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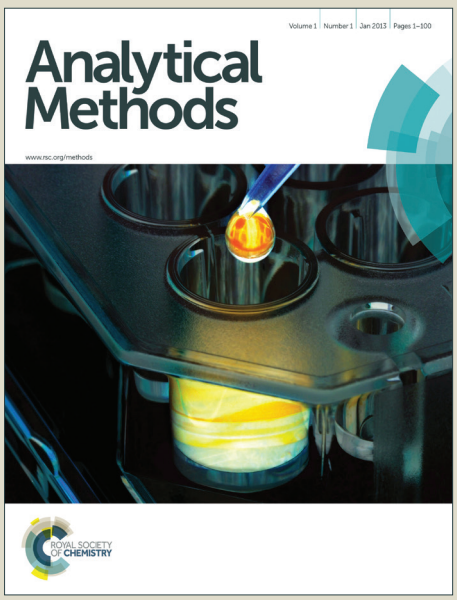

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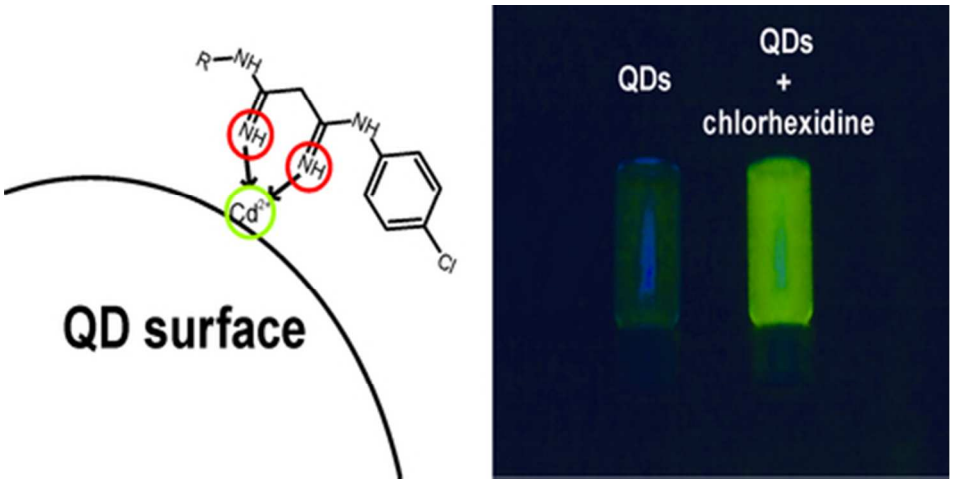

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CdTe-MPA quantum dots fluorescence enhancement flow method for chlorhexidine determination

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In this work the fluorescence enhancement that water-soluble CdTe quantum dots (QDs) capped with 3-Mercaptopropionic acid (MPA) exhibit in the presence of a biguanide compound, chlorhexidine, was investigated. Acting as an electron-donor ligand chlorhexidine was able to interact with the defects (mid-gap energy traps) on the QDs surface improving the surface passivation and the fluorescence emission. The accomplished fluorescence enhancement was used as the sensing strategy for the implementation of an analytical methodology for the determination of chlorhexidine in pharmaceutical formulations. The developed approach was implemented by resorting to a fully automated multipumping flow systems, which improved the versatility and analytical potential provided by QDs enabling to overcome some of the shortcomings associated with the commonly used batch procedures. Different sized QDs were synthesised and evaluated. A chlorhexidine analytical working range for concentrations between 0.05x10^{-3} and 0.5x10^{-3} mol L^{-1} was verified with a sampling throughput of about 63 samples h. The obtained results were in good agreement with those furnished by the reference method (RD% < ±4.77). A mechanism for the enhancing phenomenon is proposed.

