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Hydrodynamic chromatography coupled to single-particle ICP-MS for the simultaneous characterization of AgNPs and determination of dissolved Ag in human plasma and blood of burnt patients

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Abstract

Silver nanoparticles (AgNPs) are increasingly used in medical devices as innovative antibacterial agents, but no data are currently available on their chemical transformations and fate *in vivo* in the human body, particularly on their potential to reach the circulatory system. To study the processes involving AgNPs in human plasma and blood, we developed an analytical method based on hydrodynamic chromatography (HDC) hyphenated to ICP-MS in single-particle detection mode. An innovative algorithm was implemented to deconvolute the signals of dissolved Ag and AgNPs, and to extrapolate a multiparametric characterization of the particles in the same chromatogram. From a single injection, the method provides the concentration of dissolved Ag and the distribution of AgNPs in terms of hydrodynamic diameter, mass-derived diameter, number and mass concentration. This analytical approach is robust and suitable to study quantitatively the dynamics and kinetics of AgNPs in complex biological fluids, included processes such as agglomeration, dissolution, and formation of proteins coronas. The method was applied to study the transformations of AgNPs standards and an AgNPs-coated dressing in human plasma, supported by µXRF and µXANES speciation analysis and imaging, and to investigate for the first time the possible presence of AgNPs in the blood of three burnt patients treated with the same dressing. Together with our previous studies, the results strongly support the hypothesis that the systemic mobilization of the metal after topical administration of AgNPs is driven by their dissolution *in situ*.

Keywords

Silver nanoparticles; Hydrodynamic chromatography; Single-particle ICP-MS; Synchrotron radiation; Burns; Wound dressings

Introduction

The multispectral antimicrobial effects of silver (Ag) are known and have been exploited since ancient times, but its use in consumer products and medical devices has proliferated considerably in recent years [1]. Ag-containing devices are widely used in hospitals as adjuvants in the treatment of pathologies where the control of bacterial infections is a key factor for a favourable prognosis [1,2]. The treatment of burns and chronic skin lesions is one of the most important applications because the local interruption of the blood flow make systemic infection prophylaxes little effective, and topical administration of Ag-based antimicrobials may therefore be decisive in preventing sepsis [2].

The reactivity of Ag in biological systems is mainly due to the ionic form Ag^+, thanks to its ability to bind organic ligands [3]. In bacteria, such interactions allow the metal to bind to the cell wall, enter the cytoplasm, and interfere in key metabolic pathways [4]. However, the high reactivity of Ag^+ in biological systems may also lead to a rapid deactivation and clearance of the metal, mediated for example by complexation with serum proteins [5]. Engineered nanoparticles (NPs) provide innovative forms of Ag which can be specifically designed to modulate the release of ions from their surface in a gradual and highly controlled way [6]. Metallic AgNPs have the potential to persist sufficiently for mobilization within biological tissues, and exhibit enhanced affinity for cellular membranes, all of which favours their uptake and delivery to intracelluar targets [7]. Several physico-chemical characteristics of AgNPs are determinant for their dynamics, including size/shape, surface charge and coating, as well as aggregation/agglomeration state. Many properties of the medium also affect their stability in biological systems, including the ionic strength, pH, pE, and composition of the organic matter [4]. Complex interactions among these properties of AgNPs and the surrounding media have been conjectured to regulate their transformations in environmental and biological systems [3], but the actual dynamics *in situ* and *in vivo* in human tissues remain currently unknown.

A key question is to establish whether AgNPs are able to remain intact for a sufficient length of time and space to reach the bloodstream and undergo systemic distribution. To address this question, adequate analytical tools to detect AgNPs and dissolved Ag in blood must be developed. Techniques such as transmission electron microscopy (TEM), scanning electron microscopy (SEM) and atomic force microscopy (AFM) enable size characterization of NPs at high resolution [8-10], but cannot provide statistically robust and quantitative data on complex biological fluids with a very low concentration of the metal. Dynamic and static light scattering (DLS and SLS) are widely used to characterize NPs suspensions, but are also inadequate for the analysis of polydisperse particles in complex biological matrices [11,12]. In addition, none of these techniques provides information on the dissolved fraction of a metal. A powerful technique for quantitative detection of metallic NPs is ICP-MS, as it is element-specific and highly sensitive, although it has to be coupled to a separation technique to gain a dimensional characterization. A variety of separation techniques, including flow-field-flow fractionation (FFF), hydrodynamic chromatography (HDC), reverse-phase (RP) high performance liquid chromatography (HPLC), ion mobility chromatography (IMC) and micellar electrokinetic chromatography (MEC), have been coupled to ICP-MS for the characterization of AgNPs in standard solutions, plasma and serum, nutraceuticals and a beverage [13-16,11,17,18]. However, all these separation techniques have limitations. Low recoveries are a critical issue in FFF, due to the complex interactions of AgNPs with the membrane, and dissolved ions cannot be detected [11]. RP-HPLC is able to separate AgNPs from ionic Ag, but with poor resolution and low reproducibility for complex biological matrices such as bovine serum [18]. HDC is a robust and versatile method for separating NPs even in complex and heavy matrices, but with poor resolving power. Dissolved ions could also be potentially determined by HDC-ICP-MS, but this

application has not yet been explored. MEC-ICP-MS could enable the size-dependent separation of AgNPs and ionic Ag with a higher resolving power, but has only been tested on standards [19]. The recent introduction of the single-particle (sp) acquisition mode in ICP-MS has allowed this technique to detect NPs individually, providing quantitative information on their mass distribution and number concentration in solutions [20]. A number of applications have been proposed for the characterization of AgNPs in waters [21-25], but biological matrices remain virtually unexplored, with the exception of enzymatically digested chicken meat [26]. However, spICP-MS does not provide key data for the dynamics of AgNPs in complex systems, including the real diameter, shape, composition, and aggregation/agglomeration of the particles, because only their metallic mass can be revealed. The most promising strategy to obtain complete information on NPs in complex media are spICP-MS hyphenated techniques, but only a few applications have been proposed until now. Online coupling of asymmetric FFF (AF4) to spICP-MS has been explored to study AgNPs in chicken meat [27], and so has HDC-spICP-MS for Ag, Au and polymeric NPs in standards solutions and waters [28,16,12]. The determination of dissolved Ag in combination with spICP-MS remains an analytical challenge. Off-line separation of the dissolved fraction by ultrafiltration has been proposed [29,24], but simultaneous on-line methods would be preferable. Statistical separation of the signals generated by AgNPs and dissolved Ag is possible in spICP-MS by adopting a simple threshold value fixed on the standard deviation of the background [12,25,21,30], or by applying a more complex algorithm based on polygaussian fitting of the frequency distribution [31]. However, such strategies are not suitable for hyphenated techniques, in which dissolved Ag itself generates a transient signal. Thus, the deconvolution of signals from dissolved Ag and AgNPs in spICP-MS hyphenated techniques has not yet been attempted.

The goals of the present work were to set up and apply an analytical method based on HDC hyphenated to spICP-MS for the simultaneous determination of dissolved Ag and the full characterization of AgNPs in human plasma/blood based on an innovative signal deconvolution strategy. An innovative approach combining our method with µXRF imaging and µXANES speciation analysis was applied to study *in vitro* the transformations of AgNPs incubated in whole human plasma, and to investigate for the first time the presence of AgNPs in the whole blood of burnt patients treated by topical administration of AgNPs under real hospital conditions.

1. Experimental

Standards, reagents and samples

An Ag ICP-MS grade 1000 ng mL^{-1} standard solution (certificated, NIST teachable) was obtained from Ultra Scientific (Bologna, Italy) and used to calibrate the total Ag measurements. Commercial standards of AgNPs purchased from Sigma-Aldrich were used for method development, calibrations and the incubation experiments. The standards consisted of monodisperse metallic NPs with nominal diameters of 10, 20, 40, 60 and 100 nm (provided uncertainty ± 4 nm), mass concentration 20 ± 0.5 µg mL^{-1}, suspended in aqueous solution and stabilized with sodium citrate. The standards were characterized by TEM resulting in a size distribution compatible with the values provided by the manufacturer, and spherical shape. The z-potential of the mother dispersions was measured confirming their good stability (<-40 mV). Details on the experimental procedures for characterization of the standards, representative TEM images and a summary of their size/shape parameters and z-potential can be found in the appendix. The measured size of the standards was used for all calculations, but for simplicity, we refer to their nominal diameter throughout this paper. The exact mass concentration as total Ag of the mother dispersions was also measured by ICP-MS, and number concentration was calculated based on the experimental mode of the size distribution.

The commercial dressing Acticoat Flex3™ (Smith & Nephew) was used for the *in vitro* incubations and the *in vivo* treatment of burnt patients as reported elsewhere [32]. The mobile phase for chromatography was prepared using sodium dodecyl sulphate (SDS), HNa_2PO_4 dihydrate and IGEPAL® CA-630 nonionic detergent in the following concentrations: SDS 0.05 % v/v, HNa_2PO_4 0.002 M and IGEPAL 0.1 % v/v at pH 7.4. A water solution containing tetramethylammonium hydroxide (TMAH) 0.1 % v/v, NH_4OH 2.8 % w/w and Triton™ X-100 0.1 % v/v was used to dilute 20-fold the whole blood for total Ag determination by ICP-MS. L-glutathione reduced (GSH) and human serum albumin (HSA) lyophilized powders were used for incubation experiments. All incubations were carried out in a normal laboratory environment at 37 °C in a thermostated bath, under constant gentle shaking in the dark. The preparation steps for standards and samples were carried out in a class 1000 clean room environment under a class 100 laminar flow bench.

Whole human plasma for incubations and control whole blood were provided by distinct volunteers and were collected at the University Hospital of Padua. Four samples of whole blood were provided by the bio-bank of the same Hospital, and were collected from three adult patients treated in the same Hospital, at the Burns Center, following the current protocols without any additional invasive procedure. The patients did not present any pathology other than the burn. All samples were collected and stored in agreement with the guidelines of the University Hospital of Padua and informed consent of the patients was obtained according to the Helsinki Declaration. The blood was collected in purple-tip vials (K2-3EDTA) in order to prevent coagulation, was immediately frozen to lyse the red blood cells, and was stored frozen until analysis.

Instrumentation

The chromatographic system consisted of an Agilent Technologies (Tokyo, Japan) 1200 series HPLC pump fitted with an HDC 5-300 Type-1 column (linearity range from 5 to 300 nm) from the same supplier. Sample injections were performed manually using a 100 µL loop and an inert Rheodyne injection valve. The elution was performed in isocratic mode at a flow rate of 1.0 mL min^{-1}. An ICP-MS detector model 7500cx from Agilent Technologies was coupled on-line to the chromatographic system by using a polypro nebulizer mounted on a double-pass Scott spray chamber thermostated at 2°C. The instrument operated at 1500 W RF power with a carrier gas flow rate of 1.1 mL min^{-1} and make up gas flow rate of 0.1 mL min^{-1}. The lens voltages were tuned daily for best sensitivity using a 1 ng mL^{-1} solution of Ag. In order to minimize the matrix effects, robust plasma conditions were achieved by keeping oxides and double charges rates below 2 % based on the response of a Ce 1 ng mL^{-1} solution, and using 8 mm of sample depth. Acquisition was carried out by monitoring both the isotopes of Ag (m/z 107 and 109) with a dwell time of 5 ms. Automatic correction for the dead time was adopted, the parameter was estimated as reported elsewhere [33]. A settling time of 2 ms was automatically selected by the instrument and was taken into account to correct the calibration of NPs number concentration, as reported below.

Synchrotron radiation µXRF and Ag L_{III}-edge µXANES measurements were performed using the scanning transmission X-ray microscope of beamline ID21 at the European Synchrotron Radiation Facility (ESRF, Grenoble, France). Details on standards/sample preparation, instrumental parameters and data elaboration for µXRF and µXANES are provided as supporting information.

Data elaboration

Data treatment for HDC-spICP-MS was carried out by using a home-made program written in Fortran language and run using the compiler Compaq Visual Fortran (Compaq Computer Corporation). The program reads the ICP-MS raw data file directly and provides a number of output files including overall statistics and matrices. The latter were directly imported in Surfer 11 (Golden Software) for graphical elaboration of the contour plots (3D chromatograms). Excel

spreadsheets (Microsoft), OriginPro 8.5 (OriginLab) and Statistica 10 (StatSoft) were used for additional calculations and graphical elaboration. PyMca [34] and Athena [35] software were used to elaborate the μXRF and μXANES data.

2. Results and discussion

2.1. Implementation of data analysis

2.1.1. Dwell time and data pre-processing

The limit of detection (LOD) in spICP-MS has two possible interpretations: as the lowest detectable particle size (LOD_S^{NP}) and the lowest detectable particle number (LOD_N^{NP}). Measuring simultaneously the dissolved Ag introduces also a third definition, which is the lowest detectable concentration of this fraction (LOD_C^D). The choice of the dwell time is the key to determine all these parameters in samples where both NPs and dissolved Ag are present, and the overall statistical reliability of the results in spICP-MS. Individual NPs in ICP-MS generate transient signals with a temporal width of 0.3-0.5 ms [36]. Recent instrumentation allows setting the dwell time within the μs range, so that single events can be described by multiple data points. This results in a significant reduction of the background, a decreased LOD_S^{NP} and an improved range of number concentration [37]. However, the same increase in the signal-to-background ratio is expected to make more difficult the determination of the dissolved Ag by statistical deconvolution within the same analysis, increasing the LOD_C^D. Moreover, with μs dwell times, the probability to observe split of events between adjacent time windows must be taken into account [30], and the electronic and computational load due to data size can be potentially problematic when applied to hyphenated techniques, where the acquisition lasts for tens of minutes. Conversely, conventional ms dwell time leads to higher LOD_S^{NP} and requires higher dilution of the samples to avoid detecting multiple events within the same time window [30], but it is more suited for performing the simultaneous determination of dissolved Ag and using hyphenated instrumental approaches. According to other authors, a dwell time in the range of 3-5 ms is adequate to achieve good quality data in our context [38]. The minimum dwell time that can be set on our instrument for the acquisition of a single m/z is 10 ms, but a dwell time of 5 ms can be chosen by monitoring both masses of Ag. This required a data pre-processing step for normalization of the two signals to the relative natural abundance of each respective isotope, before merging them into a single chromatogram. Given the proximity of the two abundances (0.518 For ^{107}Ag and 0.482 for ^{109}Ag), the difference in signal intensity for the two masses is negligible at low counting rates, but was nevertheless taken into account when applying the threshold in the following deconvolution step. In addition, the acquisition of two masses introduces a settling time, which slightly affects the number of detected particles (see section 2.1.4.).

2.1.2. Deconvolution of the signals

The expected forms of dissolved Ag in plasma (protein complexes) have hydrodynamic diameters smaller than the LOD_S^{NP} (see section 2.1.4.), and close to the lower limit of separation range. Given also the poor resolving power of HDC, their peak cannot be chromatographically resolved from those of ~20 nm particles, thus making deconvolution a necessary operation. In this work, the statistical deconvolution of the signals from dissolved Ag species and AgNPs was based on a nonparametric statistical test applied to each data point of the chromatogram as it was sequentially scanned. The intensity value of each point was compared to that of its two adjacent neighbours, and their difference was calculated. If at least one of the two differences overcame a threshold value given by the maximum expected difference between any data generated by

dissolved Ag, the hypothesis of the point being associated to dissolved forms was rejected. For each pair of points to be compared, the relative threshold value was specifically calculated as a negative exponential function of the lower of the two intensities. The function was externally calibrated on the chromatogram of a single standard of dissolved Ag with a relatively high concentration (500 pg mL^{-1}) using the following procedure. The chromatogram was divided into consecutive windows of 2 s width, in which the signal was assumed to be stationary. For each window, the empirical distribution of the data was calculated to extract the 1^{st}-to-99^{th} interpercentile range. The range was plotted against the average value within the same window as shown in Fig. 1a. The interpercentile range can be interpreted as the maximum difference in signal intensity between two data points generated by dissolved Ag at a 98 % confidence level, and was adopted here as the threshold value to discriminate the signals. The vector of points for which the hypothesis of being generated by dissolved Ag was rejected, constituted the NPs extracted chromatogram.

