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DTT protein equalization and Tryptophan protein quantification as a powerful tool in analytical proteomics.

Inês F. Domingos[1,2], Luís B. Carvalho[1,2], José L. Capelo[1,2], Carlos Lodeiro[1,2], Hugo M. Santos[1,2]*

[1]BIOSCOPE Research Group, LAQV-REQUIMTE, Department of Chemistry, [2]NOVA School of Science and Technology, Universidade NOVA de Lisboa, 2829-516 Caparica, Portugal, PROTEOMASS Scientific Society, 2825-466 Costa da Caparica, Portugal.

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ABSTRACT

Assessing total protein levels in biological samples is a common procedure in biochemistry and molecular biology. In this study, we compare tryptophan fluorescence (WF) with Bradford and BCA assays to determine total protein in serum samples. Our results indicate that tryptophan fluorescence spectrometry is an efficient, sensitive, and straightforward technique for quantifying proteins in serum. We observed minimal variation between the three methods: BCA de one with the lowers LOD and LOQ. The tryptophan method offers the possibility of reusing the intact sample that does not need colourimetric reagents for quantification. Consequently, free tryptophan serves as a reliable universal standard. This assay can be performed using a conventional fluorescence spectrometer with cuvettes or in a 96-well plate format with a plate reader. The method was successfully used as proof of concept, using serum from patients diagnosed with myeloma and serum from healthy donors.

Keywords: DTT equalization, tryptophan, proteomics, serum, multiple myeloma.

Introduction

Quantifying total protein in biological samples illuminates interactions, signalling pathways, and cellular processes, aiding in diagnostics by comparing health versus disease conditions. Selecting a protein assay method is a complex decision, requiring consideration of the advantages and disadvantages inherent to each method, such as interferences, accuracy, reproducibility, sample handling and throughput. To minimize sample manipulation, researchers often maintain different protein assay methods in their laboratories to address diverse experimental requirements efficiently. In proteomics, protein determination is the prerequisite for optimal protein digestion and, subsequently, peptide characterization via mass spectrometry analysis.[1]

The Bradford protein assay was developed by Marion M. Bradford in 1976 [2]. It is a well-known colourimetric protein assay that relies on the change in absorption of the Coomassie Brilliant Blue G-250 dye. The Coomassie Brilliant Blue G-250 dye, existing in anionic, neutral, and cationic forms, undergoes a colour shift from red to blue under acidic conditions, binding to proteins during testing. The dye forms a strong non-covalent complex with the protein's carboxyl and amino groups through van der Waals forces and electrostatic interactions, exposing hydrophobic pockets in the protein's tertiary structure. The bound anionic form of the dye, maintained by hydrophobic and ionic interactions, exhibits a maximum absorption spectrum at 595 nm. The increase in absorbance at this wavelength is proportional to the quantity of dye that binds to amino acids, which can be linked to the protein concentration in the sample [3]. However, notable interferences include high concentrations of detergents, such as sodium dodecyl sulfate (SDS), commonly found in protein extracts used for cell lysis and protein denaturation. Moreover, the method is sensitive to time variations in sample incubation. In addition, the Coomassie Blue G250 dye binds preferentially to arginine and lysine protein groups, which may result in a varied assay response for different proteins. Despite these drawbacks, the Bradford assay remains widely used.

***Corresponding author:** Hugo M. Santos, email: hmsantos@fct.unl.pt

The Bicinchoninic Acid-based method for protein quantification, known as BCA method, was first published by Smith et al. in 1985. Later, in 2010, the Thermo Scientific™ Pierce™ BCA Protein Assay Kit [4] was introduced, which employs a detergent-compatible formulation based on bicinchoninic acid (BCA) for colourimetric protein detection and quantitation. This method uses the biuret reaction, in which proteins in an alkaline medium reduce Cu^{+2} to Cu^{+1}, which react with bicinchoninic acid, forming a purple-colored complex, which exhibits strong absorbance at 562 nm. The color formation in the BCA assay is influenced by the macromolecular structure of proteins, the number of peptide bonds, and the presence of specific amino acids (cysteine, tryptophan, and tyrosine). Limitations include incompatibility with reducing agents and metal chelators, although trace quantities may be tolerated, and reported responsiveness to common membrane lipids and phospholipids.