Introduction

Colloidal semiconductor nanocrystals, also known as quantum dots (QDs), have been finding many new analytical applications. Initially developed as molecular probes for utilisation in biomaging[1], in biotargeting[2] and drug delivery[3], QDs are being researched for organic and inorganic analyte determination mostly taking advantage of their peculiar photoluminescent (PL) properties[4]. In fact, the longer luminescence lifetimes, molar extinction coefficients, photostability, high quantum yield, broad excitation bandwidths and narrow size-tuned emission spectra along with a large surface-to-volume ratio, surface functionality, a relatively low cost and a high chemical flexibility make them attractive luminescent tools for implementing selective and sensitive analytical methodologies. In this regard, QDs have been used in environmental analysis[5], in the determination of pesticides[6] and heavy metals[7], pharmaceuticals[8], etc.

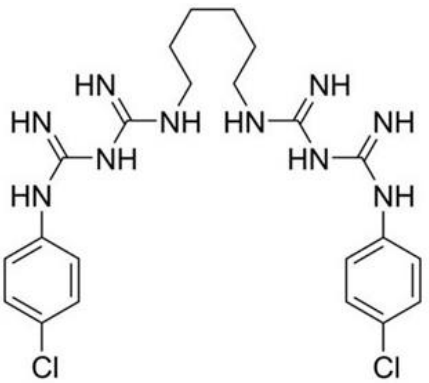

Fig 1 Chlorhexidine structure.

Quantum dots luminescence is very sensitive to micro-environmental changes because the luminescence intensity and

wavelength is determined not only by the nanocrystals size but also by their surface characteristics. Effectively, in small crystals a high percentage of the atoms, approximately 56% in 3 nm QDs, are at the surface[9]. Organic ligands coordinated to the QDs surface not only serve as passivators, as a means to increase solution stability preventing aggregation, but are also involved in electron transfer processes (as donors or acceptors) to or from dangling bonds incompletely coordinated, affecting the optical properties of QDs, namely the luminescence lifetime and quantum yield. External ligands interacting with the capping (passivating) layer or with the surface imperfections (traps) would alter electro-hole recombination and thus the photoluminescence response. A panoply of viable operating principles could be therefore devised to signal and relay the presence of a target analyte with a marked luminescence change. These mechanisms generally transduce a recognition event into a measurable signal by relating a sensor-target association with an electron or energy transfer process.

Previous works have referred that amino compounds could present "antiquenching" effect[10] as a consequence of a quantum yield enhancement. These compounds could act as passivators of the QDs surface suppressing nonradiative recombination at surface vacancies[11]. Biguanides were already identified as strongly chelating ligands that bind readily to a variety of metals, such as copper, zinc, cobalt, and manganese[12]. They could therefore interact with incompletely coordinated Cd^{2+} on the surface of CdTe quantum dots improving luminescence emission.

Chlorhexidine, N',N''''-hexane-1,6-diylbis[N-(4-chlorophenyl)(imidodicarbonimidic diamide)] (Fig 1), is an antiseptic drug with a biguanidic structure active against Gram-negative and Gram-positive bacteria. Several methods, recently reviewed[13], have been proposed for chlorhexidine determination in pharmaceuticals and biological samples. These methods include chromatography[14-17], fluorimetry[18], UV/Vis spectrophotometry[19] and capillary electrophoresis[20]. A flow-based extraction-spectrophotometric method was also proposed[21]. The official method of the European[22] and Bristish[23] Pharmacopoeias is a non-aqueous titrimetric method.

Most of the available analytical methodologies relying on the utilisation of QDs as chemosensors are based on batch approaches displaying no or a low automation level in what concerns sample handling, reaction implementation and measurements execution. They are thus generally characterized by high consumption of sample and reagents solutions, exhibit low versatility in terms of analytical parameters adjustment and reconfiguration, poor reproducibility and repeatability, are laborious and time-consuming, and are more prone to operational errors. Moreover, they require equilibrium conditions for the attainment or reproducible readouts, which in many circumstances could prevent the evaluation or utilisation of more drastic reaction conditions as they could derange QDs stability impairing detection. Multipumping Flow Systems (MPFS)[24] represent a computer controlled continuous flow-based technique providing a fully automated operation of the analytical system[25] that comprehends not only solutions handling, mixing and reaction zone implementation but also analytical signal acquisition and processing and system performance real-time adjustment. Based on the individual actuation of multiple solenoid micro-pumps that are accountable for all solutions insertion, commutation and propelling, being the only active elements of the entire flow manifold, they generate a pulsed-flowing stream that ensure fast mixing and fast reaction development[26]. MPFS are consequently well suited for the implementation of sensing schemes based on QDs nanotechnology, even enabling, due to the very short residence time, the exploitation of extreme reaction conditions that otherwise would be unpractical.

