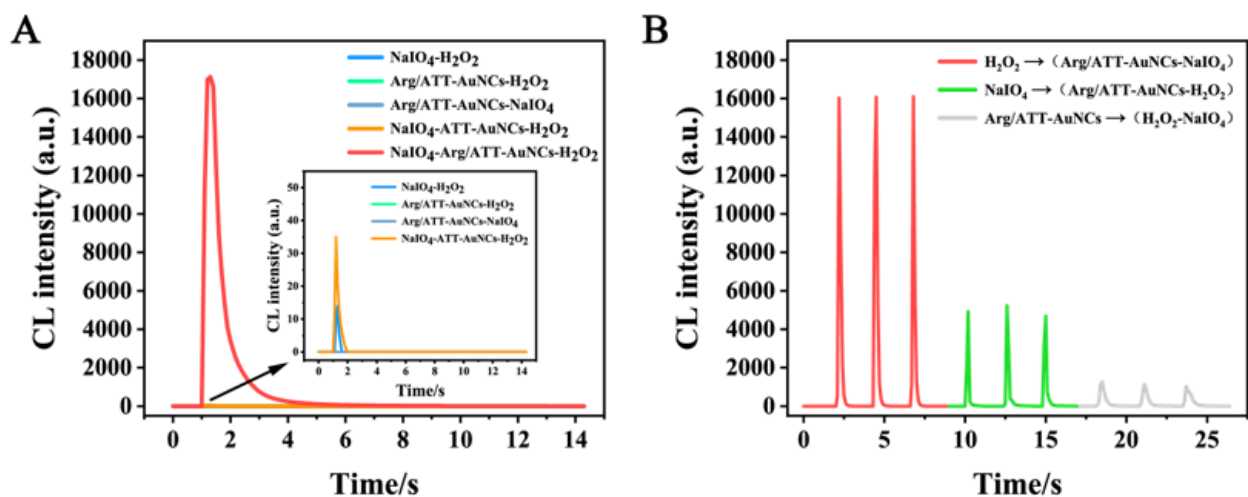


Figure 2

(A) CL Kinetic curve of NaIO₄-Arg/ATT-AuNCs-H₂O₂ system. (B) Influence of adding sequence on NaIO₄-Arg/ATT-AuNCs-H₂O₂ system.

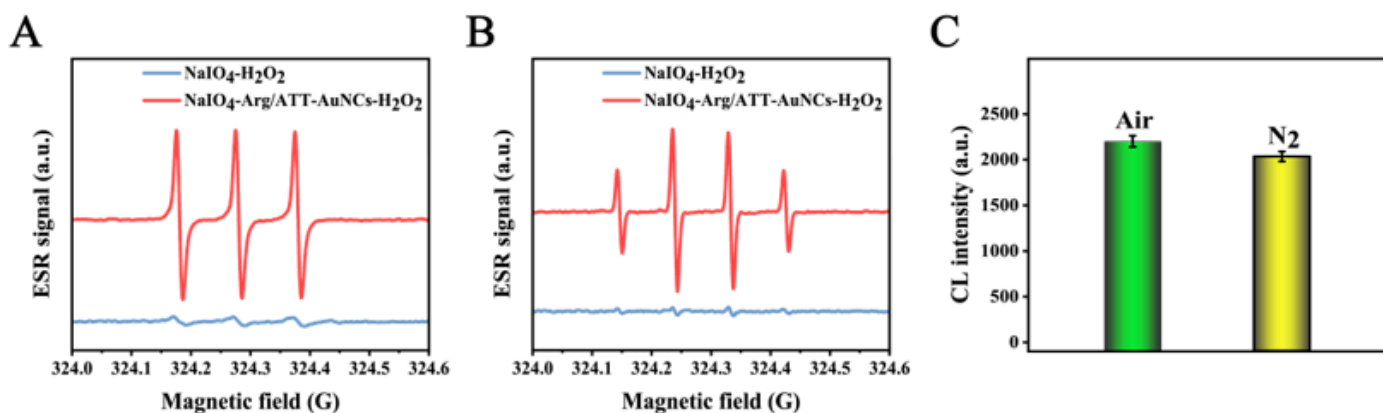


Figure 3

EPR spectra of TEMPO-¹O₂ (A) and DMPO-OH• (B) for the NaIO₄-Arg/ATT-AuNCs-H₂O₂ reaction. (C) Effect of oxygen on NaIO₄-Arg/ATT-AuNCs-H₂O₂ system.