Tryptophan [5] exhibits intrinsic fluorescence due to its indole ring. This fluorescence arises from the absorption of ultraviolet (UV) light, typically around 280 nm, followed by the emission of light at longer wavelengths, generally around 340-350 nm. Once the quantum yield of tryptophan fluorescence is relatively high, makes it a sensitive probe for protein detection. Tryptophan fluorescence can be used for the quantification of proteins because the fluorescence intensity is proportional to the concentration of tryptophan-containing proteins. Furthermore, the requirement for lower sample volumes compared to alternative quantification methods makes tryptophan fluorescence assays suitable for situations where sample amount is limited. The assay is fast, contributing to streamlined laboratory workflows. Moreover, the method demonstrates minimal interference from substances commonly present in biological samples, ensuring more accurate results, especially in complex matrices.[5,6] Overall, the combination of real-time monitoring, low sample volume, quickness, and minimal interference positions tryptophan fluorescence assay as a valuable tool for protein quantification. In this work, we have used the three aforementioned methods to compare protein quantification in the serum of healthy individuals.

Materials and methods

Human serum samples: The serum samples from 11 healthy volunteers were used. Data about the study cohort are presented in Supplementary Material 1, Table 1.

Serum sample preparation: Serum samples were collected in red glass vacutainer tubes without anticoagulants or preserves. The samples were allowed to clot at room temperature, RT, followed by centrifugation at 2 000 x g for 10 minutes at RT. After centrifugation, serum was aliquoted and stored at -80 ºC.

Bradford assay: Bovine serum albumin (BSA) was used to generate a calibration curve ranging from 0.125 to 1.4 µg/µL. Briefly, BSA working solutions containing 25 to 280 µg were pipetted into 0.5 mL microtubes, followed by adding MQ water up to 200 µL. To quantify the serum samples, we initially prepared a 1:100 serum dilution in MQ-water to ensure that concentrations were within the linear range. Five µL of each standard and diluted serum were loaded in duplicates into each well, followed by the addition of 250 µL of Bradford Reagent. MQ-water was used as a blank. Afterwards, standards, samples and blanks were incubated at room temperature for 20 minutes. Finally, absorbances at 595 nm were measured using the Clariostar microplate reader.

Bicinchoninic acid assay (BCA): For protein quantification using the BCA assay, we employed the Pierce™ BCA Protein Assay Kit from Thermo Scientific with part number 23225. Following the manufacturer's protocol, we chose the microplate procedure as outlined below: 25 µL of each standard and samples were pipetted in duplicate into individual wells of a microplate (working range = 0.02 – 2 µg/µL). Subsequently, 200 µL of the Pierce reagent was added. The plate was gently mixed for 30 seconds, covered with aluminum foil, and then incubated for 30 minutes at 37 ºC. Finally, absorbances at 562 nm were measured using the Clariostar microplate reader.

Tryptophan emission assay: The standard calibration curve was created using 0.0102 µg/µL tryptophan dissolved in 8M Urea in 0.1M Tris-HCl pH 8 to span a linear detection range from 0 to 5.1x10-3 µg/µL. For measurement, 75 µL of calibration solutions were transferred to a quartz-bottom 96-well plate. A dilution protocol was applied to align with the assay's linear range to assess the concentration of proteome and proteome digest in unknown samples. This involved adding 5 µL of each sample in duplicate to the plate wells, followed by adding 70 µL of the 8M Urea in 0.1M Tris-HCl pH 8. Measurements were performed with an excitation wavelength set at 280 nm, with a long pass dichroic mirror at 309 nm and an emission wavelength of 350 nm, utilizing a bandwidth of 20 nm. The quantification of proteome and proteome digest was derived from fluorescence intensity measurements, which applied an average tryptophan weight content assumption of 1.17% for human proteins [5].

Depletion of abundant serum proteins: To 20 µL of the raw serum sample, 2.2 µL of 500 mM DTT was added, followed by incubation for 30 minutes at 37 ºC. This procedure was performed in triplicate. After incubation, samples were centrifuged at 20,000 x g for 20 minutes. Afterwards, the supernatants were withdrawn to new microtubes, and the pellets were gently washed with ten µL of MQ H2O. The washing factions were combined with the previous supernatants. Quantifying the protein concentration in the depleted samples: Supernatants (SN) were quantified via Tryptophan Emission as described previously. Quantifying the protein content in the pellet was done using the following formula: $\mu g\ of\ Protein\ in\ Pellet = \mu g\ of\ Protein\ in\ Raw\ Serum - \mu g\ of\ Protein\ in\ SN$ - Equation 1.