In this work we took advantage of the ability of biguanides to chelate metals, in this case to chelate incompletely coordinated Cd^{2+} on the surface of CdTe quantum dots ensuring up to a 160% fluorescence enhancement, to develop an automated multi-pumping flow methodology for chlorhexidine determination.

Materials and methods

Samples, standards and reagents

All solutions were prepared with water from a Milli-Q system (specific conductivity <0.1μS cm^{-1}) and chemicals of analytical reagent grade quality.

3-Mercaptopropionic acid (MPA, 99%) was purchased from Fluka (St. Louis, USA). Sodium borohydride ($NaBH_4$, 99%), tellurium powder (200 mesh, 99.8%), cadmium chloride hemi(pentahydrate) ($CdCl_2$, 99%), Chlorhexidine digluconate 20% (w/v) solution were purchased from Sigma (St. Louis, MO, USA) and used without further treatment. Ethanol (99.5%) was purchased from Panreac (Barcelona, Spain).

Standard solutions of Chlorhexidine digluconate were daily prepared by suitable dilutions with ultrapure water.

Two commercially available pharmaceutical samples, a solid form and a liquid form containing chlorhexidine digluconate were analysed according to the proposed procedure. No special pre-treatment was required for the liquid samples prior to analysis, just a dilution in order to reach a chlorhexidine digluconate concentration of 0.267×10^{-3} mol L^{-1}. For the solid form, three tablets were accurately weighed and powdered. A certain amount of powder was dissolved in water to make a solution at 0.2×10^{-3} mol L^{-1} of chlorhexidine digluconate.

Apparatus

The developed multi-pumping flow system comprised three fixed-diaphragm solenoid actuated micro-pumps (Bio-Chem Valve Inc., Boonton, NJ, USA) (two of the micro-pumps dispensing a stroke volume of 10μL and the third one a stroke volume of 20 μL), and a modular optical-fibre spectrofluorimeter from Ocean Optics (Dunedin, MA, USA) consisting on USB4000-FL detector, a LS-450 power source equipped with a LED emitting at 395 nm , and a 8 μL internal volume flow-cell. Reaction coils were made of PTFE tubing (0.8 mm i.d.).

Homemade end-fittings, a four way confluence point and connectors were also used[27]. For the QDs characterization

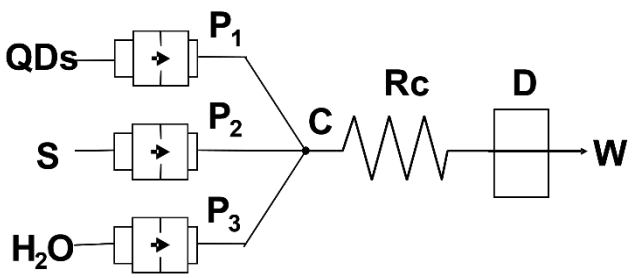

Fig 2 Schematic diagram for the multipumping flow system: P_1, P_2 and P_3 solenoid micro-pumps; Rc - reaction coil; C – confluence point; D - fluorescence detector, λ_{exc}= 395 nm, λ_{emi} = 535-537 nm; S – sample; QDs – quantum dots solution; W – waste.

absorption spectra were collected using a Perkin Elmer (Waltham, MA, USA) Lambda 45 UV/VIS spectrophotometer and the emission spectra was obtained with a luminescence spectrometer Perkin Elmer (Waltham, MA, USA) LS50B. A ThermoElectron (Waltham, MA, USA) Jouan BR4I refrigerated centrifuge was used for QDs separation. X-ray powder diffraction (XRD) studies of the nanocrystals were carried out by using a Philips X'Pert X-ray MPD diffractometer (Cu Kα radiation). XRD data were collected at a scan rate of 40.0 s for step at step intervals of 0.04º. Fluorescence lifetime measurements were carried out in a Time-Correlated Single-Photon Counting (TCSPC) TemPro-Fluorescence lifetime system (Horiba Jobin Yvon) equipped with an emission monochromator. TEM characterization was performed on a HITACHI H-8100 electron microscope operating at 200 kV, in carbon copper grids.