2.1.3. Elaboration of the 3D NPs raw chromatogram

The NPs chromatogram was firstly treated by converting the normalized signal intensities into their cube square. This step was necessary to obtain final chromatograms in which the mass-derived diameter is represented on a scale with uniform resolution. In a second step, the dimensions of elution time and normalized signal intensity were gridded into windows of selected width according to the procedure proposed by Pergantis et al. [28]. The width of the intensity windows was fixed at 0.6266 normalized $counts^{1/3}$, resulting in a resolution of 6.5 nm for the mass-derived diameter after calibration. The width of the elution time windows was fixed at 5 s in order to contain 714 data points to guarantee statistical representativity. After gridding, the number of events detected within each window was counted, and a raw 3D chromatogram was yielded as a 3-columns matrix consisting of the central values of the elution time (x-axis) and the normalized events' intensity (y-axis), and the number of detected events (z-axis) for each window.

2.1.4. Calibrations and elaboration of the 3D NPs final chromatograms

Besides the threshold function, other external calibrations based on the injection of monodisperse NPs standards were necessary to convert the normalized signal intensity into mass-derived diameter, and the elution time into hydrodynamic diameter. Standard suspensions with a 20, 40, 60 and 100 nm nominal size and variable concentration were injected to calibrate these two parameters as done by Pergantis et. al. [28]. For each standard, the mode of the 3D raw chromatogram provided the data to be included in the calibration curves, which are shown in Fig. 1b,c. A LOD_S^{NP} of 16 nm was calculated as 3 times the standard error of the intercept of the mass calibration curve. This value is in agreement with the range of those estimated by other authors both theoretically and experimentally (in water samples) using spICP-MS [22]. The extrapolation of the number concentration of AgNPs in a sample required estimating separately their transport efficiency through the nebulization system. Adapting the formula by Pace et al. [39], the overall number of detected particles n_r of radius r, using the hypothesis of purely metallic and spherical particles, can be expressed as:

$$n_r = \eta \cdot \frac{c_r^m}{\frac{4}{3}\pi r^3 \rho} \cdot v \cdot \frac{t_i}{t_s + t_i} \qquad \text{eq.1}$$

where η is the transport efficiency (independent by the radius), c_r^m is the mass concentration of the NPs (pg mL^{-1}), v is the injection volume (mL), ρ is the density of Ag in pg nm^{-3} = $1.049 \cdot 10^{-8}$, t_i is the integration time and t_s is the settling time. The transport efficiency can be estimated by analyzing a series of standards of any radius at different known mass concentrations, calculated as the slope of the regression line in eq. 1. However, one should note that even if approximately

monodisperse, a standard suspension still has a characteristic size distribution which may be not perfectly symmetric, particularly for the size ranges close to the LOD_S^{NP}, so that simple counting the overall number of detected particles would introduce a bias. In order to overcome this potential problem, we used the calibration of mass-derived diameter to convert the number of detected particles into a mass for each window of the raw chromatogram. Summing the mass of all windows provided the total detected mass of Ag, to be used in place of n_r for efficiency estimation. The method was tested on four nominal particles sizes, as shown in Fig. 1d. Consistently with the independence of η from the particles' size, an average value of 1.78 ± 0.07 % was obtained for the four calibrations. If a minimum number of 3 detected particles is arbitrarily adopted as the statistical treshold to verify their presence, taking into account the transport efficiency, settling time and injection volume, a LOD_N^{NP} of ~2300 particles mL^{-1} is achieved. This threshold can be indifferently adopted for all particles or for specific size classes. Finally, a calibration was also required for the dissolved Ag fraction by injecting standards of ionic Ag with variable concentration as shown in Fig. 1e, obtaining a LOD_C^D of 13 pg mL^{-1}.
All calibrations reported above allowed to convert the data of the 3D NPs raw chromatogram for each sample into a final chromatogram representing the experimental distribution of NPs in terms of number concentration or mass concentration depending on the hydrodynamic diameter and mass-derived diameter.

2.2. Stability of the AgNPs in the mother standards and in mobile phase.

The mother citrate-stabilized dispersions were stored at 4°C and no significant changes in their size distribution were noticed after more than 1 year (as observed by TEM). In addition, no peaks of dissolved Ag were detected by HDC-ICP-MS when injecting single standards freshly diluted in mobile phase for calibration within the same time span. The temporal stability of AgNPs standards in the mobile phase below the ng mL^{-1} level was also checked. Despite the appearance of small peaks of dissolved Ag was observed after leaving the vials exposed to light and room temperature up to 24 h, the corresponding concentration was below the LOD_C^D for all particle sizes. Nevertheless, in order to avoid any potential alteration of the dynamics of AgNPs due to interaction with the mobile phase, all standards for calibration were always prepared freshly from the mother dispersion and immediately injected, all samples were analysed immediately after preparation, and replicates were obtained from independent preparations rather than from repeated injections.

2.3. Dynamics of AgNPs incubated in human plasma

The developed method was used to study the dynamics of AgNPs in human plasma. Standards with nominal diameters of 20, 40, 60 and 100 nm were mixed in whole plasma at concentrations of 10, 16, 37 and 100 ng mL^{-1}, respectively, sonicated for 1 min and then incubated for 2 h. After incubation, the sample was diluted 20-fold in the mobile phase and directly injected without further sonication. A control sample was prepared by diluting the AgNPs mixture in the mobile phase at the same final concentration, followed by sonication for 1 min, and direct injection. Fig. 2 shows the final 3D chromatograms obtained for the control and plasma incubated mixtures. A number of significant changes were observed in the distributions of NPs after 2 h of incubation in plasma: i) a slight general decrease in the mass-derived diameter; ii) a significant decrease in the number and mass concentration of the NPs; iii) a generalized shift in the distribution towards the higher hydrodynamic diameters of 10-20 nm. While the first two effects can be ascribed to a partial dissolution of the NPs, the increased hydrodynamic diameter is compatible with two possible phenomena: agglomeration of NPs and the formation of a protein corona onto their surface. The agglomeration of uncapped NPs is a feasible process in plasma, particularly due to the

relatively high ionic strength of the medium [3]. We did not observe the appearance of new modes in the mass-derived diameter corresponding to multiples of the nominal diameters of 40, 60 and 100 nm. However, agglomeration effects cannot be excluded for the 20 nm particles due to the theoretical superimposition of the multiples of their mass on the modes of the other standards. Conversely, the formation of a proteins corona is a plausible generalized process, particularly due to the interaction of thiol groups in amino acids with the charged surface of AgNPs in a medium with a high ionic strength [40,41].

In order depict the temporal dependence of the dynamics of AgNPs in human plasma, the standard suspension with a 100 nm size was selected for further incubation experiments. An aliquot of the mother monodisperse suspension (20 µg mL^{-1}) was sonicated for 1 min, then mixed 1:1 with plasma and incubated for 24 h. At time steps of 2, 4, 6, 8, 16 and 24 h, aliquots of the solution were collected, diluted 10,000-fold in the mobile phase, and analyzed immediately. Fig. 3a shows that the dissolution of AgNPs is not linearly time-dependent on an hourly scale in a closed system. The most significant change was observed between the 4 and 8 h incubations, with a decrease in the molar fraction of Ag present in the original form of NPs, corresponding to the appearance and increase of the dissolved fraction. Between 16 and 24 h the molar fractions seem to reach equilibrium. The precision of detection efficiency (~ 4 % of relative error, see paragraph 2.1.), which affects the estimated number concentration, is the dominant source of uncertainty for AgNPs molar fraction. The calibration of dissolved Ag is more reproducible because the relative error of the slope of its calibration curve (Fig. 1e) is 1 %. The mass-derived diameter of the particles exhibits a substantial linear decrease from 100 to 80 nm in 24 h (Fig. 3b), confirming the partial dissolution of the individual particles. In this case, the standard deviation among replicates is zero because their differences are smaller than the width of the signal intensity windows adopted for gridding (see paragraph 2.1.3.). Thus, for each estimated diameter *d*, the width of the gridding windows ± 6.5/*d* % can be considered as the maximum theoretical uncertainty, and was taken to represent the whiskers in Fig. 3b.

Speciation analyses by µXANES were carried out on analogously incubated samples. Standards of AgNPs with a 10 nm size (20 µg mL^{-1}) and ionic Ag solution (nitrate, 10 µg mL^{-1} as Ag) were incubated in a water solution containing HSA (~ 0.5 mg mL^{-1}) and in whole plasma. After 2 h a drop of each solution was freeze-dried between Ultralene® windows and was directly analyzed by µXANES. Representative spectra for each of the incubated standards and pure species of Ag, as shown in Fig. 4a-b, allowed us to identify the chemical forms of Ag after incubation and their relative molar fractions estimated by linear combination fitting (LCF), as reported in Table 1. The µXANES analysis showed that after 2 h of incubation in HSA the Ag^+ ions were mostly complexed by thiols (represented by the Ag-GSH bound). Conversely, AgNPs remained intact almost quantitatively, even if Ag-thiols were also detectable. This confirms that the formation of a protein corona on the surface of AgNPs has a major inhibiting effect on their dissolution in the short term. Differently, in whole plasma, the early dynamics of Ag were dominated by chlorides, with formation of insoluble AgCl from free Ag^+, and significant agglomeration of the AgNPs, as marked by the high weight of the metallic Ag foil spectrum obtained by LCF.

2.4. Dynamics of AgNPs agglomerates released from a dressing incubated in human plasma

The 2 h incubation experiment in whole plasma was carried out also by using the intact dressing Acticoat Flex3™. The dressing consists of a net of polyethylene fibers, individually and uniformly coated with a layer of uncapped AgNPs of 10 nm size; other characteristics of the product can be found elsewhere [33]. Previous experiments showed that the dressing releases AgNPs as agglomerates with widely variable size *in vitro* in human serum substitute [42], and agglomerates

were also detected in the fibroblasts of burnt patients after 7 days of treatment [32]. In this experiment, 2.45 mg of the dressing (0.32 mg as Ag) were dipped into 1 mL of whole plasma and sonicated for 10 min to accelerate the release of AgNPs as individual particles or small agglomerates. After 2 h of incubation, the plasma was centrifuged at 3000 rpm for 10 min in order to remove the fibers, cloth debris and micrometric agglomerates of AgNPs, then an aliquot was diluted 100-fold in the mobile phase and directly injected into the chromatographic system. The 3D chromatograms in Fig. 5a-b show a few particles with size >16 nm, corresponding to small agglomerates of 2-5 NPs with 10 nm size. Significantly higher hydrodynamic diameters, with respect to the mass-derived diameter, were also observed. The latter effect supports the hypothesis that the observed particles are small (non-spherical) agglomerates, and is also compatible with additional proteins capping effects. The dissolved Ag fraction resulted lower than the LOD_C^D.

A 20 µL aliquot of the same sample after incubation was collected before centrifugation, was freeze-dried and analyzed by µXRF and µXANES. Preliminary µXRF mapping of the sample allowed us to detect a number of micrometric agglomerates of AgNPs or fragments of the dressing. A region surrounding one of the particles was selected, and the distribution of Ag, Cl and S was mapped as shown in Fig. 6a. A characteristic non-uniform accumulation of Cl was observed at the border of the Ag particle, while S was uniformly distributed in the surrounding medium. µXANES spectra were collected in the same region for each pixel to be individually elaborated by LCF in order to extract a coarse estimation of the molar fraction of the three main expected species: intact AgNPs, AgCl and Ag-thiols. The resulting µXANES map is shown in Fig. 6b. Although total Ag and Cl presented widely different distributions, a relatively uniform distribution of the Ag species was observed, consistent with the participation of the whole surface of the AgNPs agglomerates in the chemical dynamics of the metal. The average molar distribution of the species within the entire region was 49 % AgCl, 22 % AgNPs and 20 % Ag-thiols (9 % unidentified species). The overall distribution was also estimated by firstly merging all the spectra within the region, and then performing the LCF on the pooled spectrum. This procedure allowed us to weight the contribution of each pixel on the base of the total Ag level, and provided the values: 53 % AgCl, 31 % AgNPs and 15 % Ag-thiols. Compatibly with Fig. 6b, the slight variations with respect to the previous estimation are consistent with a major localization of AgCl and AgNPs in the regions with elevated Ag level, while Ag-thiols are mainly present in the peripheral areas. The assignment of previously unidentified species could also have affected the latter values. The co-presence and relative proportion of the three species reveal that the dynamics of AgNPs in plasma involve integrated and complex processes. Free Ag ions are expected to be a negligible fraction in biological systems due to the high formation constant for chloride and thiol bonds [43,3], so that dissolution and formation of complexes may take place directly on the surface of the AgNPs as an integrated process. Properties of the medium such as its general composition, concentration of chloride and pH, and kinetics of complexation influence the dynamics. Although protein thiols should be thermodynamically favoured for Ag binding in plasma with respect to chlorides [6,3], our data support the hypothesis that the latter have a kinetic advantage when interacting with Ag ions directly on the charged surface of the bare NPs, leading to an early effect of partial dissolution, and possibly agglomeration of the smallest NPs. Still, protein thiols may co-participate to these dynamics by enclosing the particles and superficial chlorides, inhibiting further interactions with the medium, the removal of AgCl from the surface and further agglomeration effects. Given the affinity of thiols for Ag, subsequent displacement of the metal from the chlorides is likely, resulting in its final mobilization. In agreement with Liu et al. [3], thiols binding appears to be the limiting process in regulating the dissolution of AgNPs in plasma, and the mediator for systemic

distribution of the metal, but our findings suggest that kinetic factors play a crucial role in this complex dynamics.

2.5. Whole blood from burnt patients treated with a AgNPs-containing dressing

In addition to the temporal dynamics of the chemical transformations of AgNPs, the particles could also undergo simultaneous mobilization through the tissues, with consequent change in the properties of the surrounding medium. The formation of a proteins corona is probably the main favouring factor for the cellular uptake on AgNPs [41], which has been observed in human skin both *in vitro* and *in vivo* in burnt patients [32]. However, the few available experimental data suggest that the metal has a poor capability to penetrate the skin in depth, even if penetration may be enhanced in damaged tissue [32,44].

In order to evaluate the actual potential of AgNPs to reach the bloodstream before dissolution, we used HDC-spICP-MS to analyze four whole blood samples collected from three adult patients (A-C) treated for mid-thickness skin burns with a single application of the dressing. The main clinical information is summarized in Table 2. The patients had a comparable % of burned body surface, which represents the wound area exposed to AgNPs. Three blood samples were collected from distinct patients 3 days after the application; and an additional sample was collected from patient A after 6 days of treatment. Compatibly with our previous estimations that the dose of Ag released by the dressing into the patient's tissues *in vivo* would be elevated [33], a significant level of total circulating Ag was observed in all patients after 3 days of application of the dressing (Table 2). The values ranged between ~30 to 80 ng mL^{-1} and were more than 2 orders of magnitude higher than the baseline level in an unexposed population [45], and slightly lower than those observed in the serum of paediatric burnt patients treated with the same dressing (average 114 ng mL^{-1}) [46]. Differently from the latter cited work, we did not observe any apparent correlation between blood Ag and the percentage of burnt body area, and just a slight increase in Ag was noticed after 3 additional days of application for patient A.

An aliquot of the blood was then centrifuged at 3000 rpm for 10 min to remove the cell debris in order to avoid clogging the chromatographic system. The surnatant was recovered and analyzed for total Ag. The average recovery of total Ag after centrifugation was ≥ 96 % for all samples except patient C (76 %), and a minimal loss of Ag due to co-precipitation was therefore assumed for most cases. The possibly co-precipitated Ag can be ascribed to its association to cellular debris and large biomolecules whose size exceeds the effective separation range of the HDC system. Based on the total concentration of Ag, the centrifuged samples were diluted in the mobile phase according to specific dilution factors (see Table 2), optimized to obtain the same final concentration of ~400 pg mL^{-1} of Ag. This target value was selected from preliminary tests as the optimum concentration for detecting a significant number of AgNPs with a mass-derived size close to the LOD_S^{NP} under the hypothesis that they were present as a significant molar fraction of Ag (> 10 %).

We did not detect any significant event associated to AgNPs agglomerates >16 nm in the four blood samples (chromatograms are not shown). Conversely, from the chromatograms of dissolved Ag shown in Fig. 7, an average molar fraction of 94 ± 9 % was estimated for the dissolved species (see Table 2), which is not statistically different from the total level of the metal.