Protein reduction, alkylation and digestion: Sample preparation was performed as described previously, with optimization for the supernatant and pellet samples.[7,8] Initially, supernatant samples were diluted to achieve a target protein concentration of 103 ± 8 µg per 20 µL of sample volume. This step was followed by adding 5 µL of a Reduction/Alkylation solution consisting of 10 mM TCEP, 40 mM CAA, 0.1M Tris-HCl pH 8.8, to

each sample. The mixture was then incubated for 30 minutes at 37 °C. The pellets were solubilized with 150 µL of 70 mM TEAB followed by probe sonication for 1 minute (Ultrasonic frequency: 30kHz, Ultrasonic Amplitude: 100%, Cycle time: 0,8 s). Afterwards, 100 ± 2 µg of the pellets' proteins (final volume of 20 µL) were reduced with 5 µL of Reduction/Alkylation solution. Before trypsin digestion, samples were diluted to 150 µL with 70 mM TEAB.

For the proteome digestion phase, 5 µL of a Trypsin/Lysine-C solution, at a concentration of 0.67 µg/µL prepared in 70 mM TEAB, was added to each reduced and alkylated sample. The samples were left to digest overnight at 37 °C. Following digestion, the resultant peptide mixtures were concentrated by drying in a speed vacuum concentrator. Before downstream analysis, peptides were resolubilized in 150 µL of 3% (v/v) Acetonitrile (ACN) in 0.1% (v/v) aqueous formic acid (FAaq), followed by 10 minutes of sonication using an ultrasonic bath at 100% ultrasonic amplitude.

LC-MS/MS analysis was performed using UltiMate 3000 ultra-high performance liquid chromatographer from Thermo Scientific, coupled to Ultra High-Resolution Quadrupole Time-of-Flight (UHR-QTOF) IMPACT HD mass spectrometer from Bruker. 0.5 µL of the sample with a total peptide concentration of 0.6 µg/µL were loaded onto a µPAC™ Trapping column and desalted for 2.7 min with 1% (v/v) ACN in 0.1% FAaq at a flow rate of 15 µL min-1. Then the peptides were separated using an analytical column (200 cm µPACTM PharmaFluidics). with a linear gradient at 500 nL min-1 (mobile phase A: FAaq 0.1% (v/v); mobile phase B: 99.9% (v/v) ACN and 0.1% (v/v) FAaq) 0–2 min from 3% to 5% of mobile phase B, 5–76 min from 5% to 17% of mobile phase B, 76–104 17% to 25% B, 104–121 25% to 35% B. Chromatographic separation was carried out at 35 °C. MS acquisition was set to MS (2 Hz) cycles, followed by MS/MS (8–32Hz), cycle time 3.0 seconds, active exclusion, exclude after one spectrum, release after 2 min. The precursor was reconsidered if its current intensity was 3.0 higher than the previous intensity and intensity threshold for fragmentation of 2500 counts.

Bioinformatics data analysis and functional enrichment: Raw LC−MS/MS data were processed in MaxQuant (V.1.6.10.43) for protein identification and label-free quantification using standard settings.[9] Peptide lists were searched against the human Uniprot FASTA database. A contaminant database generated by the Andromeda search engine was configured with cysteine carbamidomethylation as a fixed modification and N terminal acetylation and methionine oxidation as variable modifications.[10] We set the false discovery rate (FDR) to 0.01 for protein and peptide levels with a minimum length of seven amino acids for peptides, and the FDR was determined by searching a reverse database. Enzyme specificity was set as C-terminal to arginine and lysine as expected using trypsin. A maximum of 2 missed cleavages were allowed. Data processing was performed using Perseus (version 1.6.10.50) with default settings [11]. All proteins and peptides matching the reversed database were filtered out[12].