A computer was used for system control, the software being developed in Microsoft Visual Basic 6.0. The computer was equipped with a PC-LABCard model PCL-711B (Advantech, Cincinnati, OH, USA) interface card. A CoolDrive (NResearch Inc., West Caldwell, NJ, USA) power drive was used to operate the solenoid micro-pumps. Analytical signals were computer recorded and processed by using Spectra Suite software version 2007 (OceanOptics, Dunedin, MA, USA).

Synthesis of CdTe-MPA quantum dots

MPA-capped CdTe QDs were synthesized as described by Zou L. *et al.* 2008[28] with some modifications. Briefly, NaHTe solution was prepared by the reaction between $NaHB_4$ and Te powder in N_2 saturated water. CdTe QDs was synthesized adding freshly prepared NaHTe into a second flask containing 4.0 x 10^{-3} mol of $CdCl_2$ and 6.8 x 10^{-3} mol of MPA in a 100 mL N_2 saturated 11.5 by addition of 1 mol L^{-1} NaOH. The molar ratio of Cd^{2+}/Te^{2-}/MPA was fixed at 1:0.1:1.7. Precursors were converted into nanocrystals by refluxing the mixture at 100ºC under open air conditions and the CdTe QDs size was tuned by varying the heating time. For the present work, the synthesis was stopped at 15, 120 and 300 minutes, respectively.
The solutions obtained were precipitated with ethanol, in order to remove the excess of precursors, centrifuged and finally the QDs were dried and stored at 4ºC under N_2 atmosphere, in order Working solutions were prepared daily with ultrapure water.

Multi-pumping flow manifold and procedure

The developed system, shown in Figure 2, comprised three solenoid micro-pumps (P_1, P_2 and P_3) for inserting and propelling the sample, the reagent (QDs) and the carrier (H_2O). Each solenoid micro-pump was individually actuated allowing the utilisation of various sample/reagent insertion sequences and therefore the establishment of distinct strategies for reaction zone implementation. The sequential micro-pump switching on/off created a pulsed flowing stream where the pulse volume corresponded to the stroke volume. The pulse volume in combination with the pulse frequency (for each micro-pump actuation) was used to determine the flow rate of each propelled solution.
The extremely simple analytical cycle was started by establishing baseline which was accomplished with water by actuating P_3. Blank readings were obtained by measuring the fluorescence emission upon the simultaneous insertion of QDs and water. To this end P_1 and P_2 were simultaneously actuated for a pre-determined number of pulses (6 pulses each, corresponding to 60 μL of H_2O and 60 μL of QDs solution for a global volume of 120 μL) at a global flow rate of 2 mL min^{-1}(1 mL min^{-1} for each solution corresponding to a pulse frequency of 100 min^{-1}) allowing the merging of H_2O and QDs solution at the confluence point C (Fig 2). P_3 was then actuated (55 pulses of a 20 μL per stroke micro-pump) at a flow rate of 1.2 mL min^{-1} (pulse frequency of 60 min^{-1}) to transport the reaction zone through the reaction coil Rc toward the detector. A similar procedure was used for measuring the PL of samples and standards, inserted as a replacement for H_2O in P_2 (the insertion and propelling sequence was the abovementioned one). The excitation wavelength was set at 395 nm and the emission was an average of the signals acquired between 535 and 537 nm. Integration time was of 500 ns and each value was the average of 3 acquisitions.

Reference procedure

Aiming accuracy in evaluation of the results obtained with the developed procedure, chlorhexidine bulk drug and chlorhexidine pharmaceutical formulations were analysed according to the European Pharmacopoeia[22] by non-aqueous titration in glacial acetic acid with perchloric acid. The end-point was potentiometrically determined.