Considering that: i) our previous studies have shown that in burnt patients treated with Acticoat Flex3™, AgNPs are released as agglomerates and maintain this form even in the tissue; ii) a poor dermal penetration of PVP-coated AgNPs, restricted to small (<30 nm) particles in damaged skin, was observed *in vitro* [44]; and iii) we documented here that small AgNPs exhibit both agglomeration and partial dissolution effects at an hourly time scale in plasma; the results of blood

analysis strongly support the hypothesis that the systemic mobilization of Ag is driven by the *in situ* dissolution of NPs in the skin. The first medium entering in contact with the AgNPs released by the dressing onto the wound bed is the exudate, whose composition is similar to the serum. This medium is the major candidate to host the *in situ* transformations of AgNPs, where dissolution may be also enhanced by the lower pH (5.7), typical of the inflammatory phase in wounds [47]. It is also likely that the reduced blood circulation in burns further inhibits the dispersion of AgNPs. However, let us keep in mind that the specific local characteristics of the wound may dramatically affect the release of AgNPs from the dressing and the composition/production/turnover of the exudate. This can lead to significantly different AgNPs dynamics at a local level, resulting in the possible penetration of agglomerates into the shallow tissue layers. Photochemical reduction of Ag complexes with formation of secondary Ag/S/Se particles can also occur in the skin [3]. We previously observed a few electron-dense particles in skin biopsies after application of the dressing, which are potentially representative of photoprecipitation [32]. However, this phenomenon appears to be limited to the most severe lesions, which require long-term treatments and replacement of the dressing, leading to exposure to light and an increased Ag dose.

3. Conclusion

The exponentially growing market of consumer and medical products containing AgNPs has raised the urgent need for regulatory standards targeted at health and safety. Developing adequate analytical methods to achieve detection and characterization of AgNPs and their ionic counterpart in biological media is the key requisite to support regulatory requirements with robust scientific evidence.

An innovative method is proposed here for the simultaneous determination of dissolved Ag and the characterization of AgNPs in human plasma and blood. By coupling HDC separation, spICP-MS detection and a dedicated algorithm for data elaboration, comprehensive information on the chemical state of the Ag^+/AgNPs system can be retrieved in a single analytical run. While HDC separates the NPs based on their hydrodynamic diameter and spICP-MS provides information on their mass distribution, both techniques have the potential to discriminate physically and statistically (respectively) the signal of NPs from that of dissolved Ag, but this advantage was not exploited before. We combined the two techniques and a home-made software based on a new algorithm able to process the raw ICP-MS chromatogram for deconvoluting the signal of dissolved Ag from that of AgNPs. From a single injection, the method provides the chromatogram and concentration of dissolved Ag; the distribution of NPs in terms of hydrodynamic diameter, mass-derived diameter, size-dependent number of detected NPs; the total number concentration and size-dependent mass concentration of the NPs. A variety of 3D chromatograms can be obtained from the results to achieve a comprehensive characterization of AgNPs.

The method is robust when applied to heavy matrices such as plasma and blood, and in principle can be extended to other biological media and to other metallic NPs. The algorithm in particular is suitable for the deconvolution and determination of particulate and dissolved fractions independently by the element, or just for the removal of non-stationary background in any separation technique coupled to spICP-MS.

Combining the method with µXANES speciation and imaging provides an integrated approach which opens the way to elucidate the dynamics of AgNPs in biological fluids or extracts *in vivo* under realistic conditions (real human subjects, real administered doses).

We applied this strategy to study the behaviour of AgNPs standards and of an AgNPs-coated dressing incubated in human plasma, and to investigate for the first time the capability of AgNPs to reach the systemic circulation after topical application to burnt patients.
The results showed that partial dissolution of uncoated AgNPs takes place in plasma on an hourly time scale with nonlinear dynamics in a closed system. Chlorides and protein thiols co-participate in the process through complex temporal and spatial mechanisms, forced by kinetic factors. The early dynamics and dissolution of AgNPs are dominated by interaction with chlorides directly on their surface. Formation of a protein corona takes place in the meantime, resulting in the inhibition of further reactions with the medium, slower displacement of Ag from chlorides and final mobilization of the metal. As a whole, thiols binding is proposed as the main regulator of AgNPs dissolution in plasma and of the systemic distribution of the metal. The analysis of whole blood from burnt patients suggested that the dynamics of AgNPs dissolution after topical administration takes place mainly *in situ*, most probably in the exudate, so that their potential to undergo systemic distribution in the intact form is minimal. Further studies are currently in progress to investigate the chemical speciation of Ag directly in wound tissues.

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Disclaimer: The authors declare that they have no conflict of interest.

Appendix

Characterization of the commercial AgNPs standards dispersions

The morphological characterization of the mother AgNPs standard dispersions was carried out by TEM using a Tecnai 12 G^2 instrument (FEI, USA). For the analysis, a 3 µL drop of each dispersion was deposited on a support Formvar/Carbon on 200 mesh thick grid, let dry at room temperature and directly analysed. The images were acquired at 120 kV high voltage and using tungsten filament, twin optics and an Olympus side-mounted camera. The software ImageJ (National Institutes of Health, USA) was used for particles' counting and shape characterization. Representative TEM images of the standard NPs and a summary of their size/shape parameters are shown in Fig. 8 and reported in Table 3, respectively.
The z-potential was measured by using a Zetasizer Nano (Malvern, UK) at 24°C in DTS1070 cells pre-washed with a citrate 60 µg mL^{-1} water solution. For the analysis, each standard suspension was sonicated for 5 min, equilibrated for 120 s in the cell, and 5 replicate measurements of 10 to 100 readings were acquired. The z-potential of the standard NPs is also reported in Table 3.
Total mass concentration of Ag in the standards was measured by ICP-MS *previa* dissolution in HNO_3 5% v/v and subsequent dilution in NH_4OH 2.8 % w/w. The analysis was carried out in full-quant mode by external calibration with Rh as internal standard.

Methods for µXRF and µXANES analyses

Standards and samples

Solid-state reference compounds for µXANES included: Ag^0 foil, AgCl, Ag_2SO_4, $AgNO_3$, Ag_2O, Ag sulfadiazine (AgSD) and a fragment of intact dressing Acticoat Flex3™. Reference standards of Ag^0NPs 10 and 100 nm were prepared from mother water suspensions (citrate stabilized, 20 µg mL^{-1} as Ag) by deposition of a 20 µL drop between Ultralene® windows and microscopy slides, followed by rapid freezing and freeze-drying for 24 h. A standard of Ag bonded to GSH was prepared by incubating ionic Ag (from $AgNO_3$, 10 µg mL^{-1} as Ag) in a water solution of GSH ~0.5 mg mL^{-1}, at 37° C under gentle shaking for 2 h and in dark conditions, followed by freeze-drying as reported above. Standards of Ag^0NPs 10 nm, ionic Ag and the intact dressing Acticoat Flex3™ (2.45 mg fragment) were also incubated in a water solution containing HSA, (~0.5 mg mL^{-1}) and in whole human plasma, freeze-dried as reported above, and analyzed as unknown samples.

Instrumental parameters and data elaboration

The µXRF and Ag L_{III}-edge µXANES measurements were performed using the scanning X-ray microscope of beamline ID21 at the European Synchrotron Radiation Facility (ESRF, Grenoble, France), working at room temperature conditions. Detectors included a Si_3N_7 diode for I_0 and an 80 mm active area Silicon Drift Detector (Bruker) for the emitted fluorescence. Focusing was achieved using fixed curvature Kirkpatrick-Baez mirror optics. The photon flux was 3.6 x 10^9 ph s^{-1} at 3.42 keV with a beam size of 1.0 x 1.2 µm².

µXRF maps of signal intensities for individual elements (Ag, S and Cl) were collected for preliminary analysis to select optimal regions for the subsequent µXANES analysis. The µXRF maps were acquired with variable lateral resolution (0.5 to 2 µm) and integration time of 100 ms. The raw data (counts) were elaborated using the PyMca software as follows: i) correction for the settling time and conversion to counts per second (cps); ii) deconvolution (batch fitting of the µXRF spectra); iii) normalization for the incident beam flux.

Batch Ag L_{III}-edge µXANES spectra of 30 s were collected and averaged for each spot of interest from 3.32 to 3.42 keV energy range with 0.5 eV steps. The beam position was slightly moved from one spectrum to another to avoid radiation damage. At least 10 spectra were averaged for each region of interest. After background removal and normalization, the spectra were calibrated by taking the first inflection point of at 3.3545 keV and then smoothed by interpolation with 5 iteractions. The µXANES spectra of Acticoat Flex3™ and HSA/plasma incubated standards were treated by LCF using the Athena Software with the following set of reference spectra as independent variables: Ag^0 foil, Ag^0NPs 10 nm, AgCl, Ag_2SO_4, $AgNO_2$, Ag_2O, AgSD and AgGSH. A linear term was allowed to compensate for small differences in data normalization, no energy shift was allowed, and weights and their sum were forced to sum to 1. The energy range used for fitting was 3.3345 to 3.4145 keV (e0 - 0.02 to e0 + 0.06). The quality of fitting was quantified by the normalized sum-square residuals NSS = $\Sigma(\mu experimental - \mu fit)^2/\Sigma(\mu experimental)^2$ x 100, where µ is the normalized absorbance. Linear combinations of one, two and three reference standards were examined. The best fit with n+1 components was retained if NSS was decreased by more than 15 % as compared to the best fit using n components. Based on the results, four main Ag species were revealed in the samples: Ag^0 foil, Ag^0NPs 10 nm, AgCl and AgGSH; the other minority species were pooled as "other". When two or more fits of equivalent quality (relative difference of NSS < 10 %) were obtained with different combinations of such a minority species, proportions and NSS were expressed as mean percentage with standard deviation (SD) between brackets, calculated for the equivalent fits.

The µXANES spectra acquired in fluorescence mapping mode by scanning the beam with a 2 x 2 μm^2 step size and a 50 ms dwell time per pixel with 3 eV energy steps in the region from 3.320 KeV

to 3.341 KeV, 0.5 eV from 3.341 KeV to 3.381 KeV, and 1 eV from 3.382 KeV to 3.42 KeV. This resulted in a total of 126 images recorded using a region of interest selective for Ag L3M4 and L3M5 emission lines, corrected for detector dead time (always kept below 20%) and normalized by the incident beam flux. The stack of images was converted to an hdf5 file containing intensities and the energy values for each map to be processed using PyMca for µXANES spectra extraction. The map was treated by moving merge of the spectra on 2 x 2 pixels areas and with 1 pixel step, in order to reduce the noise and improve the statistical representativity. After background removal and normalization, the spectra were calibrated and individually processed by LCF as above, but using only the reference spectra of Ag^0NPs 10 nm, AgCl, and AgGSH as independent variables. Based on visual inspection of the fits, an arbitrary threshold of NSS < 0.1 was adopted to remove from the map the pixels with insufficient quality of the fit. A number of pixels in the upper right side of the map (see Fig. 4b) were discarded based on this criterion. These pixels were affected by the sharp change in intensity at the border of the analyzed particle coupled to beam drift caused by scanning the energy with the double crystal monochromator. The retained pixels were re-processed by LCF testing all combinations in which one of the three reference standard was removed. Each standard was considered significant if its introduction decreased the NSS by more than 3 %. This threshold was calibrated *a posteriori* to guarantee that all pixels in the map had at least one significant component, and a coefficient equal to zero was assigned to the non significant components. For each pixel, the coefficients were finally multiplied for the corresponding signal intensity of total Ag (from the µXRF map), also treated by the moving merge procedure, to obtain the absolute contribute of each species expressed in cps.

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Table 1 Semiquantitative speciation of Ag in the dressing Acticoat Flex3™, 10 nm size AgNPs and ionic Ag incubated in solutions containing HSA or in whole human plasma for 2 h. Data were obtained by LCF of the μXANES spectra; the AgGSH standard is representative of Ag-thiol bonds.

Experiment	Species	Molar fraction %
Ag^0NPs 10 nm in plasma	Ag^0 foil	66
	Ag^0NPs 10nm	28
	other	6
Ag^+ in plasma	AgCl	63
	other(x2)	37
Ag^0NPs 10 nm in HSA	Ag^0NPs 10nm	93
	AgGSH	7
Ag^+ in HSA	AgGSH	67
	other	33
Acticoat Flex3™	Ag^0NPs 10nm	66
	Ag^0 foil	34
Acticoat Flex3™ in plasma	AgCl	59
	Ag^0NPs 10nm	32
	AgGSH	10

Table 2 Main clinical information on the burnt adult patients treated with Acticoat Flex3^{TM}, and concentration of total Ag and dissolved Ag fraction in their whole blood.

	Patient A		Patient B	Patient C
Burn location	Torso + left arm		Torso	Torso + arms
Burned body surface, %	22		27	30
Degree	II		II	II
Dermabrasion	yes		yes	yes
Treatment duration, days	3	6	3	3
Total Ag in blood, ng mL^{-1}	46.6	48.9	83.1	36.9
Total Ag in centrifugated blood, ng mL^{-1} (recovery %)	44.5 (96)	46.7 (96)	81.4 (98)	28.1 (76)
Dilution factor	100	100	250	75
Dissolved Ag in centrifugated blood, ng mL^{-1} (molar fraction %)	37.9 (85)	41.6 (89)	83.9 (103)	28.0 (100)

Table 3 Characterization of the AgNPs standards (mother suspensions) used throughout the study. Particles' diameter and geometry were measured by TEM on a minimum sample of 400 particles; for the z-potential n = 5.

Nominal size ± SD (nm)	Measured diameter (nm): Median (interquartile range) Average ± SD Mode	Geometry: Circularity ± SD Roundness ± SD Solidity ± SD	z-potential (mV)
10 ± 4	8.6 (7.1 – 10.8) 9.2 ± 3.2 7.2	0.90 ± 0.03 0.91 ± 0.06 0.95 ± 0.01	-46.4 ± 2.2
20 ± 4	22.2 (20.7 – 23.5) 21.9 ± 2.4 23.1	0.90 ± 0.02 0.91 ± 0.05 0.95 ± 0.01	-46.6 ± 2.0
40 ± 4	40.7 (40.2 – 45.1) 42.4 ± 3.8 43.5	0.89 ± 0.02 0.90 ± 0.05 0.96 ± 0.01	-45.3 ± 1.7
60 ± 4	56.4 (50.6 – 59.7) 56.5 ± 4.5 58.7	0.89 ± 0.02 0.89 ± 0.06 0.96 ± 0.01	-48.6 ± 1.2
100 ± 4	98.7 (95.6 – 102.3) 99.0 ± 5.1 98.7	0.88 ± 0.02 0.89 ± 0.05 0.95 ± 0.01	-53.2 ± 1.4

Figure captions

Fig. 1 External calibrations applied to elaborate the HDC-spICP-MS chromatograms. a) 1^{st}-99^{th} interpercentile range of the normalized signal intensity relative to the average value calculated for dissolved Ag 500 pg mL^{-1} within 2 s time windows, plotted against the corresponding average intensity. The range was adopted as the variable threshold for deconvolution of dissolved Ag and AgNPs signals. b) Calibration of the normalized signal intensity as a function of the mass of AgNPs standards with 20, 40, 60 and 100 nm nominal diameter (hypothesis of purely metallic spherical particles, n = 3). c) Calibration of the elution time as function of the diameter of AgNPs standards with 20, 40, 60 and 100 nm nominal diameter (n = 3). d) Calculation of the AgNPs detection efficiency as slope of the regression line, detected mass *vs*. injected mass (bilog scale). The injected standards were: 20 nm (5, 10, 20, 30, 40 pg), 40 nm (2.5, 5, 10, 20, 50 pg), 60 nm (10, 20, 50, 100, 200 pg) and 100 nm (25, 50, 100, 200, 500 pg). e) Calibration of the peak area for dissolved Ag (n = 3).

Fig. 2 3D contour plot chromatograms of AgNPs obtained for a mixture of 20, 40, 60 and 100 nm standards diluted in mobile phase (a, b) and the same mixture incubated for 2 h in plasma (c, d).

Fig. 3 a) Temporal variation of the molar fractions of AgNPs and dissolved Ag in plasma after incubation of a 100 nm standard from 2 to 24 h, average ± standard deviation, n = 3. b) Temporal variation of the mode of the AgNPs mass-derived distribution in the same incubated standard, average ± theoretical uncertainty, n = 3.

Fig. 4 3D contour plot chromatograms of AgNPs after incubation of the dressing Acticoat Flex3^{TM} in plasma for 2 h.

Fig. 5 a) µXANES spectra of pure standards of Ag species; b) µXANES spectra of the intact dressing Acticoat Flex3^{TM}, and AgNPs 10 nm and ionic Ag incubated in a solution containing HSA or in whole human plasma. The original spectra of the incubated standards are superimposed to their best fitting (dotted lines) obtained by LCF using the pure standards as the input variables. The fitting parameters (molar fractions) are reported in Table 1. AgGSH is representative of the Ag-thiol bounds.