Results and Discussion

Comparison between Bradford-, BCA- and Tryptophan-based assays

To compare the Bradford, BCA, and Tryptophan assays, we used sera from 11 healthy individuals. For the Bradford and BCA assays, we used BSA to generate a calibration curve, as described in the material and methods section. For the tryptophan emission assay, the calibration curve was generated with L-Tryptophan. After the calibration curve was generated, we calculated the limit of detection (LOD) and limit of quantification (LOQ) for each assay. For the Bradford assay, the LOD was 0.002 µg/µL, and the LOQ 0.06 µg/µL. In contrast, for the BCA method, the LOD was 0.01 µg/µL, and the LOQ was 0.05 µg/µL. Finally, the tryptophan emission assay, with a LOD of 0.001 µg/µL and LOQ of 0.01 µg/µL, proved to be the most sensitive. Our LOQ for tryptophan-based assay matches those reported in the literature [5]. Subsequently, the protein content of the raw sera, pellets, and supernatants was determined in triplicate. Results are shown in Figure 1a and in Supplementary Material 1 Table 2. When comparing the assays, the Bradford provides less scattered data, while the BCA consistently provides slightly higher protein concentration values. The Bradford assay was found to be the most accurate. It is worth noting that the normal range for serum total protein concentration typically falls within the range of 60–80 g/L.[13] Figure 1a shows (i) that the Bradford assay analysis revealed a total protein concentration ranging between 57 and 70 g/L; (ii) that the BCA assay was found to present a more extensive range spanning from 62 to 81 g/L, and (iii) that the assessment conducted via the tryptophan emission assay exhibited a range of 56 to 76 g/L.

Assessment of the DTT-based serum protein equalization process

Serum constitutes a complex mixture of tens of thousands of proteins, some highly abundant while others are in significantly lower concentrations. For an in-depth analysis of plasma proteomics, it is imperative to employ a depletion or equalization strategy to target the less abundant, potentially more insightful, proteins. Treatment of serum with DTT results in a pellet (P) containing highly abundant proteins and a supernatant (SN) rich in less abundant protein, among them, and remarkably, immunoglobulins 14. We applied the DTT approach, tryptophan quantification and label-free quantitative proteomics to access the serum proteome of raw serum and the depletion faction (SN and P). The effect of DTT over raw serum is shown in Figures 1 b and 1c. For the proteomics analysis, we performed a comparison using Z score normalization of the log-2 transformed data derived from the mass spectrometry measurements. A multiple-sample ANOVA test was employed, utilizing a permutation-based false discovery rate (FDR) approach with a threshold of 0.05 FDR and S0 set to 0. The statistically significant different proteins were selected, and a Hierarchical cluster was generated using Euclidean Distance for both tree rows and columns as depicted in Figure 1 c, which shows in a heatmap the proteins differentially expressed among raw, the Ps and the SNs. The list of these proteins is depicted in Supplementary 1 Table 5. Thus, a group of proteins (in green) with lower levels than in the P or in the raw data can be seen in the SN. This group constitutes the most abundant proteins present in lower levels in the supernatant as they tend to