Results and discussion

Preliminary batch experiments aiming at evaluating the influence of several amino compounds on the photoluminescence intensity of CdTe solutions revealed that chlorhexidine, exhibiting a biguanidic structure (Fig 1), had a pronounced enhancing effect. However, the CdTe-chlorhexidine surface interaction affected quantum dots stability, which tended to aggregate, resulting in the solution precipitation. Since in a batch approach reaction equilibrium conditions are required to accomplished reproducible measurements, the precipitate formed as consequence of the increased reaction time impaired any fluorescence measurement. The implementation of the

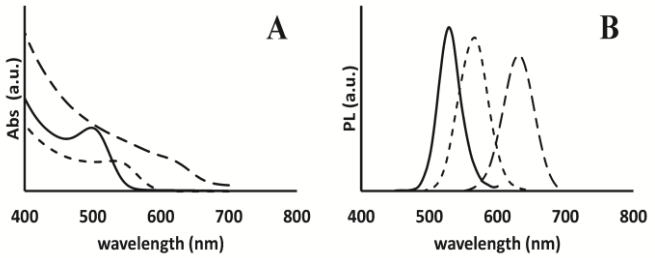

Fig. 3 Absorption spectra (A) and photoluminescence spectra (B) of CdTe QDs with different size. The excitation wavelength is 400 nm.

reactional scheme in a flow-based procedure relying in both a reproducible sample/reagent mixing and time-based signal measurement, under no-equilibrium conditions, appeared as an expeditious strategy to overcome this problem. Due to its versatility, mixing capacity and operational simplicity a multi-pumping flow system was selected for carrying out the assays.

In the subsequent trials, water was used as the blank and the signal obtained upon mixing with the CdTe QD solution was used as the blank fluorescence signal. The assessment of the fluorescence enhancement effect (ΔPL (%)) was carried out by means of the ratio between the photoluminescence intensity of the sample solution (PLs) minus the photoluminescence intensity of the blank (PL_0) and (PL_0) according to the equation (eq. 1):

$$\Delta PL\ (\%) = ((PLs-PL_0)/PL_0)\ x100 \qquad (1)$$

All experimental conditions were optimised in order to obtain the highest ΔPL(%).

Characterization of CdTe-MPA quantum dots

The powder X-ray diffraction pattern showed the highly crystalline feature of the CdTe nanocrystals (Fig S1†), and is consistent with the bulk cubic structure. Fig. 3 show the normalized absorption/emission spectrum of CdTe-MPA nanocrystals. All samples showed a well resolved maximum corresponding to the first transition. The particle size of the synthesized QDs was calculated according to the expression[29] (eq. 2):

$$D = \left(9.8127\times10^{-7}\right)\lambda^3 - \left(1.7147\times10^{-3}\right)\lambda^2 + \left(1.0064\right)\lambda - \left(194.84\right) \qquad (2)$$

where D is the diameter (nm) and λ (nm) the wavelength maximum corresponding to the first excitonic absorption peak of the crystal. The calculated diameter was found in good agreement with the size observed by TEM (Fig S2†).

In order to standardize the preparation of the QDs solutions it was also necessary to calculate the molar weight of the different sized nanocrystals. This was possible by establishing firstly the extinction coefficient (ε) using the expression eq. 3[29]:

Table 1 - Optimized parameters used in the analysis.

Parameter	Studied values	Selected values
QDs concentration (10^{-6} mol L^{-1})	1.25 - 5	2.5
Chlorhexidine concentration (10^{-3} mol L^{-1})	0.0005-1	0.05–0.5
Volume QDs (μL)	20 – 100	60
Flow rate (mL min^{-1})	1.2 – 2	1.2
Reactor length (cm)	0 – 100	60
Sampling frequency (sample per hour)		63

$$\varepsilon = 3450\Delta E(D)^{2.4} \qquad (3)$$

where ΔE is the transition energy corresponding to the first absorption peak and the unit is eV. From the ε value the molar mass can be easily estimated by measuring the absorbance of a known concentration solution and by applying the Lambert-Beer law.