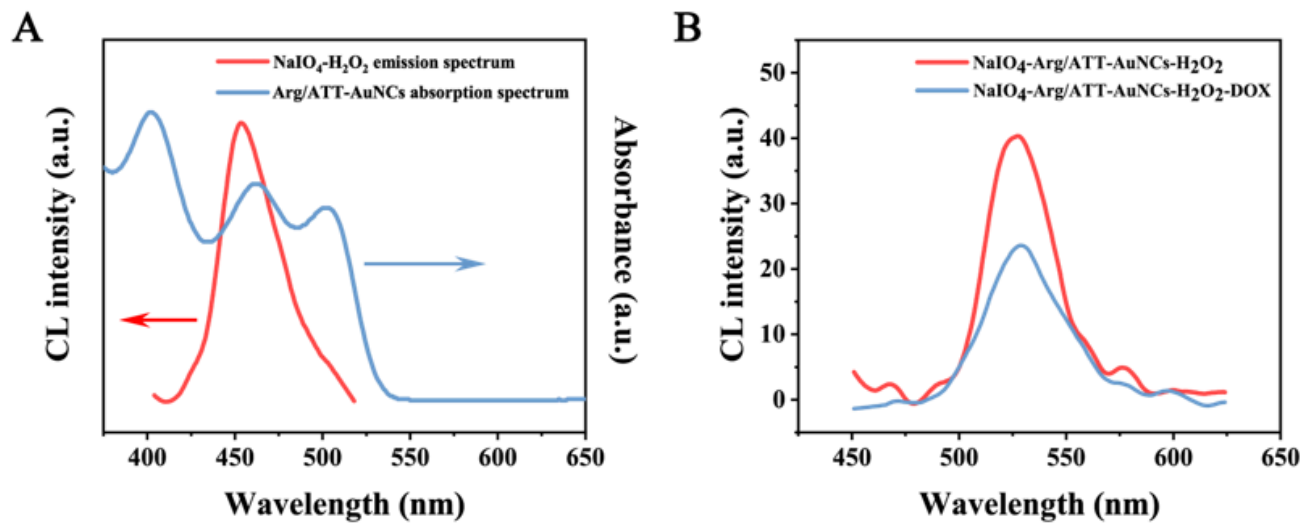


Figure 4

(A) CL spectrum (red line) of $\text{NaIO}_4\text{-H}_2\text{O}_2$ and absorption spectrum (blue spectrum) of Arg/ATT-AuNCs.
 (B) CL spectrum of $\text{NaIO}_4\text{-Arg/ATT-AuNCs-H}_2\text{O}_2$.