Fig. 6 a) µXRF map of the distribution of Ag, Cl and S in the region surrounding a micrometric agglomerate of AgNPs released by Acticoat Flex3^{TM} after 2 h incubation in plasma. Scale is linear in cps with independent full-scale values. b) µXANES map of Ag speciation in the same region. Scale is linear in cps with the same full-scale value for all species. AgGSH is representative of the Ag-thiol bounds.

Fig. 7 Deconvoluted chromatograms of dissolved Ag in whole blood of burnt patients obtained by HDC-spICP-MS. The blood was collected 3 days (patients A3, B and C) and 6 days (patient A6) after the application of the dressing Acticoat Flex3^{TM} containing AgNPs. Each sample was differently diluted (see Table S-1) before injection to achieve a comparable concentration (~400 pg mL^{-1}).

Fig. 8 TEM images of the AgNPs standards (mother suspensions) used throughout the study; the nominal sizes are 10 (a), 20 (b), 40 (c), 60 (d) and 100 (e) nm

Online Abstract Figure Simplified scheme of the combined analytical approach adopted for studying the chemical dynamics of AgNPs in human plasma/blood.

Hydrodynamic chromatography coupled to single-particle ICP-MS for the ~~S~~simultaneous characterization of AgNPs and determination of dissolved Ag in human plasma and blood ~~by~~ of burnt patients~~HDC-spICP-MS combined with µXANES to elucidate the fate of AgNPs after topical administration to burnt patients~~

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Abstract

Silver nanoparticles (AgNPs) are increasingly used in medical devices as innovative antibacterial agents, but no data are currently available on their chemical transformations and fate *in vivo* in the human body, particularly on their potential to reach the circulatory system. To study the processes involving AgNPs in human plasma and blood, ~~W~~we developed a ~~n~~ analytical method ~~for the simultaneous determination of dissolved Ag and the characterization of AgNPs in human plasma and blood,~~ based on hydrodynamic chromatography (HDC) hyphenated to ICP-MS in single-particle detection mode~~.~~, ~~and c~~Anombined with a innovative ~~new~~ algorithm was implemented to deconvolute the signals of dissolved Ag and AgNPs, and to extrapolate a multiparametric characterization of the particles~~for data treatment~~ in the same chromatogram.~~.~~ From a single injection, the method provides the concentration of dissolved Ag and the distribution of AgNPs in terms of hydrodynamic diameter, mass-derived diameter, number and mass concentration. This analytical approach is robust and suitable to study quantitatively the dynamics and kinetics of AgNPs in complex biological fluids, included processes such as agglomeration, dissolution, and formation of proteins coronas. ~~-~~The method was applied to study the transformations of AgNPs standards and an AgNPs-coated dressing in human plasma, supported by µXRF and µXANES speciation analysis and imaging, and ~~. The results showed that chlorides and protein thiols co-participate in the partial dissolution of AgNPs on an hourly time scale through complex dynamics driven by kinetic factors. The method was then applied~~ to investigate for the first time the possible presence of AgNPs in the ~~analysis of whole~~ blood of ~~samples collected from~~ three burnt patients treated with the same ~~AgNPs-coated~~ dressing. ~~Of the 30 to 80 ng mL^{-1} of total Ag found in the blood, the dissolved fraction was not statistically different~~

~~from the total level of the metal, while NPs were not detected.~~ Together with our previous studies, the results strongly support the hypothesis that the systemic mobilization of the metal after topical administration of AgNPs is driven by their dissolution *in situ*.

Keywords
Silver nanoparticles; ~~Burns;~~ Hydrodynamic chromatography; Single-particle ICP-MS; Synchrotron radiation~~.~~; Burns; Wound dressings

Introduction

The multispectral antimicrobial effects of silver (Ag) are known and have been exploited since ancient times, but its use in consumer products and medical devices has proliferated considerably in recent years [1]. Ag-containing devices are widely used in hospitals as adjuvants in the treatment of pathologies where the control of bacterial infections is a key factor for a favourable prognosis [1,2]. The treatment of burns and chronic skin lesions is one of the most important applications because the local interruption of the blood flow make systemic infection prophylaxes little effective, and topical administration of Ag-based antimicrobials may therefore be decisive in preventing sepsis [2].

The reactivity of Ag in biological systems is mainly due to the ionic form Ag^+, thanks to its ability to bind organic ligands [3]. In bacteria, such interactions allow the metal to bind to the cell wall, enter the cytoplasm, and interfere in key metabolic pathways [4]. However, the high reactivity of Ag^+ in biological systems may also lead to a rapid deactivation and clearance of the metal, mediated for example by complexation with serum proteins [5]. Engineered nanoparticles (NPs) provide innovative forms of Ag which can be specifically designed to modulate the release of ions from their surface in a gradual and highly controlled way [6]. Metallic AgNPs have the potential to persist sufficiently for mobilization within biological tissues, and exhibit enhanced affinity for cellular membranes, all of which favours their uptake and delivery to intracelluar targets [7]. Several physico-chemical characteristics of AgNPs are determinant for their dynamics, including size/shape, surface charge and coating, as well as aggregation/agglomeration state. Many properties of the medium also affect their stability in biological systems, including the ionic strength, pH, pE, and composition of the organic matter [4]. Complex interactions among these properties of AgNPs and the surrounding media have been conjectured to regulate their transformations in environmental and biological systems [3], but the actual dynamics *in situ* and *in vivo* in human tissues remain currently unknown.

A key question is to establish whether AgNPs are able to remain intact for a sufficient length of time and space to reach the bloodstream and undergo systemic distribution. To address this question, adequate analytical tools to detect AgNPs and dissolved Ag in blood must be developed. Techniques such as transmission electron microscopy (TEM), scanning electron microscopy (SEM) and atomic force microscopy (AFM) enable size characterization of NPs at high resolution [8-10], but cannot provide statistically robust and quantitative data on complex biological fluids with a very low concentration of the metal. Dynamic and static light scattering (DLS and SLS) are widely used to characterize NPs suspensions, but are also inadequate for the analysis of polydisperse particles in complex biological matrices [11,12]. In addition, none of these techniques provides information on the dissolved fraction of a metal. A powerful technique for quantitative detection of metallic NPs is ICP-MS, as it is element-specific and highly sensitive, although it has to be coupled to a separation technique to gain a dimensional characterization. A variety of separation techniques, including flow-field-flow fractionation (FFF), hydrodynamic chromatography (HDC), reverse-phase (RP) high performance liquid chromatography (HPLC), ion mobility chromatography (IMC) and micellar electrokinetic chromatography (MEC), have been coupled to ICP-MS for the characterization of AgNPs in standard solutions, plasma and serum, nutraceuticals and a beverage [13-16,11,17,18]. However, all these separation techniques have limitations. Low recoveries are a critical issue in FFF, due to the complex interactions of AgNPs with the membrane, and dissolved ions cannot be detected [11]. RP-HPLC is able to separate AgNPs from ionic Ag, but with poor resolution and low reproducibility for complex biological matrices such as bovine serum [18]. HDC is a robust and versatile method for separating NPs even in complex and heavy matrices, but with poor resolving power. Dissolved ions could also be potentially determined by HDC-ICP-MS, but this

application has not yet been explored. MEC-ICP-MS could enable the size-dependent separation of AgNPs and ionic Ag with a higher resolving power, but has only been tested on standards [19]. The recent introduction of the single-particle (sp) acquisition mode in ICP-MS has allowed this technique to detect NPs individually, providing quantitative information on their mass distribution and number concentration in solutions [20]. A number of applications have been proposed for the characterization of AgNPs in waters [21-25], but biological matrices remain virtually unexplored, with the exception of enzymatically digested chicken meat [26]. However, spICP-MS does not provide key data for the dynamics of AgNPs in complex systems, including the real diameter, shape, composition, and aggregation/agglomeration of the particles, because only their metallic mass can be revealed. The most promising strategy to obtain complete information on NPs in complex media are spICP-MS hyphenated techniques, but only a few applications have been proposed until now. Online coupling of asymmetric FFF (AF4) to spICP-MS has been explored to study AgNPs in chicken meat [27], and so has HDC-spICP-MS for Ag, Au and polymeric NPs in standards solutions and waters [28,16,12]. The determination of dissolved Ag in combination with spICP-MS remains an analytical challenge. Off-line separation of the dissolved fraction by ultrafiltration has been proposed [29,24], but simultaneous on-line methods would be preferable. Statistical separation of the signals generated by AgNPs and dissolved Ag is possible in spICP-MS by adopting a simple threshold value fixed on the standard deviation of the background [12,25,21,30], or by applying a more complex algorithm based on polygaussian fitting of the frequency distribution [31]. However, such strategies are not suitable for hyphenated techniques, in which dissolved Ag itself generates a transient signal. Thus, the deconvolution of signals from dissolved Ag and AgNPs in spICP-MS hyphenated techniques has not yet been attempted.

The goals of the present work were to set up and apply an analytical method based on HDC hyphenated to spICP-MS for the simultaneous determination of dissolved Ag and the full characterization of AgNPs in human plasma/blood based on an innovative signal deconvolution strategy. An innovative approach combining our method with µXRF imaging and µXANES speciation analysis was applied to study *in vitro* the transformations of AgNPs incubated in whole human plasma, and to investigate for the first time the presence of AgNPs in the whole blood of burnt patients treated by topical administration of AgNPs under real hospital conditions.

1. Experimental

Standards, reagents and samples

An Ag ICP-MS grade 1000 ng mL^{-1} standard solution (certificated, NIST teachable) was obtained from Ultra Scientific (Bologna, Italy) and used to calibrate the total Ag measurements. Commercial standards of AgNPs purchased from Sigma-Aldrich were used for method development, calibrations and the incubation experiments. The standards consisted of monodisperse metallic NPs with nominal diameters of 10, 20, 40, 60 and 100 nm (provided uncertainty ± 4 nm), mass concentration 20 ± 0.5 µg mL^{-1}, suspended in aqueous solution and stabilized with sodium citrate. The standards were characterized by TEM resulting in a size distribution compatible with the values provided by the manufacturer, and spherical shape. The z-potential of the mother dispersions was measured confirming their good stability (<-40 mV). Details on the experimental procedures for characterization of the standards, representative TEM images and a summary of their size/shape parameters and z-potential can be found in the appendix. The measured size of the standards was used for all calculations, but for simplicity, we refer to their nominal diameter throughout this paper. The exact mass concentration as total Ag of the mother dispersions was also measured by ICP-MS, and number concentration was calculated based on the experimental mode of the size distribution.

The commercial dressing Acticoat Flex3™ (Smith & Nephew) was used for the *in vitro* incubations and the *in vivo* treatment of burnt patients as reported elsewhere [32]. The mobile phase for chromatography was prepared using sodium dodecyl sulphate (SDS), HNa_2PO_4 dihydrate and IGEPAL® CA-630 nonionic detergent in the following concentrations: SDS 0.05 % v/v, HNa_2PO_4 0.002 M and IGEPAL 0.1 % v/v at pH 7.4. A water solution containing tetramethylammonium hydroxide (TMAH) 0.1 % v/v, NH_4OH 2.8 % w/w and Triton™ X-100 0.1 % v/v was used to dilute 20-fold the whole blood for total Ag determination by ICP-MS. L-glutathione reduced (GSH) and human serum albumin (HSA) lyophilized powders were used for incubation experiments. All incubations were carried out in a normal laboratory environment at 37 °C in a thermostated bath, under constant gentle shaking in the dark. The preparation steps for standards and samples were carried out in a class 1000 clean room environment under a class 100 laminar flow bench.

Whole human plasma for incubations and control whole blood were provided by distinct volunteers and were collected at the University Hospital of Padua. Four samples of whole blood were provided by the bio-bank of the same Hospital, and were collected from three adult patients treated in the same Hospital, at the Burns Center, following the current protocols without any additional invasive procedure. The patients did not present any pathology other than the burn. All samples were collected and stored in agreement with the guidelines of the University Hospital of Padua and informed consent of the patients was obtained according to the Helsinki Declaration. The blood was collected in purple-tip vials (K2-3EDTA) in order to prevent coagulation, was immediately frozen to lyse the red blood cells, and was stored frozen until analysis.

Instrumentation

The chromatographic system consisted of an Agilent Technologies (Tokyo, Japan) 1200 series HPLC pump fitted with an HDC 5-300 Type-1 column (linearity range from 5 to 300 nm) from the same supplier. Sample injections were performed manually using a 100 µL loop and an inert Rheodyne injection valve. The elution was performed in isocratic mode at a flow rate of 1.0 mL min^{-1}. An ICP-MS detector model 7500cx from Agilent Technologies was coupled on-line to the chromatographic system by using a polypro nebulizer mounted on a double-pass Scott spray chamber thermostated at 2°C. The instrument operated at 1500 W RF power with a carrier gas flow rate of 1.1 mL min^{-1} and make up gas flow rate of 0.1 mL min^{-1}. The lens voltages were tuned daily for best sensitivity using a 1 ng mL^{-1} solution of Ag. In order to minimize the matrix effects, robust plasma conditions were achieved by, keeping oxides and double charges rates below 2 % based on the response of a Ce 1 ng mL^{-1} solution, and using 8 mm of sample depth. Acquisition was carried out by monitoring both the isotopes of Ag (m/z 107 and 109) with a dwell time of 5 ms. Automatic correction for the dead time was adopted, the parameter was estimated as reported elsewhere [33]. A settling time of 2 ms was automatically selected by the instrument and was taken into account to correct the calibration of NPs number concentration, as reported below.

Synchrotron radiation µXRF and Ag L_{III}-edge µXANES measurements were performed using the scanning transmission X-ray microscope of beamline ID21 at the European Synchrotron Radiation Facility (ESRF, Grenoble, France). Details on standards/sample preparation, instrumental parameters and data elaboration for µXRF and µXANES are provided as supporting information.

Data elaboration

Data treatment for HDC-spICP-MS was carried out by using a home-made program written in Fortran language and run using the compiler Compaq Visual Fortran (Compaq Computer Corporation). The program reads the ICP-MS raw data file directly and provides a number of output files including overall statistics and matrices. The latter were directly imported in Surfer 11 (Golden Software) for graphical elaboration of the contour plots (3D chromatograms). Excel

spreadsheets (Microsoft), OriginPro 8.5 (OriginLab) and Statistica 10 (StatSoft) were used for additional calculations and graphical elaboration. PyMca [34] and Athena [35] software were used to elaborate the µXRF and µXANES data.

2. Results and discussion

2.1. Implementation of data analysis

2.1.1. Dwell time and data pre-processing

The limit of detection (LOD) in spICP-MS has two possible interpretations: as the lowest detectable particle size (LOD_S^{NP}) and the lowest detectable particle number (LOD_N^{NP}). Measuring simultaneously the dissolved Ag introduces also a third definition, which is the lowest detectable concentration of this fraction (LOD_C^D). The choice of the dwell time is the key to determine ~~the limit of detection~~ all these ~~(LOD)~~parameters in samples where both NPs and dissolved Ag are present, and the overall statistical reliability of the results in spICP-MS. Individual NPs in ICP-MS generate transient signals with a temporal width of 0.3-0.5 ms [36]. Recent instrumentation allows setting the dwell time within the µs range, so that single events can be described by multiple data points. This results in a significant reduction of the background, a decreased LOD_S^{NP} ~~dimensional LOD for the NPs~~ and an improved range of number concentration [37]. However, the same increase in the signal-to-background ratio is expected to make more difficult the determination of the dissolved Ag by statistical deconvolution within the same analysis, increasing the LOD_C^D. Moreover, with µs dwell times, the probability to observe split of events between adjacent time windows must be taken into account [30], and the electronic and computational load due to data size can be potentially problematic when applied to hyphenated techniques, where the acquisition lasts for tens of minutes. Conversely, conventional ms dwell time leads to higher LOD_S^{NP} ~~LOD for the mass-derived diameter~~ and requires higher dilution of the samples to avoid detecting multiple events within the same time window [30], but it is more suited for performing the simultaneous determination of dissolved Ag and using hyphenated instrumental approaches. According to other authors, a dwell time in the range of 3-5 ms is adequate to achieve good quality data in our context [38]. The minimum dwell time that can be set on our instrument for the acquisition of a single m/z is 10 ms, but a dwell time of 5 ms can be chosen by monitoring both masses of Ag. This required a data pre-processing step for normalization of the two signals to the relative natural abundance of each respective isotope, before merging them into a single chromatogram. Given the proximity of the two abundances (0.518 For ^{107}Ag and 0.482 for ^{109}Ag), the difference in signal intensity for the two masses is negligible at low counting rates, but was nevertheless taken into account when applying the threshold in the following deconvolution step. In addition, the acquisition of two masses introduces a settling time, which slightly affects the number of detected particles (see section 2.1.4.).