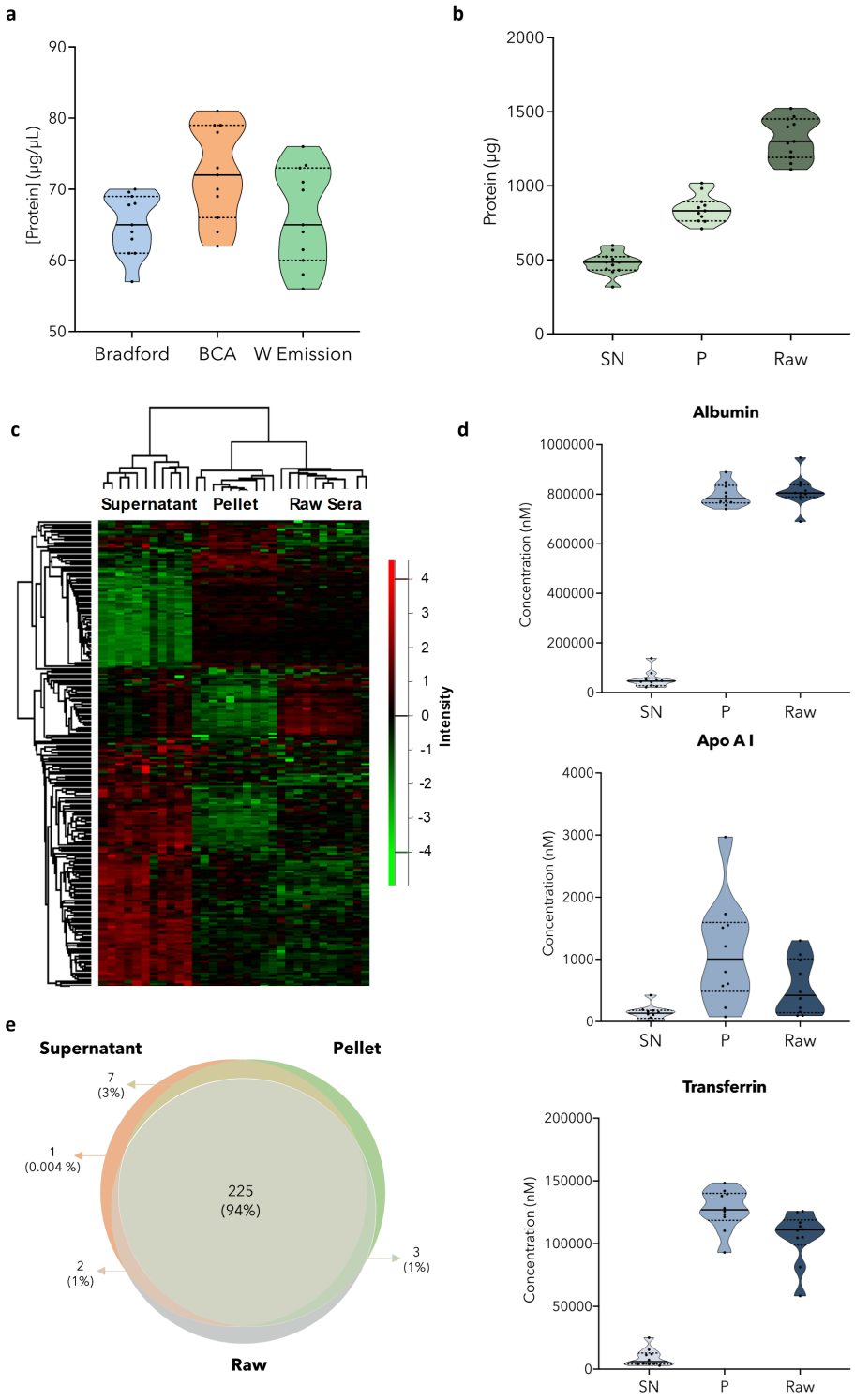

Figure 1 – Comprehensive proteomic analysis of human health serum. a) Violin plot of data distribution from three methods comparison in healthy individuals (n=11). Blue: Bradford assay. Orange: BCA assay. Green: tryptophan emission assay. Each sample was analyzed in duplicate. **b)** Distribution and density variation of protein mass (including two biological replicates) at each point for each fraction. The continuous bar in the middle represents the median. Discontinuous line represents the quartile lines. **c)** Hierarchical clustering of the three fractions analyzed (raw sera, supernatant and the pellet). Protein LFQ values were used to perform the cluster analysis (with average linkage, no constraint, preprocessing with k-means and Euclidean distance). **d)** Violin plot illustrating the data distribution of the three most abundant proteins in serum samples obtained from healthy individuals. SN corresponds to Supernatant, P corresponds to Pellet, and Raw corresponds to raw sera. Concentrations were derived from LC-MS/MS raw intensities using the total protein approach. **e)** Venn diagram illustrating the overlap of proteins identified in the raw serum, and in the depleted SN and Pellet fractions.

precipitate into the pellet. In this group of depleted proteins, we found, for instance, albumin, serotransferrin, a-1-Antitrypsin, plasminogen, complement-associated proteins, and apolipoproteins, which are some of the most abundant proteins present in serum. On the other hand, the less abundant proteins in the raw sera (in green) become more abundant in the supernatant (in red). This is a clear example of the highly abundant protein DTT equalization effect on the raw sera. This effect is further exemplified in the case of 3 individual proteins, as presented in Figure 1 d. Thus, albumin, the most abundant protein constituting circa 90% of the total protein content in serum, is found to be the most abundant protein in the pellet, with its level reduced about 16-fold in the supernatant. This is also an exciting characteristic of the DTT approach; instead of depleting the complete protein, some remains in solution. As albumin can also carry other proteins, its complete depletion from serum is not recommended. A similar situation can be observed for Apo A1 and Transferrin. The DTT works by equalizing the levels of the proteins in the supernatant rather than depleting a set of proteins. This concept is visualized in Figure 1e, where it can be seen that 94% of the proteins are commonly identified in raw serum, pellet, and supernatant.

Conclusions

The tryptophan assay is more sensitive than the Bradford and BCA analysis for proteomics purposes, with the advantage of simplicity and throughput. Furthermore, it is non-destructive, and the sample can be reutilized, further validating its use in proteomics. By applying DTT and tryptophan quantification, this study demonstrates the effectiveness of the DTT-based equalization process in revealing less abundant proteins, offering a promising avenue for deep proteomic analysis. The ability of DTT to maintain some proteins in solution, rather than completely depleting them, is particularly beneficial for preserving proteins like albumin that carry other proteins, thus avoiding their complete removal from serum analysis.

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