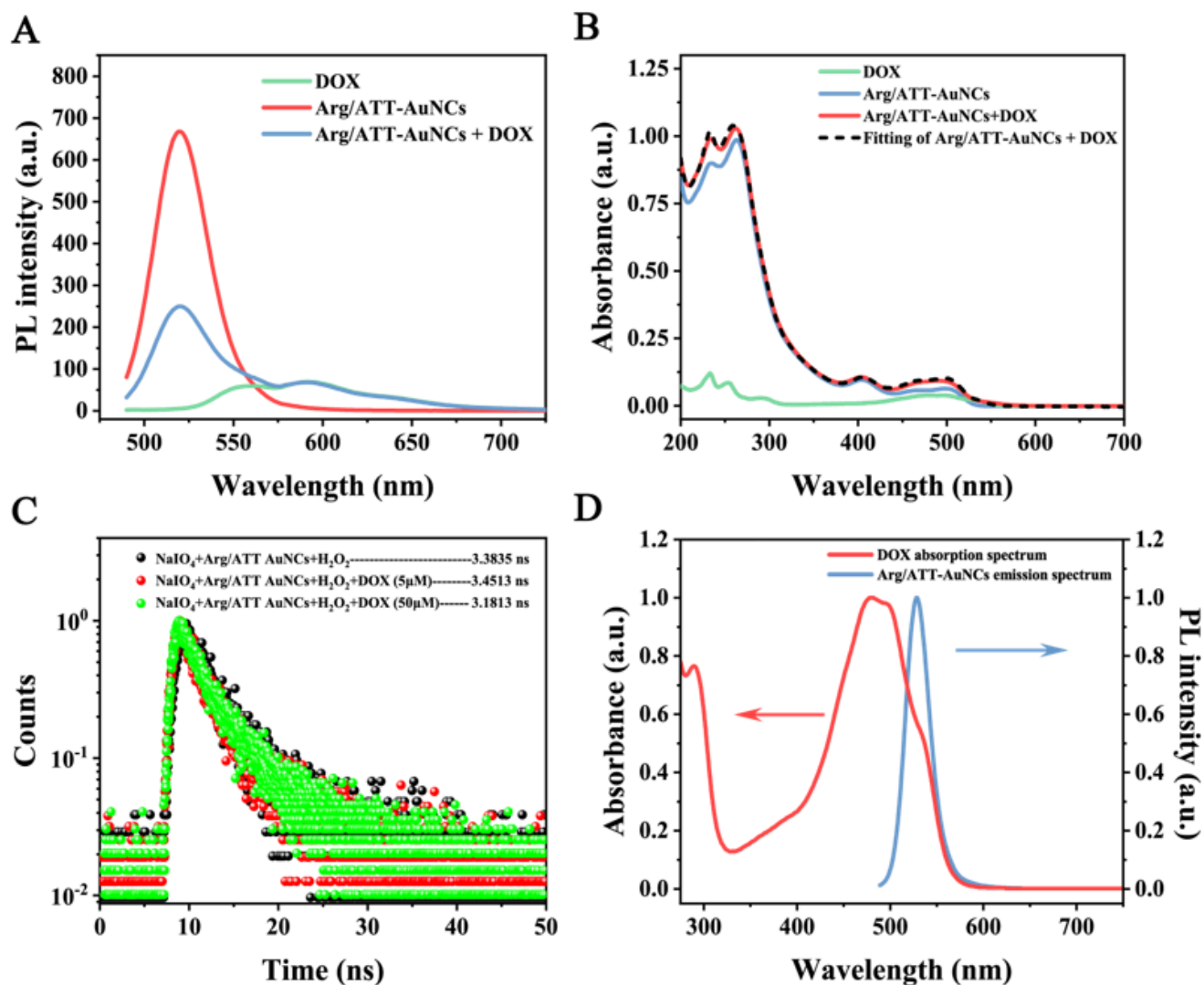


Figure 5

Fluorescence spectrum (A) and UV-vis absorption spectrum (B) of DOX, Arg/ATT-AuNCs, and mixture of DOX and Arg/ATT-AuNCs. (C) Time-resolved fluorescence decay curves of Arg/ATT-AuNCs and mixture of DOX and Arg/ATT-AuNCs. (D) UV-vis absorption spectrum (red line) of DOX and fluorescence spectrum (blue line) of Arg/ATT-AuNCs.