2.1.2. Deconvolution of the signals

The expected forms of dissolved Ag in plasma (protein complexes) have hydrodynamic diameters smaller than the LOD_S^{NP} ~~LOD of mass-derived diameter for NPs,~~(see section 2.1.4.), and close to the lower limit of separation range. Given also the poor resolving power of HDC, their peak cannot be chromatographically –resolved from those of ~20 nm particles, thus making deconvolution a necessary operation. In this work, the statistical deconvolution of the signals from dissolved Ag species and AgNPs was based on a nonparametric statistical test applied to each data point of the chromatogram as it was sequentially scanned. The intensity value of each point was compared to that of its two adjacent neighbours, and their difference was calculated. If at least one of the two

differences overcame a threshold value given by the maximum expected difference between any data generated by dissolved Ag, the hypothesis of the point being associated to dissolved forms was rejected. For each pair of points to be compared, the relative threshold value was specifically calculated as a negative exponential function of the lower of the two intensities. The function was externally calibrated on the chromatogram of a single standard of dissolved Ag with a relatively high concentration (500 pg mL^{-1}) using the following procedure. The chromatogram was divided into consecutive windows of 2 s width, in which the signal was assumed to be stationary. For each window, the empirical distribution of the data was calculated to extract the 1^{st}-to-99^{th} interpercentile range. The range was plotted against the average value within the same window as shown in Fig. 1a. The interpercentile range can be interpreted as the maximum difference in signal intensity between two data points generated by dissolved Ag at a 98 % confidence level, and was adopted here as the threshold value to discriminate the signals. The vector of points for which the hypothesis of being generated by dissolved Ag was rejected, constituted the NPs extracted chromatogram.

2.1.3. Elaboration of the 3D NPs raw chromatogram

The NPs chromatogram was firstly treated by converting the normalized signal intensities into their cube square. This step was necessary to obtain final chromatograms in which the mass-derived diameter is represented on a scale with uniform resolution. In a second step, the dimensions of elution time and normalized signal intensity were gridded into windows of selected width according to the procedure proposed by Pergantis et al. [28]. The width of the intensity windows was fixed at 0.6266 normalized $counts^{1/3}$, resulting in a resolution of 6.5 nm for the mass-derived diameter after calibration. The width of the elution time windows was fixed at 5 s in order to contain 714 data points to guarantee statistical representativity. After gridding, the number of events detected within each window was counted, and a raw 3D chromatogram was yielded as a 3-columns matrix consisting of the central values of the elution time (x-axis) and the normalized events' intensity (y-axis), and the number of detected events (z-axis) for each window.

2.1.4. Calibrations and elaboration of the 3D NPs final chromatograms

Besides the threshold function, other external calibrations based on the injection of monodisperse NPs standards were necessary to convert the normalized signal intensity into mass-derived diameter, and the elution time into hydrodynamic diameter. Standard suspensions with a 20, 40, 60 and 100 nm nominal size and variable concentration were injected to calibrate these two parameters as done by Pergantis et. al. [28]. For each standard, the mode of the 3D raw chromatogram provided the data to be included in the calibration curves, which are shown in Fig. 1b,c. A LOD_S^{NP} ~~LOD for mass-derived particles' size~~ of 16 nm was calculated as 3 times the standard error of the intercept of the mass calibration curve. This value is in agreement with the range of those estimated by other authors both theoretically and experimentally (in water samples) using spICP-MS [22]. The extrapolation of the number concentration of AgNPs in a sample required estimating separately their ~~detection~~ transport efficiency ~~of NPs~~through the nebulization system~~, which corresponds to their transport efficiency corrected for the settling time~~. Adapting the formula by ~~According to~~ Pace et al. [39], the overall number of detected particles n_r of radius r, using the hypothesis of purely metallic and spherical particles, can be expressed as:

$$n_r = \eta \cdot \frac{c_r^m}{\frac{4}{3}\pi r^3 \rho} \cdot v \cdot \frac{t_i}{t_s + t_i} \qquad \text{eq.1}$$

where η is the transport efficiency (independent by the radius), c_r^m is the mass concentration of the NPs (pg mL^{-1}), v is the injection volume (mL), ~~and~~ ρ is the density of Ag in pg nm^{-3} = 1.049 ·10^{-8},

t_i is the integration time and t_s is the settling time~~.~~. The transport efficiency can be estimated by analyzing a series of standards of any radius at different known mass concentrations, calculated as the slope of the regression line in eq. 1. However, one should note that even if approximately monodisperse, a standard suspension still has a characteristic size distribution which may be not perfectly symmetric, particularly for the size ranges close to the LOD_S^{NP} ~~LOD~~, so that simple counting the overall number of detected particles would introduce a bias. In order to overcome this potential problem, we used the calibration of mass-derived diameter to convert the number of detected particles into a mass for each window of the raw chromatogram. Summing the mass of all windows provided the total detected mass of Ag, to be used in place of n_r for efficiency estimation. The method was tested on four nominal particles sizes, as shown in Fig. 1d. Consistently with the independence of η from the particles' size, an average value of 1.78 ± 0.07 % was obtained for the four calibrations. If a minimum number of 3 detected particles is arbitrarily adopted as the statistical treshold to verify their presence, taking into account the transport efficiency, settling time and injection volume, a LOD_N^{NP} of ~2300 particles mL^{-1} is achieved. This threshold can be indifferently adopted for all particles or for specific size classes~~which is very close to that (~1.7 %) obtained by Pergantis et al. [28] using the number of detected gold NPs with 60 nm size, and a V-groove nebulizer~~. Finally, a calibration was also required for the dissolved Ag fraction by injecting standards of ionic Ag with variable concentration as shown in Fig. 1e, obtaining a LOD_C^D ~~LOD~~ of 13 pg mL^{-1}.

All calibrations reported above allowed to convert the data of the 3D NPs raw chromatogram for each sample into a final chromatogram representing the experimental distribution of NPs in terms of number concentration or mass concentration depending on the hydrodynamic diameter and mass-derived diameter.

2.2. Stability of the AgNPs in the mother standards and in mobile phase.

The mother citrate-stabilized dispersions were stored at 4°C and no significant changes in their size distribution were noticed after more than 1 year (as observed by TEM). In addition, no peaks of dissolved Ag were detected by HDC-ICP-MS when injecting single standards freshly diluted in mobile phase for calibration within the same time span. The temporal stability of AgNPs standards in the mobile phase below the ng mL^{-1} level was also checked. Despite the appearance of small peaks of dissolved Ag was observed after leaving the vials exposed to light and room temperature up to 24 h, the corresponding concentration was below the LOD_C^D ~~LOD~~ for all particle sizes. Nevertheless, in order to avoid any potential alteration of the dynamics of AgNPs due to interaction with the mobile phase, all standards for calibration were always prepared freshly from the mother dispersion and immediately injected, all samples were analysed immediately after preparation, and replicates were obtained from independent preparations rather than from repeated injections.

2.3. Dynamics of AgNPs incubated in human plasma

The developed method was used to study the dynamics of AgNPs in human plasma. Standards with nominal diameters of 20, 40, 60 and 100 nm were mixed in whole plasma at concentrations of 10, 16, 37 and 100 ng mL^{-1}, respectively, sonicated for 1 min and then incubated for 2 h. After incubation, the sample was diluted 20-fold in the mobile phase and directly injected without further sonication. A control sample was prepared by diluting the AgNPs mixture in the mobile phase at the same final concentration, followed by sonication for 1 min, and direct injection. Fig. 2 shows the final 3D chromatograms obtained for the control and plasma incubated mixtures. A number of significant changes were observed in the distributions of NPs after 2 h of incubation in plasma: i) a slight general decrease in the mass-derived diameter; ii) a significant decrease in the

number and mass concentration of the NPs; iii) a generalized shift in the distribution towards the higher hydrodynamic diameters of 10-20 nm. While the first two effects can be ascribed to a partial dissolution of the NPs, the increased hydrodynamic diameter is compatible with two possible phenomena: agglomeration of NPs and the formation of a protein corona onto their surface. The agglomeration of uncapped NPs is a feasible process in plasma, particularly due to the relatively high ionic strength of the medium [3]. We did not observe the appearance of new modes in the mass-derived diameter corresponding to multiples of the nominal diameters of 40, 60 and 100 nm. However, agglomeration effects cannot be excluded for the 20 nm particles due to the theoretical superimposition of the multiples of their mass on the modes of the other standards. Conversely, the formation of a proteins corona is a plausible generalized process, particularly due to the interaction of thiol groups in amino acids with the charged surface of AgNPs in a medium with a high ionic strength [40,41].

In order depict the temporal dependence of the dynamics of AgNPs in human plasma, the standard suspension with a 100 nm size was selected for further incubation experiments. An aliquot of the mother monodisperse suspension (20 µg mL^{-1}) was sonicated for 1 min, then mixed 1:1 with plasma and incubated for 24 h. At time steps of 2, 4, 6, 8, 16 and 24 h, aliquots of the solution were collected, diluted 10,000-fold in the mobile phase, and analyzed immediately. Fig. 3a shows that the dissolution of AgNPs is not linearly time-dependent on an hourly scale in a closed system. The most significant change was observed between the 4 and 8 h incubations, with a decrease in the molar fraction of Ag present in the original form of NPs, corresponding to the appearance and increase of the dissolved fraction. Between 16 and 24 h the molar fractions seem to reach equilibrium. The precision of detection efficiency (~ 4 % of relative error, see paragraph 2.1.), which affects the estimated number concentration, is the dominant source of uncertainty for AgNPs molar fraction. The calibration of dissolved Ag is more reproducible because the relative error of the slope of its calibration curve (Fig. 1e) is 1 %. The mass-derived diameter of the particles exhibits a substantial linear decrease from 100 to 80 nm in 24 h (Fig. 3b), confirming the partial dissolution of the individual particles. In this case, the standard deviation among replicates is zero because their differences are smaller than the width of the signal intensity windows adopted for gridding (see paragraph 2.1.3.). Thus, for each estimated diameter *d*, the width of the gridding windows ± 6.5/*d* % can be considered as the maximum theoretical uncertainty, and was taken to represent the whiskers in Fig. 3b.

Speciation analyses by µXANES were carried out on analogously incubated samples. Standards of AgNPs with a 10 nm size (20 µg mL^{-1}) and ionic Ag solution (nitrate, 10 µg mL^{-1} as Ag) were incubated in a water solution containing HSA (~ 0.5 mg mL^{-1}) and in whole plasma. After 2 h a drop of each solution was freeze-dried between Ultralene® windows and was directly analyzed by µXANES. Representative spectra for each of the incubated standards and pure species of Ag, as shown in Fig. 4a-b, allowed us to identify the chemical forms of Ag after incubation and their relative molar fractions estimated by linear combination fitting (LCF), as reported in Table 1. The µXANES analysis showed that after 2 h of incubation in HSA the Ag^+ ions were mostly complexed by thiols (represented by the Ag-GSH bound). Conversely, AgNPs remained intact almost quantitatively, even if Ag-thiols were also detectable. This confirms that the formation of a protein corona on the surface of AgNPs has a major inhibiting effect on their dissolution in the short term. Differently, in whole plasma, the early dynamics of Ag were dominated by chlorides, with formation of insoluble AgCl from free Ag^+, and significant agglomeration of the AgNPs, as marked by the high weight of the metallic Ag foil spectrum obtained by LCF.

2.4. Dynamics of AgNPs agglomerates released from a dressing incubated in human plasma

The 2 h incubation experiment in whole plasma was carried out also by using the intact dressing Acticoat Flex3^{TM}. The dressing consists of a net of polyethylene fibers, individually and uniformly coated with a layer of uncapped AgNPs of 10 nm size; other characteristics of the product can be found elsewhere [33]. Previous experiments showed that the dressing releases AgNPs as agglomerates with widely variable size *in vitro* in human serum substitute [42], and agglomerates were also detected in the fibroblasts of burnt patients after 7 days of treatment [32]. In this experiment, 2.45 mg of the dressing (0.32 mg as Ag) were dipped into 1 mL of whole plasma and sonicated for 10 min to accelerate the release of AgNPs as individual particles or small agglomerates. After 2 h of incubation, the plasma was centrifuged at 3000 rpm for 10 min in order to remove the fibers, cloth debris and micrometric agglomerates of AgNPs, then an aliquot was diluted 100-fold in the mobile phase and directly injected into the chromatographic system. The 3D chromatograms in Fig. 5a-b show a few particles with size >16 nm, corresponding to small agglomerates of 2-5 NPs with 10 nm size. Significantly higher hydrodynamic diameters, with respect to the mass-derived diameter, were also observed. The latter effect supports the hypothesis that the observed particles are small (non-spherical) agglomerates, and is also compatible with additional proteins capping effects. The dissolved Ag fraction resulted lower than the ~~LOD~~ LOD_C^D.

A 20 µL aliquot of the same sample after incubation was collected before centrifugation, was freeze-dried and analyzed by µXRF and µXANES. Preliminary µXRF mapping of the sample allowed us to detect a number of micrometric agglomerates of AgNPs or fragments of the dressing. A region surrounding one of the particles was selected, and the distribution of Ag, Cl and S was mapped as shown in Fig. 6a. A characteristic non-uniform accumulation of Cl was observed at the border of the Ag particle, while S was uniformly distributed in the surrounding medium. µXANES spectra were collected in the same region for each pixel to be individually elaborated by LCF in order to extract a coarse estimation of the molar fraction of the three main expected species: intact AgNPs, AgCl and Ag-thiols. The resulting µXANES map is shown in Fig. 6b. Although total Ag and Cl presented widely different distributions, a relatively uniform distribution of the Ag species was observed, consistent with the participation of the whole surface of the AgNPs agglomerates in the chemical dynamics of the metal. The average molar distribution of the species within the entire region was 49 % AgCl, 22 % AgNPs and 20 % Ag-thiols (9 % unidentified species). The overall distribution was also estimated by firstly merging all the spectra within the region, and then performing the LCF on the pooled spectrum. This procedure allowed us to weight the contribution of each pixel on the base of the total Ag level, and provided the values: 53 % AgCl, 31 % AgNPs and 15 % Ag-thiols. Compatibly with Fig. 6b, the slight variations with respect to the previous estimation are consistent with a major localization of AgCl and AgNPs in the regions with elevated Ag level, while Ag-thiols are mainly present in the peripheral areas. The assignment of previously unidentified species could also have affected the latter values. The co-presence and relative proportion of the three species reveal that the dynamics of AgNPs in plasma involve integrated and complex processes. Free Ag ions are expected to be a negligible fraction in biological systems due to the high formation constant for chloride and thiol bonds [43,3], so that dissolution and formation of complexes may take place directly on the surface of the AgNPs as an integrated process. Properties of the medium such as its general composition, concentration of chloride and pH, and kinetics of complexation influence the dynamics. Although protein thiols should be thermodynamically favoured for Ag binding in plasma with respect to chlorides [6,3], our data support the hypothesis that the latter have a kinetic advantage when interacting with Ag ions directly on the charged surface of the bare NPs, leading to an early effect of partial dissolution, and possibly agglomeration of the smallest NPs. Still, protein thiols may co-participate to these dynamics by enclosing the particles and superficial chlorides, inhibiting further interactions with

the medium, the removal of AgCl from the surface and further agglomeration effects. Given the affinity of thiols for Ag, subsequent displacement of the metal from the chlorides is likely, resulting in its final mobilization. In agreement with Liu et al. [3], thiols binding appears to be the limiting process in regulating the dissolution of AgNPs in plasma, and the mediator for systemic distribution of the metal, but our findings suggest that kinetic factors play a crucial role in this complex dynamics.

2.5. Whole blood from burnt patients treated with a AgNPs-containing dressing

In addition to the temporal dynamics of the chemical transformations of AgNPs, the particles could also undergo simultaneous mobilization through the tissues, with consequent change in the properties of the surrounding medium. The formation of a proteins corona is probably the main favouring factor for the cellular uptake on AgNPs [41], which has been observed in human skin both *in vitro* and *in vivo* in burnt patients [32]. However, the few available experimental data suggest that the metal has a poor capability to penetrate the skin in depth, even if penetration may be enhanced in damaged tissue [32,44].