Fluorescence emission spectra of the three nanocrystals show maximums at 530 nm (D = 2.3 nm), 576 nm (D = 3.1 nm) and 632 nm (D = 3.8 nm). In order to evaluate the size dispersion, the PL peak width (full width at half maximum, FWHM) was assessed. For the smaller QDs the FWHM was 37 nm, being 49 nm for those with a diameter of 3.1 nm and reaching the maximum value, 53 nm for the bigger ones (D = 3.8 nm). This defocusing was expected and extensively described in literature as a consequence of the Ostwald Ripening growing mechanism.

System optimization

In order to study the reaction development and to improve its application performance in terms of sensitivity, accuracy, precision and sample rate, several parameters, both chemical and physical, were studied (Table 1) using concentrations of 0.5 x 10^{-3} mol L^{-1} for chlorhexidine and 2.5 x 10^{-6} mol L^{-1} for the quantum dots.

The volume of the QDs solution was optimised aiming at assuring an easily detectable and reproducible blank PL signal at the QDs working concentrations. In order to simplify system operation, and since the pulsed flowing stream generated by micro-pumps actuation provided a good mixing, a merging zones strategy with equal volumes of sample (water for the blank) was selected as reaction zone intercalation scheme. For the four volumes assayed (20, 40, 60 and 80 μL) the PL signal strongly increased with the volume increment from 20 to 60 μL and then tended towards stabilization (Fig 4A). In opposition the analytical signal reproducibility increased linearly with the increment of the volume (Fig 4B), but in all instances the RDS% was very low (<3%) confirming a good precision. As it was expected, the peak broadening showed a linear relationship with the rise in QDs volume (Fig 4C). As a consequence of these results a QDs volume of 60 μL was selected for the subsequent experiments, which enabled a good compromise between sensibility and reproducibility of the analytical signal.

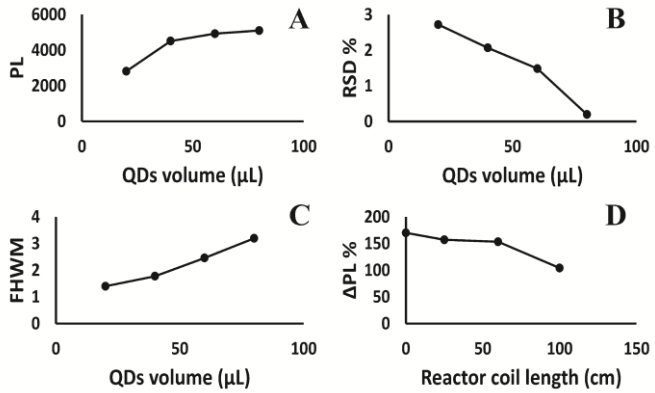

Fig. 4 Results obtained in the evaluation of several analytical parameters: 4A - photoluminescence variation versus QDs volume; 4B - relative standard deviation of the photoluminescence signal versus QDs volume; 4C - peak dispersion for the QDs volume used (FHWM, Full width at half maximum); 4D - effect of the reactor coil (Rc) length on photoluminescence enhancement (ΔPL%, fluorescence variation).

The influence of the flow rate used to insert the samples and to propel the reaction mixture to the detector were assessed between 1.2 and 2.0 mL min^{-1}. The obtained results revealed that this parameter had no influence on the PL signal, although the lower value provided improved reproducibility.

Effect of the serpentine reaction coil (Rc) length was also studied in a range from 0 to 100 cm (Fig 4D). The fluorescence enhancing effect remained almost stable for a coil length between 25 and 60 cm and diminished for longer coils. These results showed that the reaction is fast and that the formed products were unstable (as it happened in the batch method).

Concerning reproducibility, this was not affected by the reactor coil length.

The influence of the pH was also evaluated. For pH values ranging from 5.7 to 10.5 it was observed that signal magnitude remained unchanged. Lower pH values weren't assayed because the QDs aren't stable in acidic media, precipitating and losing their photoluminescence properties.