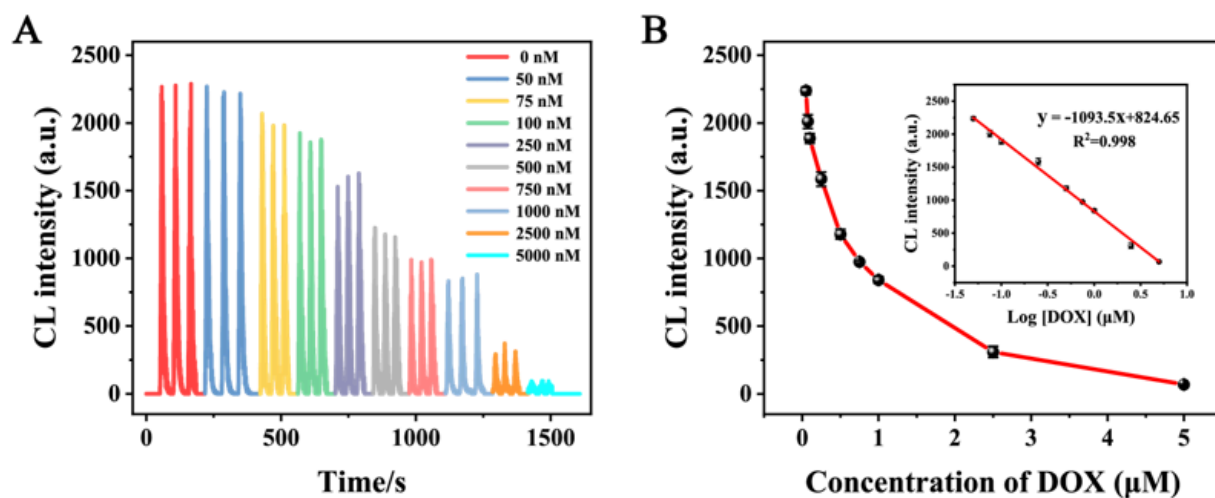


Figure 6

(A) CL intensity of $\text{NaIO}_4\text{-Arg/ATT-AuNCs-H}_2\text{O}_2$ system with different concentration of DOX. (B) DOX calibration curve. Inset: the calibration curve for DOX concentration ranging from 0.05 to 5 μM .

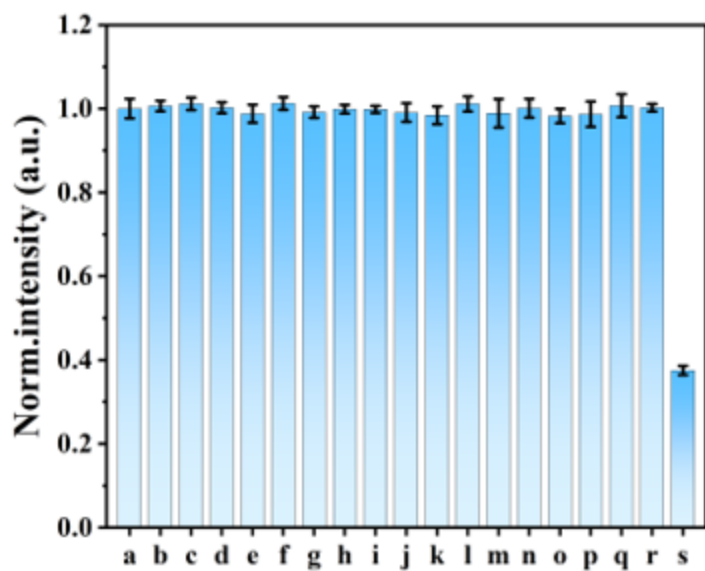


Figure 7

Selective study of DOX detection. (a-s: Blank, Glycine (Gly), Arginine (Arg), Isoleucine (Ile), Lysine (Lys), Phenylalanine (Phe), Alanine (Ala), Cysteine (Cys), Tryptophan (Trp), Histidine (His), Glucose (Glu), Glutathione (GSH), Ascorbic acid (AA), Uric acid (UA), Ca^{2+} , Fe^{2+} , K^+ , Na^+ , DOX). The concentration of DOX, Cys, Trp, His, UA, GSH, AA, Ca^{2+} , and Fe^{2+} is 1 μM , and the concentration of other interfering substances is 10 μM .

Supplementary Files

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