In order to evaluate the actual potential of AgNPs to reach the bloodstream before dissolution, we used HDC-spICP-MS to analyze four whole blood samples collected from three adult patients (A-C) treated for mid-thickness skin burns with a single application of the dressing. The main clinical information is summarized in Table ~~1~~2. The patients had a comparable % of burned body surface, which represents the wound area exposed to AgNPs. Three blood samples were collected from distinct patients 3 days after the application ~~of the dressing~~; and an additional sample was collected from patient A after 6 days of treatment. Compatibly with our previous estimations that the dose of Ag released by the dressing into the patient's tissues *in vivo* would be elevated [33], a significant level of total circulating Ag was observed in all patients after 3 days of application of the dressing (Table 2). The values ranged between ~30 to 80 ng mL^{-1} and were more than 2 orders of magnitude higher than the baseline level in an unexposed population [45], and slightly lower than those observed in the serum of paediatric burnt patients treated with the same dressing (average 114 ng mL^{-1}) [46]. Differently from the latter cited work, we did not observe any apparent correlation between blood Ag and the percentage of burnt body area, and just a slight increase in Ag was noticed after 3 additional days of application for patient A.

An aliquot of the blood was then centrifuged at 3000 rpm for 10 min to remove the cell debris in order to avoid clogging the chromatographic system. The surnatant was recovered and analyzed for total Ag. The average recovery of total Ag after centrifugation was ≥ 96 % for all samples except patient C (76 %), and a minimal loss of Ag due to co-precipitation was therefore assumed for most cases. The possibly co-precipitated Ag can be ascribed to its association to cellular debris and large biomolecules whose size exceeds the effective separation range of the HDC system. Based on the total concentration of Ag, the centrifuged samples were diluted in the mobile phase according to specific dilution factors (see Table 2), optimized to obtain the same final concentration of ~400 pg mL^{-1} of Ag. This target value was selected from preliminary tests as the optimum concentration for detecting a significant number of AgNPs with a mass-derived size close to the LOD_S^{NP} ~~LOD~~ under the hypothesis that they were present as a significant molar fraction of Ag (> 10 %).

We did not detect any significant event associated to AgNPs agglomerates >16 nm in the four blood samples (chromatograms are not shown). Conversely, from the chromatograms of dissolved Ag shown in Fig. 7, an average molar fraction of 94 ± 9 % was estimated for the dissolved species (see Table 2), which is not statistically different from the total level of the metal.

Considering that: i) our previous studies have shown that in burnt patients treated with Acticoat Flex3^{TM}, AgNPs are released as agglomerates and maintain this form even in the tissue; ii) a poor dermal penetration of PVP-coated AgNPs, restricted to small (<30 nm) particles in damaged skin, was observed *in vitro* [44]; and iii) we documented here that small AgNPs exhibit both agglomeration and partial dissolution effects at an hourly time scale in plasma; the results of blood analysis strongly support the hypothesis that the systemic mobilization of Ag is driven by the *in situ* dissolution of NPs in the skin. The first medium entering in contact with the AgNPs released by the dressing onto the wound bed is the exudate, whose composition is similar to the serum. This medium is the major candidate to host the *in situ* transformations of AgNPs, where dissolution may be also enhanced by the lower pH (5.7), typical of the inflammatory phase in wounds [47]. It is also likely that the reduced blood circulation in burns further inhibits the dispersion of AgNPs. However, let us keep in mind that the specific local characteristics of the wound may dramatically affect the release of AgNPs from the dressing and the composition/production/turnover of the exudate. This can lead to significantly different AgNPs dynamics at a local level, resulting in the possible penetration of agglomerates into the shallow tissue layers. Photochemical reduction of Ag complexes with formation of secondary Ag/S/Se particles can also occur in the skin [3]. We previously observed a few electron-dense particles in skin biopsies after application of the dressing, which are potentially representative of photoprecipitation [32]. However, this phenomenon appears to be limited to the most severe lesions, which require long-term treatments and replacement of the dressing, leading to exposure to light and an increased Ag dose.

3. Conclusion

The exponentially growing market of consumer and medical products containing AgNPs has raised the urgent need for regulatory standards targeted at health and safety. Developing adequate analytical methods to achieve detection and characterization of AgNPs and their ionic counterpart in biological media is the key requisite to support regulatory requirements with robust scientific evidence.

An innovative method is proposed here for the simultaneous determination of dissolved Ag and the characterization of AgNPs in human plasma and blood. By coupling HDC separation, spICP-MS detection and a dedicated algorithm for data elaboration, comprehensive information on the chemical state of the Ag^{+}/AgNPs system can be retrieved in a~~one~~ single analytical run. While HDC separates the NPs based on their hydrodynamic diameter and spICP-MS provides information on their mass distribution, both techniques have the potential to discriminate physically and statistically (respectively) the signal of NPs from that of dissolved Ag, but this advantage was not exploited before. We combined the two techniques and a home-made software based on a new algorithm able to process the raw ICP-MS chromatogram for deconvoluting the signal of dissolved Ag from that of AgNPs. From a single injection, the method provides the chromatogram and concentration of dissolved Ag; the distribution of NPs in terms of hydrodynamic diameter, mass-derived diameter, size-dependent number of detected NPs; the total number concentration and size-dependent mass concentration of the NPs. A variety of 3D chromatograms can be obtained from the results to achieve a comprehensive characterization of AgNPs.

The method is robust when applied to heavy matrices such as plasma and blood, and in principle can be extended to other biological media and to other metallic NPs. The algorithm in particular is suitable for the deconvolution and determination of particulate and dissolved fractions independently by the element, or just for the removal of non-stationary background in any separation technique coupled to spICP-MS.

Combining the method with ~~other techniques, such as~~ μXANES speciation and imaging~~,~~ provides an integrated approach which opens the way to elucidate the dynamics of AgNPs in biological fluids or extracts *in vivo* under realistic conditions (real human subjects, real administered doses).

~~-~~We applied this strategy to study the behaviour of AgNPs standards and of an AgNPs-coated dressing incubated in human plasma, and to investigate for the first time the capability of AgNPs to reach the systemic circulation after topical application to burnt patients.

The results showed that partial dissolution of uncoated AgNPs takes place in plasma on an hourly time scale with nonlinear dynamics in a closed system. Chlorides and protein thiols co-participate in the process through complex temporal and spatial mechanisms, forced by kinetic factors. The early dynamics and dissolution of AgNPs are dominated by interaction with chlorides directly on their surface. Formation of a protein corona takes place in the meantime, resulting in the inhibition of further reactions with the medium, slower displacement of Ag from chlorides and final mobilization of the metal. As a whole, thiols binding is proposed as the main regulator of AgNPs dissolution in plasma and of the systemic distribution of the metal. The analysis of whole blood from burnt patients suggested that the dynamics of AgNPs dissolution after topical administration takes place mainly *in situ*, most probably in the exudate, so that their potential to undergo systemic distribution in the intact form is minimal. Further studies are currently in progress to investigate the chemical speciation of Ag directly in wound tissues.

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Disclaimer: The authors declare that they have no conflict of interest.

Appendix

Characterization of the commercial AgNPs standards dispersions

The morphological characterization of the mother AgNPs standard dispersions was carried out by TEM using a Tecnai 12 G^2 instrument (FEI, USA). For the analysis, a 3 μL drop of each dispersion was deposited on a support Formvar/Carbon on 200 mesh thick grid, let dry at room temperature and directly analysed. The images were acquired at 120 kV high voltage and using tungsten filament, twin optics and an Olympus side-mounted camera. The software ImageJ (National Institutes of Health, USA) was used for particles' counting and shape characterization. Representative TEM images of the standard NPs and a summary of their size/shape parameters are shown in Fig. 8 and reported in Table 3, respectively.

The z-potential was measured by using a Zetasizer Nano (Malvern, UK) at 24°C in DTS1070 cells pre-washed with a citrate 60 μg mL^{-1} water solution. For the analysis, each standard suspension was sonicated for 5 min, equilibrated for 120 s in the cell, and 5 replicate measurements of 10 to 100 readings were acquired. The z-potential of the standard NPs is also reported in Table 3.

Total mass concentration of Ag in the standards was measured by ICP-MS *previa* dissolution in HNO_3 5% v/v and subsequent dilution in NH_4OH 2.8 % w/w. The analysis was carried out in full-quant mode by external calibration with Rh as internal standard.

Methods for µXRF and µXANES analyses

Standards and samples

Solid-state reference compounds for µXANES included: Ag^0 foil, AgCl, Ag_2SO_4, $AgNO_3$, Ag_2O, Ag sulfadiazine (AgSD) and a fragment of intact dressing Acticoat Flex3™. Reference standards of Ag^0NPs 10 and 100 nm were prepared from mother water suspensions (citrate stabilized, 20 µg mL^{-1} as Ag) by deposition of a 20 µL drop between Ultralene® windows and microscopy slides, followed by rapid freezing and freeze-drying for 24 h. A standard of Ag bonded to GSH was prepared by incubating ionic Ag (from $AgNO_3$, 10 µg mL^{-1} as Ag) in a water solution of GSH ~0.5 mg mL^{-1}, at 37° C under gentle shaking for 2 h and in dark conditions, followed by freeze-drying as reported above. Standards of Ag^0NPs 10 nm, ionic Ag and the intact dressing Acticoat Flex3™ (2.45 mg fragment) were also incubated in a water solution containing HSA, (~0.5 mg mL^{-1}) and in whole human plasma, freeze-dried as reported above, and analyzed as unknown samples.

Instrumental parameters and data elaboration

The µXRF and Ag L_{III}-edge µXANES measurements were performed using the scanning X-ray microscope of beamline ID21 at the European Synchrotron Radiation Facility (ESRF, Grenoble, France), working at room temperature conditions. Detectors included a Si_3N_7 diode for I_0 and an 80 mm active area Silicon Drift Detector (Bruker) for the emitted fluorescence. Focusing was achieved using fixed curvature Kirkpatrick-Baez mirror optics. The photon flux was 3.6 x 10^9 ph s^{-1} at 3.42 keV with a beam size of 1.0 x 1.2 µm².

µXRF maps of signal intensities for individual elements (Ag, S and Cl) were collected for preliminary analysis to select optimal regions for the subsequent µXANES analysis. The µXRF maps were acquired with variable lateral resolution (0.5 to 2 µm) and integration time of 100 ms. The raw data (counts) were elaborated using the PyMca software as follows: i) correction for the settling time and conversion to counts per second (cps); ii) deconvolution (batch fitting of the µXRF spectra); iii) normalization for the incident beam flux.

Batch Ag L_{III}-edge µXANES spectra of 30 s were collected and averaged for each spot of interest from 3.32 to 3.42 keV energy range with 0.5 eV steps. The beam position was slightly moved from one spectrum to another to avoid radiation damage. At least 10 spectra were averaged for each region of interest. After background removal and normalization, the spectra were calibrated by taking the first inflection point of at 3.3545 keV and then smoothed by interpolation with 5 iteractions. The µXANES spectra of Acticoat Flex3™ and HSA/plasma incubated standards were treated by LCF using the Athena Software with the following set of reference spectra as independent variables: Ag^0 foil, Ag^0NPs 10 nm, AgCl, Ag_2SO_4, $AgNO_2$, Ag_2O, AgSD and AgGSH. A linear term was allowed to compensate for small differences in data normalization, no energy shift was allowed, and weights and their sum were forced to sum to 1. The energy range used for fitting was 3.3345 to 3.4145 keV (e0 - 0.02 to e0 + 0.06). The quality of fitting was quantified by the normalized sum-square residuals $NSS = \Sigma(\mu experimental - \mu fit)^2/\Sigma(\mu experimental)^2 \times 100$, where µ is the normalized absorbance. Linear combinations of one, two and three reference standards were examined. The best fit with n+1 components was retained if NSS was decreased by more than 15 % as compared to the best fit using n components. Based on the results, four main Ag species were revealed in the samples: Ag^0 foil, Ag^0NPs 10 nm, AgCl and AgGSH; the other minority species were pooled as "other". When two or more fits of equivalent quality (relative difference of

NSS < 10 %) were obtained with different combinations of such a minority species, proportions and NSS were expressed as mean percentage with standard deviation (SD) between brackets, calculated for the equivalent fits.

The µXANES spectra acquired in fluorescence mapping mode by scanning the beam with a 2 x 2 μm^2 step size and a 50 ms dwell time per pixel with 3 eV energy steps in the region from 3.320 KeV to 3.341 KeV, 0.5 eV from 3.341 KeV to 3.381 KeV, and 1 eV from 3.382 KeV to 3.42 KeV. This resulted in a total of 126 images recorded using a region of interest selective for Ag L3M4 and L3M5 emission lines, corrected for detector dead time (always kept below 20%) and normalized by the incident beam flux. The stack of images was converted to an hdf5 file containing intensities and the energy values for each map to be processed using PyMca for µXANES spectra extraction. The map was treated by moving merge of the spectra on 2 x 2 pixels areas and with 1 pixel step, in order to reduce the noise and improve the statistical representativity. After background removal and normalization, the spectra were calibrated and individually processed by LCF as above, but using only the reference spectra of Ag^0NPs 10 nm, AgCl, and AgGSH as independent variables. Based on visual inspection of the fits, an arbitrary threshold of NSS < 0.1 was adopted to remove from the map the pixels with insufficient quality of the fit. A number of pixels in the upper right side of the map (see Fig. 4b) were discarded based on this criterion. These pixels were affected by the sharp change in intensity at the border of the analyzed particle coupled to beam drift caused by scanning the energy with the double crystal monochromator. The retained pixels were re-processed by LCF testing all combinations in which one of the three reference standard was removed. Each standard was considered significant if its introduction decreased the NSS by more than 3 %. This threshold was calibrated *a posteriori* to guarantee that all pixels in the map had at least one significant component, and a coefficient equal to zero was assigned to the non significant components. For each pixel, the coefficients were finally multiplied for the corresponding signal intensity of total Ag (from the µXRF map), also treated by the moving merge procedure, to obtain the absolute contribute of each species expressed in cps.

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Table 1 Semiquantitative speciation of Ag in the dressing Acticoat Flex3™, 10 nm size AgNPs and ionic Ag incubated in solutions containing HSA or in whole human plasma for 2 h. Data were obtained by LCF of the μXANES spectra; the AgGSH standard is representative of Ag-thiol bonds.

Experiment	Species	Molar fraction %
Ag^0NPs 10 nm in plasma	Ag^0 foil	66
	Ag^0NPs 10nm	28
	other	6
Ag^+ in plasma	AgCl	63
	other(x2)	37
Ag^0NPs 10 nm in HSA	Ag^0NPs 10nm	93
	AgGSH	7
Ag^+ in HSA	AgGSH	67
	other	33
Acticoat Flex3™	Ag^0NPs 10nm	66
	Ag^0 foil	34
Acticoat Flex3™ in plasma	AgCl	59
	Ag^0NPs 10nm	32
	AgGSH	10

Table 2 Main clinical information on the burnt adult patients treated with Acticoat Flex3^{TM}, and concentration of total Ag and dissolved Ag fraction in their whole blood.

	Patient A		Patient B	Patient C
Burn location	Torso + left arm		Torso	Torso + arms
Burned body surface, %	22		27	30
Degree	II		II	II
Dermabrasion	yes		yes	yes
Treatment duration, days	3	6	3	3
Total Ag in blood, ng mL^{-1}	46.6	48.9	83.1	36.9
Total Ag in centrifugated blood, ng mL^{-1} (recovery %)	44.5 (96)	46.7 (96)	81.4 (98)	28.1 (76)
Dilution factor	100	100	250	75
Dissolved Ag in centrifugated blood, ng mL^{-1} (molar fraction %)	37.9 (85)	41.6 (89)	83.9 (103)	28.0 (100)

Table 3 Characterization of the AgNPs standards (mother suspensions) used throughout the study. Particles' diameter and geometry were measured by TEM on a minimum sample of 400 particles; for the z-potential n = 5.