Influence of QDs size and concentration

Fluorescence of QDs could be strongly enhanced by reaction with chlorhexidine, being the enhancing effect pronouncedly dependent of the size and concentration of nanocrystals.

Three different size QDs were assayed, A (2.3 nm) < B (3.1 nm) < C (3.8 nm) at three different concentrations 5, 2.5, and 1.25 µmol L^{-1}.

For QDs C it was only possible to test a concentration value of 2.5 µmol L^{-1}, because at 5 µmol L^{-1} an inner filter effect was observed and at 1.25 µmol L^{-1} the PL intensity was too low for the detector sensitivity. Fig 5A represents the slope of the chlorhexidine calibration curves obtained for QDs of size A and B at different concentrations. Fig 5B displays the slope value of the calibration curve for the different QDs size (A, B and C) at the same concentration (2.5 µmol L^{-1}). By analysing the referred

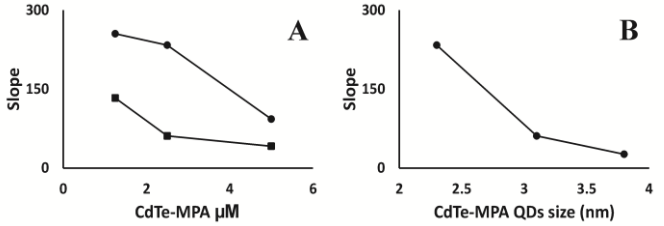

Fig. 5 Sensitivity variation for different size QDs. 5A - slope values of the chlorhexidine calibration curves obtained for QDs of different sizes (A ●, B ■) and concentrations; 5B - slope value of the chlorhexidine calibration curve for the different QDs size (A, B and C) at the same concentration (2.5 µmol L^{-1}).

figures it is evident that the QDs with the lower size (QDs A, 2.3 nm) are more sensitive to a chlorhexidine concentration variation and are therefore more efficiently enhanced. It is also perceptible that at lower QDs concentration the chlorhexidine PL enhancing effect is more pronounced. This fact can be explained by the possible interaction between chlorhexidine and the CdTe surface traps: smaller QDs are more imperfect[28] and therefore more prone to interact. The 2.3 nm QDs were therefore selected for the experiments, at a 2.5 µmol L^{-1} concentration, which assured improved reproducibility and accuracy.

Mechanism of the PL enhancing

In literature two principal mechanisms of interaction between organic ligands and QDs are reported[30-34]: the reaction with Cd^{2+} traps and the direct reaction with the capping agents at the QDs surface. Photoluminescence enhancement promoted by thiol-compounds interaction with surface traps was recently exploited for analytical propouse[35]. As described by Knowles *et al.*[9] an interaction between amino compounds and Cd^{2+} sites is feasible and the electron donor character of the ligand is fundamental for yielding a quenching or an enhancing effect of the nanocrystal photoluminescence. Incompletely coordinated Cd^{2+} existing on the QDs surface act as midgap states diminishing the probability of radiant recombination of the excitons. These electron-trapping midgap states are successfully eliminated binding strong σ-donors, which form an antibonding orbital with energy higher than the conduction band of the QD. The result of this interaction is an enhancing of the QDs quantum yield. Chlorhexidine is a strong electron-donor compound containing two biguanide groups, that are known to coordinate various metals ions like Co(II), Cu(II) and Ni(II)[12,35-37]. In the present work the effective interaction with the CdTe-MPA QDs surface was proved by time resolved photoluminescence measurements. Due to some instrumental limitations (λex = 564 nm) the influence of the proposed reaction on the QDs photoluminescence lifetime was studied with a CdTe-MPA nanoparticle with a size of 3.4 nm.

The photoluminescence decay obtained for the CdTe-MPA QDs was fitted with triexponential equation, showing the existence of at least two populations and an average lifetime of 35.2 ns.

As reported in figure 6 the interaction with chlorhexidine promoted a consistent increase in the fluorescence lifetime to 40.6 ns, more specifically enhancing longer time recombination processes.

Table 2 – Results obtained in the analysis of chlorhexidine in pharmaceutical formulations.