Nominal size ± SD (nm)	Measured diameter (nm): Median (interquartile range) Average ± SD Mode	Geometry: Circularity ± SD Roundness ± SD Solidity ± SD	z-potential (mV)
10 ± 4	8.6 (7.1 – 10.8) 9.2 ± 3.2 7.2	0.90 ± 0.03 0.91 ± 0.06 0.95 ± 0.01	-46.4 ± 2.2
20 ± 4	22.2 (20.7 – 23.5) 21.9 ± 2.4 23.1	0.90 ± 0.02 0.91 ± 0.05 0.95 ± 0.01	-46.6 ± 2.0
40 ± 4	40.7 (40.2 – 45.1) 42.4 ± 3.8 43.5	0.89 ± 0.02 0.90 ± 0.05 0.96 ± 0.01	-45.3 ± 1.7
60 ± 4	56.4 (50.6 – 59.7) 56.5 ± 4.5 58.7	0.89 ± 0.02 0.89 ± 0.06 0.96 ± 0.01	-48.6 ± 1.2
100 ± 4	98.7 (95.6 – 102.3) 99.0 ± 5.1 98.7	0.88 ± 0.02 0.89 ± 0.05 0.95 ± 0.01	-53.2 ± 1.4

Figure captions

Fig. 1 External calibrations applied to elaborate the HDC-spICP-MS chromatograms. a) 1^{st}-99^{th} interpercentile range of the normalized signal intensity relative to the average value calculated for dissolved Ag 500 pg mL^{-1} within 2 s time windows, plotted against the corresponding average intensity. The range was adopted as the variable threshold for deconvolution of dissolved Ag and AgNPs signals. b) Calibration of the normalized signal intensity as a function of the mass of AgNPs standards with 20, 40, 60 and 100 nm nominal diameter (hypothesis of purely metallic spherical particles, n = 3). c) Calibration of the elution time as function of the diameter of AgNPs standards with 20, 40, 60 and 100 nm nominal diameter (n = 3). d) Calculation of the AgNPs detection efficiency as slope of the regression line, detected mass *vs*. injected mass (bilog scale). The injected standards were: 20 nm (5, 10, 20, 30, 40 pg), 40 nm (2.5, 5, 10, 20, 50 pg), 60 nm (10, 20, 50, 100, 200 pg) and 100 nm (25, 50, 100, 200, 500 pg). e) Calibration of the peak area for dissolved Ag (n = 3).

Fig. 2 3D contour plot chromatograms of AgNPs obtained for a mixture of 20, 40, 60 and 100 nm standards diluted in mobile phase (a, b) and the same mixture incubated for 2 h in plasma (c, d).

Fig. 3 a) Temporal variation of the molar fractions of AgNPs and dissolved Ag in plasma after incubation of a 100 nm standard from 2 to 24 h, average ± standard deviation, n = 3. b) Temporal variation of the mode of the AgNPs mass-derived distribution in the same incubated standard, average ± theoretical uncertainty, n = 3.

Fig. 4 3D contour plot chromatograms of AgNPs after incubation of the dressing Acticoat Flex3^{TM} in plasma for 2 h.

Fig. 5 a) µXANES spectra of pure standards of Ag species; b) µXANES spectra of the intact dressing Acticoat Flex3^{TM}, and AgNPs 10 nm and ionic Ag incubated in a solution containing HSA or in whole human plasma. The original spectra of the incubated standards are superimposed to their best fitting (dotted lines) obtained by LCF using the pure standards as the input variables. The fitting parameters (molar fractions) are reported in Table 1. AgGSH is representative of the Ag-thiol bounds.

Fig. 6 a) µXRF map of the distribution of Ag, Cl and S in the region surrounding a micrometric agglomerate of AgNPs released by Acticoat Flex3^{TM} after 2 h incubation in plasma. Scale is linear in cps with independent full-scale values. b) µXANES map of Ag speciation in the same region. Scale is linear in cps with the same full-scale value for all species. AgGSH is representative of the Ag-thiol bounds.

Fig. 7 Deconvoluted chromatograms of dissolved Ag in whole blood of burnt patients obtained by HDC-spICP-MS. The blood was collected 3 days (patients A3, B and C) and 6 days (patient A6) after the application of the dressing Acticoat Flex3^{TM} containing AgNPs. Each sample was differently diluted (see Table S-1) before injection to achieve a comparable concentration (~400 pg mL^{-1}).

Fig. 8 TEM images of the AgNPs standards (mother suspensions) used throughout the study; the nominal sizes are 10 (a), 20 (b), 40 (c), 60 (d) and 100 (e) nm

Online Abstract Figure Simplified scheme of the combined analytical approach adopted for studying the chemical dynamics of AgNPs in human plasma/blood.

Prof. Alfredo Sanz-Medel
Editor,

Dr. Nicola Oberbeckmann-Winter
Managing Editor,

Analytical and Bioanalytical Chemistry

Venice, 20 August 2015

Reference: Manuscript ID: ABC-01228-2015

Dear Editors,

I enclose the revised version of our paper entitled: "Hydrodynamic chromatography coupled to single-particle ICP-MS for the simultaneous characterization of AgNPs and determination of dissolved Ag in human plasma and blood of burnt patients"
by Marco Roman, Chiara Rigo, Hiram Castillo-Michel, Ivan Munivrana, Vincenzo Vindigni, Ivan Mičetić, Federico Benetti, Laura Manodori and Warren R.L. Cairns.

We appreciate the positive judgment given by the Editor and the Referees to our work. We have carefully considered their comments when preparing this revised version of improved quality. A detailed list of the responses to the points raised during the evaluation of the manuscript is provided below, and is traced in the amended version of the revised manuscript. A new figure and corresponding caption is also provided to be used as accompanying graphic for the online abstract.

Editor

The authors have made important contributions here with respect to the use of HDC coupled to ICP-MS in single particle mode (deconvolution of dissolved and NP signals, determination of dissolved silver), applying this methodology to complex samples for the first time.
Thus, I agree with both referees that the MS deserves publication in ABC.

We thank the Editor for appreciating the impact and the quality of our study concerning both the analytical aspects and the applicative implications.

However, both expert reviewers have raised some minor points to enhance the quality of the final MS. In particular, the overall novelty here is not highlighted enough (see referee 2 comments) and should be better detailed in the revised version.

We agree with the Editor and Referee B in considering the need to highlight the analytical novelty beside the specific medical application. Accordingly with the detailed comments of Referee B (see below), we made the following changes to give more emphasis to the innovative methodological aspects:

1) The title was changed in: ”Hydrodynamic chromatography coupled to single-particle ICP-MS for the simultaneous characterization of AgNPs and determination of dissolved Ag in human plasma and blood of burnt patients”
2) The abstract was substantially modified to be focused on the analytical method.
3) The conclusion was significantly expanded (doubled) starting from page 11 line 23, to highlight the methodological novelties and their potential impact for the scientific community.

Referee A

Generally a very detailed and clear manuscript that shows the application of a hyphenated technique with spICP-MS data acquisition. This combination clearly complements the strengths and weaknesses of both techniques.

We thank the Referee for appreciating the technical quality of our work.

There are a few points where additional comments by the author would be helpful:

- Why was the instrument tuned with respect to oxide formation using Ce? For spIC-MS, detection sensitivity is decisive, and hence a dedicated Tuning for the element that is actually targeted may lead to improved particle size detection limits. This was correctly accomplished through tuning using a 1 ng mL solution of Ag, but in my opinion the sensitivity could be further improved if oxide Formation below 2% would have been discarded as a tuning criterion.

Choosing between tuning for sensitivity and tuning for robustness (as measures by the Ce oxide ratio) is an interesting point in spICP-MS. It is true that tuning for sensitivity would have a direct advantage in lowering the minimum detectable particle size and dissolved Ag concentration. However, in our study we also engaged the challenge of applying sp to heavy matrices: not only the plasma and whole blood, but also the mobile phase (included with a high flow rate). In this case signal suppression or just fluctuation due to matrix effects, and background rising after repeated injections could seriously affect the overall reliability of the method, thus we preferred to adopt robust plasma conditions. For the same reason, for example, we kept the sample depth at 8 mm. We mentioned the motivation of our choice in this revised version of the manuscript at page 4 line 38.

- The term limit of detection in conjunction with spICP-MS needs additional clarification since it can be understood in two ways: The lowest detectable particle size and the lowest detectable particle number. Whereas the first one describes an Instrument related characteristic, the latter one represents a statistical consideration of the number of evaluated signals. Experts in the field are able to distinguish the correct use, but people not directly familiar with the technique may be confused.

A third definition of the LOD is also used in this paper, which is the lowest detectable concentration of dissolved Ag. We agree that the manuscript in its original form was not sufficiently clear for a generic reader, thus we made the following changes:

1) A short definition of the three LODs is given at the beginning of the discussion section (par. 2.1.1. page 5 line 12) and specific acronims are introduced to be used along the whole manuscript.
2) An estimation of the LOD for the number of particles, originally missing, is now provided and briefly discussed at page 7 line 5.

- Has the number of wound dressings that all patients received been identical? With what frequency is the dressing exchanged? This information is relevant to judge the exposure to ionic silver over the entire Treatment, and would definitely influence the concentration of Ag in whole blood over time.

The referee is absolutely right, these points are pivotal. At page 10 line 10 we mention now that all patients were treated with a single application of the dressing. Concerning the number of dressings,

that's a more complex issue: application is the last step of a surgical intervention in which the dressing is cut out and modeled depending on the specific shape and characteristics of the wound. Thus, referring to the number of dressings would be not so informative, while the % of burned body surface (reported in Table 2), which is entirely treated, is a good estimate of the wound area exposed to Ag. We now mention also this at page 10 line 10.

- *Page 3, line 3: should be recent introduction of THE single-particle ...*

The sentence was changed accordingly.

- *The reference "Table 1" on page 10 is not correct. The clinical Information is displayed in table 2.*

The referee is right, the number was changed accordingly.

Referee B

The work has enough significance, originality, interest and quality to deserve publication.

We thank the Referee for appreciating the novelty and quality of our work.

However, the manuscript is unbalanced in the sense that the title, the abstract and the main conclusions are related to the study about the fate of silver NP and silver NP-coated dressing in human plasma by HDC-sp-ICPMS and μXRF and μXANES, as well as the fate of silver NP-coated dressing after topical administration in burnt patients. On the other hand, the authors have made novel contributions with respect to the use of HDC coupled to ICP-MS in single particle mode (deconvolution of dissolved and NP signals, determination of dissolved silver), applying this methodology to complex samples for the first time. In my opinion, this methodological part is not highlighted enough. At least, the title and the abstract should reflect these novelties.

We agree with this comment, which was also supported by the Editor, and made the changes reported above.

Additional comments
The authors mention a "detection efficiency" (p.6 l. 41, p.8 l.14) as a corrected transport efficiency (in fact, nebulization efficiency) taking into account the settle time. In my opinion, this correction is unnecessary, if all data acquisition is performed under the same conditions. Moreover, this detection efficiency is not considered in equation 1 or any other calculation shown.

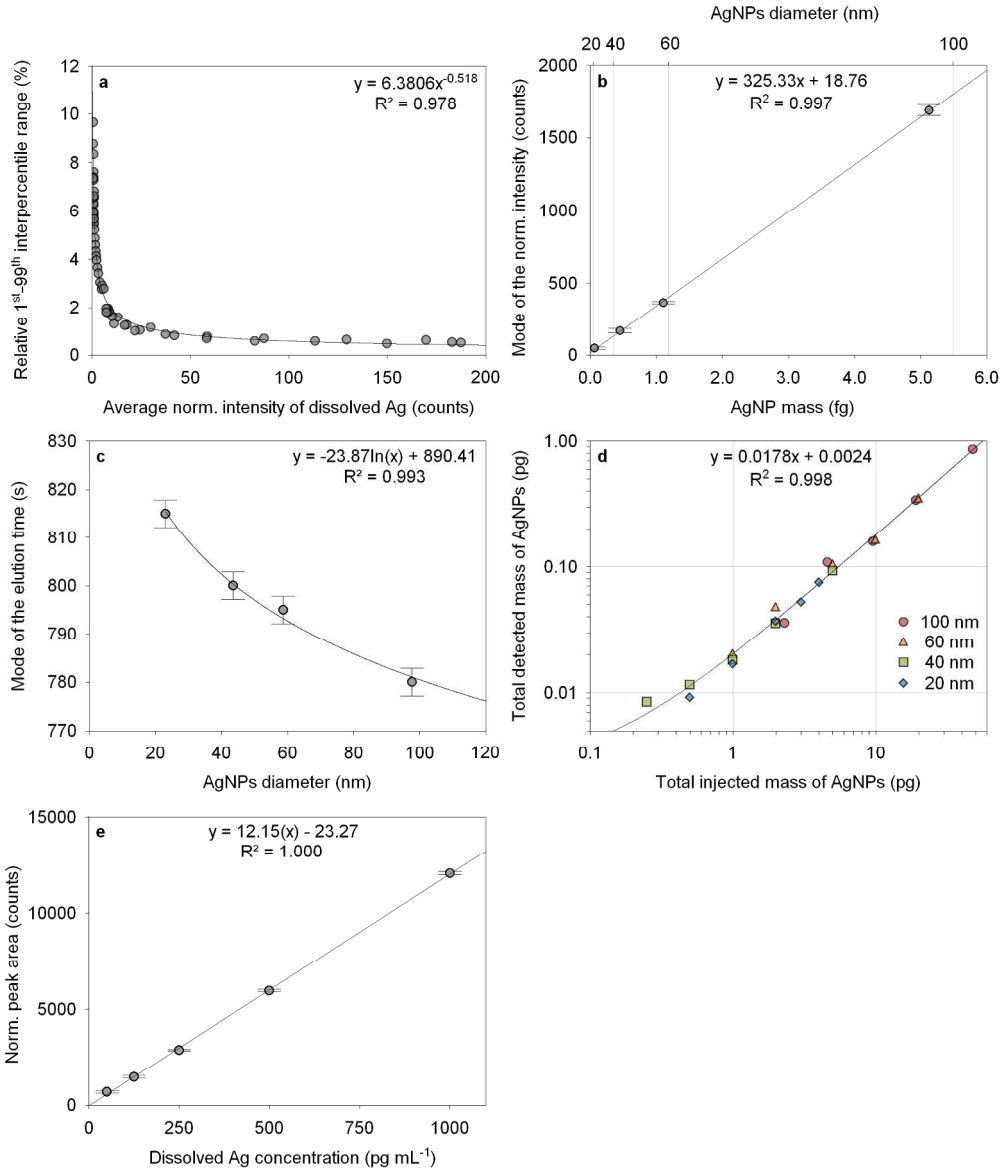
This issue was probably presented in a bad way in the original version of the manuscript. Differently by all works on spICP-MS in the literature, we acquired 2 masses. This introduced a settling time, which affects the number of detected particles beside the classical transport (nebulization) efficiency. The referee is right: since the efficiency is calibrated under the same conditions, correcting for the settling time is irrelevant for the final results. However, introducing the correction allows providing a value for transport efficiency which is more correct with respect to its definition, and directly comparable with the literature.
For this reason, in this revised version we preferred keeping the settling time correction, but we made some changes in order to make the text more simple and clear (without any change in the meaning of the contents):

1) At page 5 line 38, explaining the choice of the acquisition strategy, we added the sentence "In addition, the acquisition of two masses introduces a settling time, which slightly affects the number of detected particles (see section 2.1.4.)." to make explicit the origin of the correction.

2) In the paragraph 2.1.4. we removed the confusing concept of "detection efficiency". The settling time correction was explicited in eq. 1 to make possible referring direcctly to the transport efficiency along the rest of the manuscript.

The nebulization efficiency calculated (p. 7 l.5-8) is characteristic of the nebulizer, spray chamber and flow rate used. Thus there is no point to compare the nebulization efficiency obtained by the authors with the Pergantis' values that was obtained with a different nebulization system. Please remove the comments.

The sentence was removed.



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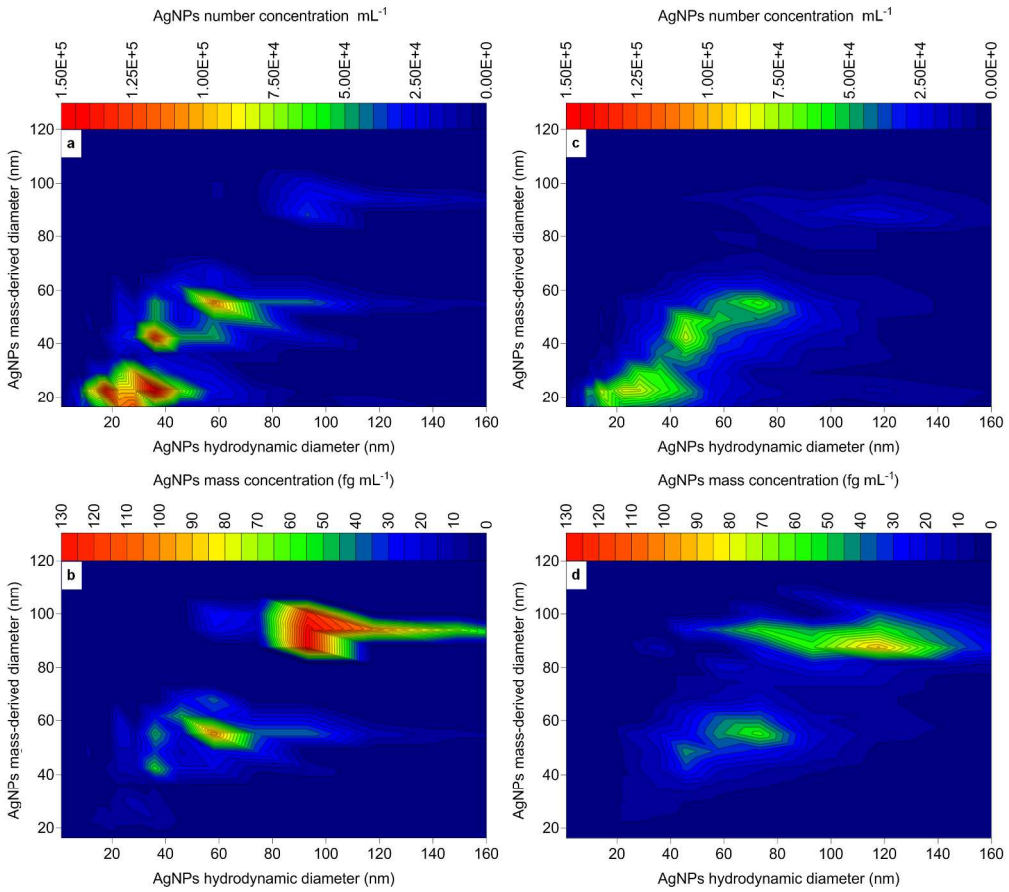

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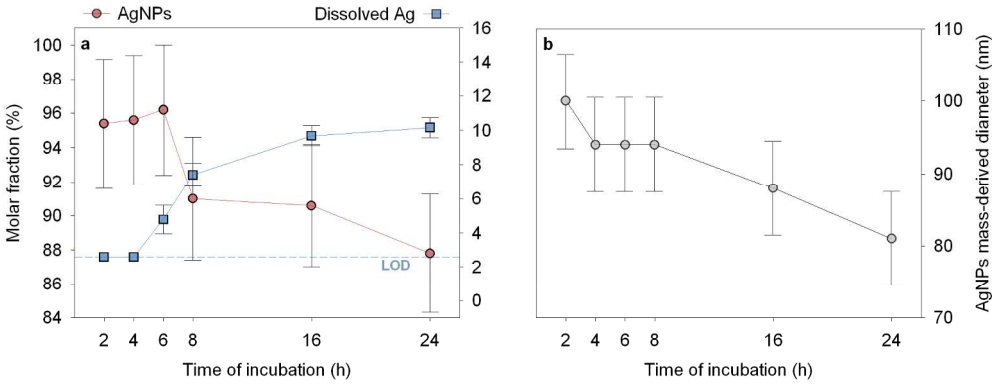

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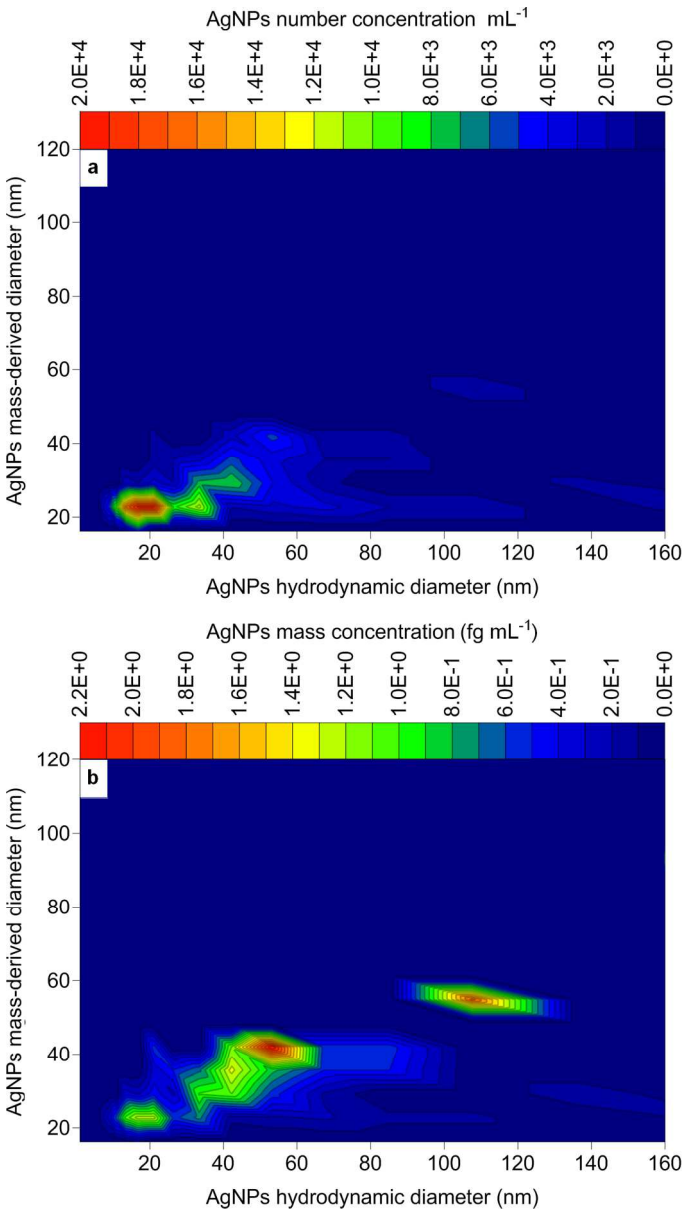

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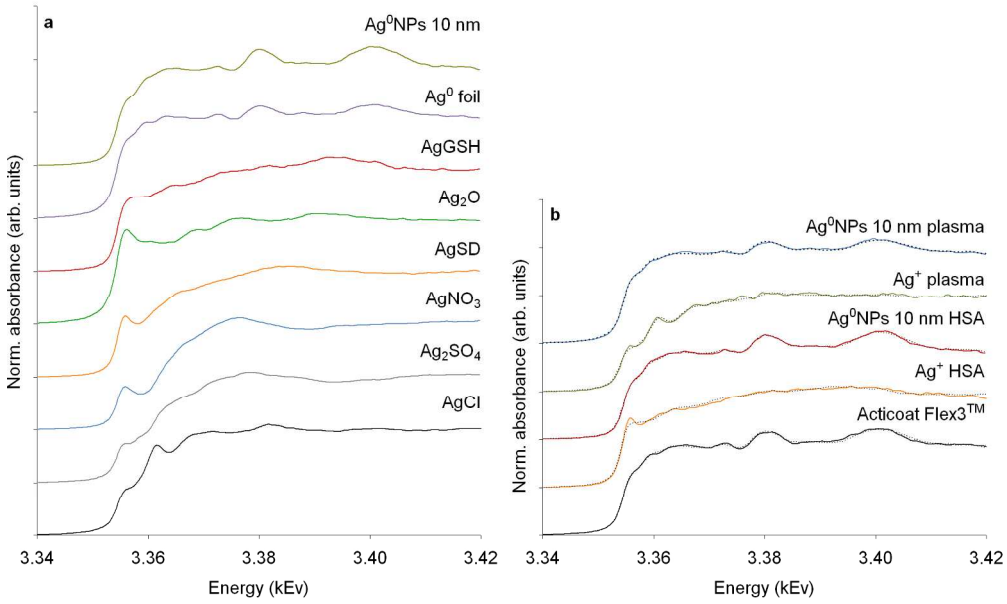

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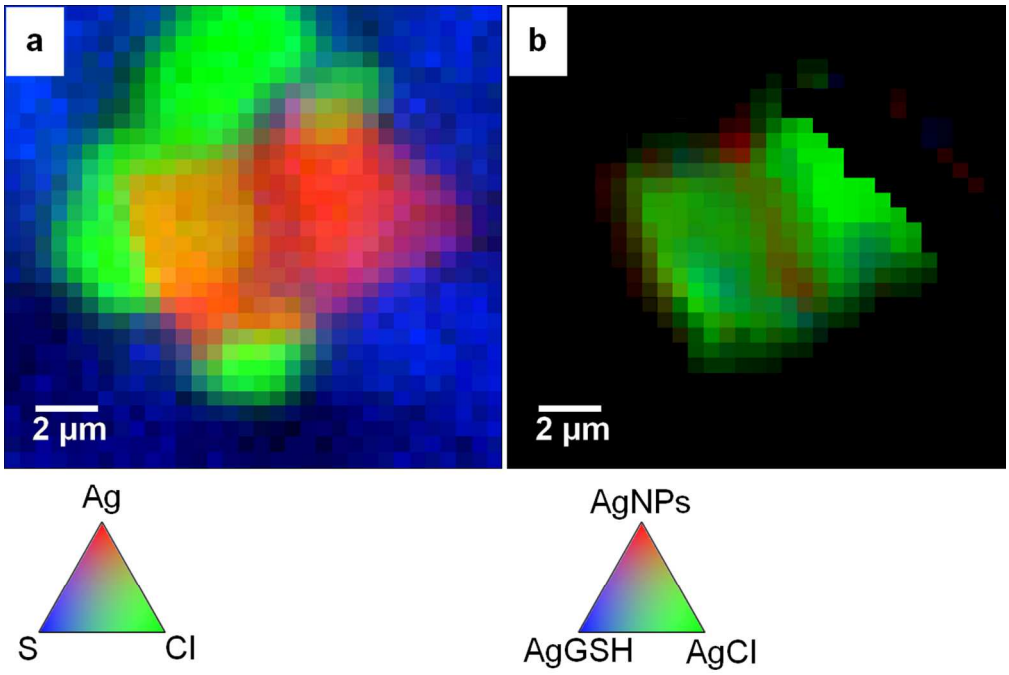

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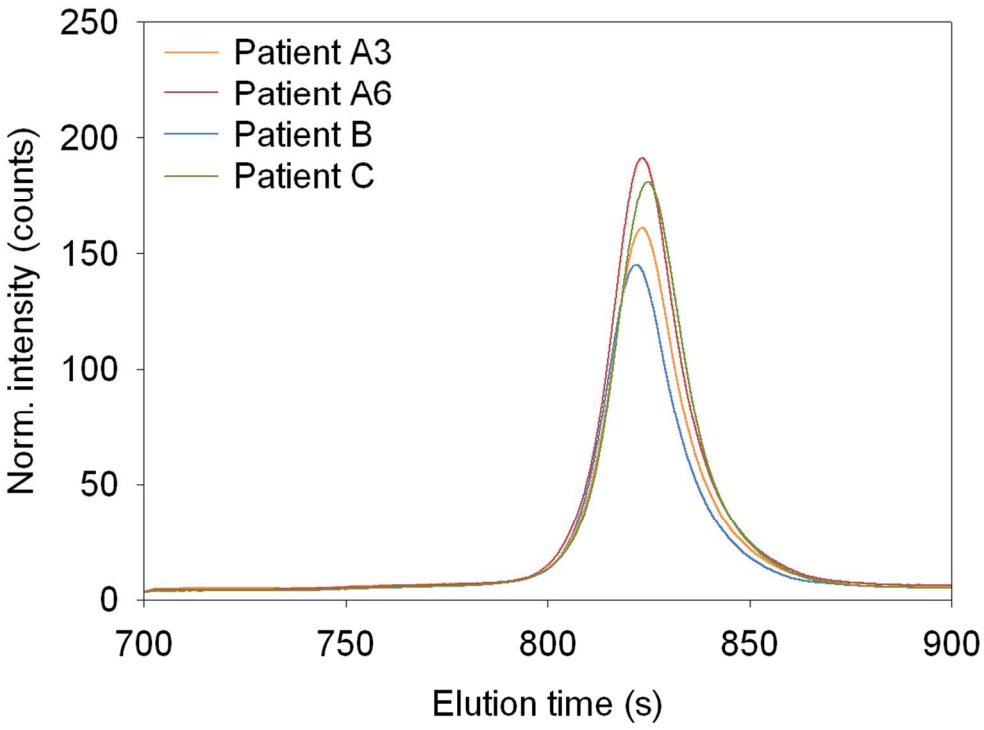

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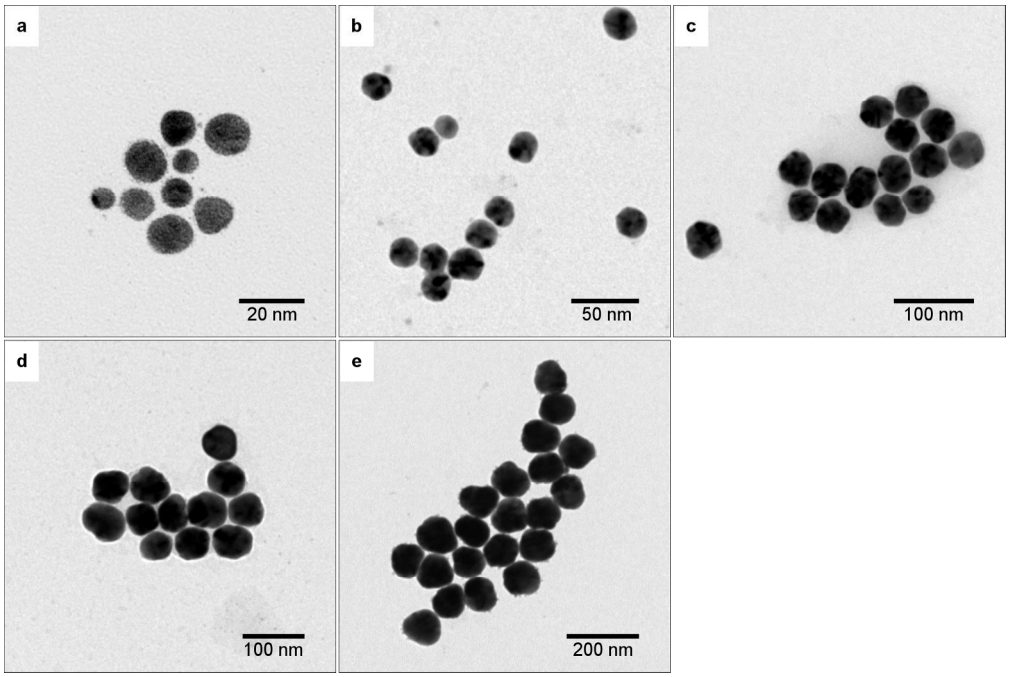

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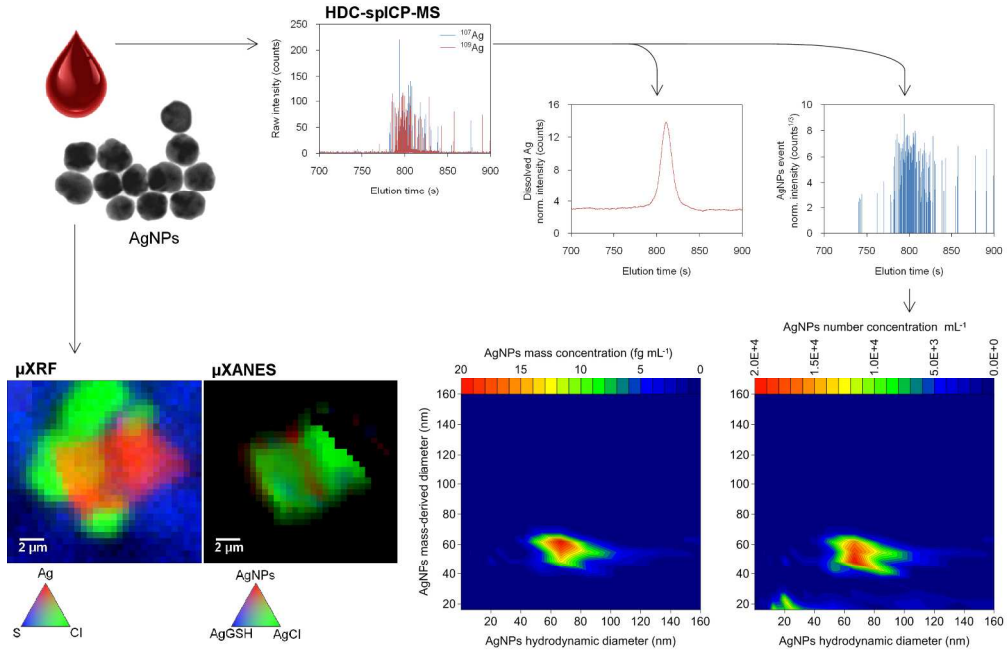

Simplified scheme of the combined analytical approach adopted for studying the chemical dynamics of AgNPs in human plasma/blood
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