Sample	Reference method	Developed method	R.D.%[a]
Drill (tablets)	3.02 ±0.16	3.15±0.14	4.12
Diaseptyl (topic solution)	0.208±0.013	0.199±0.002	-4.77

[a]Relative deviation of the amount found by the developed method regarding the reference method.

The observed effect was found to be static, as confirmed by the independence of the lifetime enhancing to chlorhexidine concentration variation. This fact reveal the formation of stable complexes between chlorhexidine and the surface traps.
Lower size QDs, normally, are those with more surface traps (lower quantum yield), thus are more prone to establish interactions and to have a greater PL variation in the presence of chlorhexidine, providing a more sensitive and selective PL response.

Analytical figures of merit

After analytical system optimisation the developed methodology was evaluated in the determination of chlorhexidine in pharmaceutical formulations. It was observed, that depending on chlorhexidine concentration, two linear working ranges were obtained (Fig. S3†): one for concentrations ranging from $0.005x10^{-3}$ to $0.025x10^{-3}$ mol L-1 (Eq. 4) and a second working range for chlorhexidine concentration between $0.05x10^{-3}$ and $0.5x10^{-3}$ mol L-1 (Eq. 5). The calibration curves for the two working ranges were expressed by the following respective equations:

$$\Delta PL = 1975.4C - 5.229 \quad (4)$$

$$\Delta PL = 196.34C + 64.632 \quad (5)$$

where ΔPL represents the relative fluorescence enhancement regarding the blank (expressed in percentage) and C is the chlorhexidine concentration expressed in 10^{-3} mol L^{-1}, with correlation coefficients of 0.9980 (n=6) and 0.994 (n=4), respectively. Due to the improved reproducibility, the second analytical working range calibration curve was used in the determinations, providing a sampling frequency of about 63 samples per hour. The implemented multipumping flow system showed a good reproducibility, with a r.s.d<1.5% (n=8), and a good accuracy, with a relative deviation (RD%), regarding the reference method, lower than ±4.77 (Table 2). No interference from the compounds commonly used as excipients was verified (up to a 100 excipient/chlorhexidine molar ratio).

Conclusion

Chlorhexidine interacts with the surface of CdTe quantum dots fostering a significant enhancing of fluorescence emission. However, it also deteriorates QDs solution stability that thus tended to aggregate and precipitate, impairing detection. This problem was overcame by implementing a pulsed multipumping flow system that enabled fast sample/reagent mixing, even under limited dispersion conditions, assuring the carrying out of reproducible measurements after short residence times yet yielding a 160% fluorescence enhancement. The obtained results confirmed the potential of combining quantum dots nanotechnology with flow-based analysis, as more drastic and sometime damaging reaction conditions could be used for assorted sensing schemes based in various surface ligand interactions, while assuring reproducible and reliable measurements. In addition, similar fluorescence enhancement effects could be exploited for improving sensitivity whenever low analyte concentration is observed, for improving nanoparticles photoluminescence or for providing high analytical signals when a fast readout should be carried out.

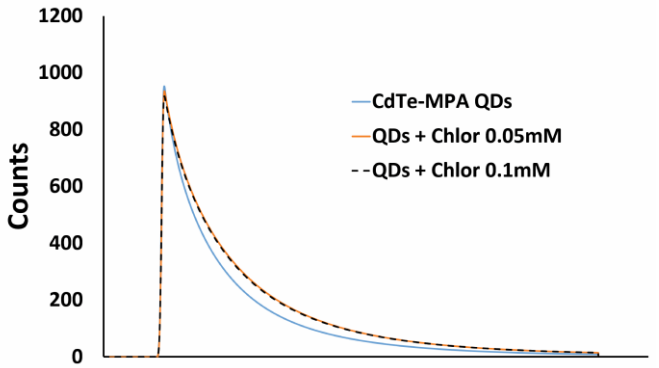

Fig. 6 Luminescence lifetime decay curves for CdTe-MPA and after addition of chlorhexidine 0.05 and 0.1 mM.

Notes and references

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† Electronic Supplementary Information (ESI) available: p-XRD pattern. See DOI: 10.1039/b000000x/

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