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Compensation of inorganic acid interferences in ICP-OES and ICP-MS using a Flow Blurring® multinebulizer†

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† *Electronic supplementary information (ESI) available: Further experimental results.*

Abstract

A new and easy method has been proposed for compensation of inorganic acid matrix effects in ICP-OES and ICP-MS. The method consists on an on-line standard addition calibration using a *Flow Blurring*® multinebulizer (FBMN-based system). Experimental conditions of the FBMN-based system are optimized for both ICP-OES and ICP-MS. Under optimized conditions recovery values obtained in the analysis of synthetic acid samples were close to 100% for HNO_3 and HCl (with acid concentrations of up to 15% (w w^{-1})) and H_2SO_4 (up to 10% (w w^{-1})) for both plasma-based spectrochemical techniques.

The applicability of the proposed method has been evaluated analyzing two whole milk powders, certified reference material and a commercial product, showing excellent recovery values.

Compared with other calibration strategies and experimental setups used, the on-line standard addition calibration using the FBMN-based system is faster, easier to handle and significantly reduces reagents and sample consumption.

1. Introduction

Inductively coupled plasma optical emission spectrometry (ICP-OES) and inductively coupled plasma mass spectrometry (ICP-MS) are widely used instrumental techniques allowing multi-elemental analysis at trace and ultra levels, respectively. It is well known that conventional liquid sample introduction systems for ICP techniques are based on the use of nebulizers, which transform the liquid sample into an aerosol. Small changes

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in the fundamental processes occurring during both liquid-aerosol transformation and aerosol transport to the plasma, as well as in the excitation/ionization processes in the plasma, can result in non-spectroscopic interferences, also known as matrix effects. These kinds of matrix effects lead to similar effects in ICP-MS and ICP-OES provided that both techniques use similar liquid sample introduction systems and excitation/atomization/ionization sources.

Inorganic acids are often present at high concentrations in sample solutions for ICP-MS and ICP-OES analysis, as a result of previous sample preparation steps such as microwave-assisted or conventional sample digestion. The effects of solutions containing inorganic acids differ from those of matrix-free solutions: (i) a change in primary and tertiary drop size distributions of the generated aerosol;[1, 2] and/or (ii) a change in the ICP energetic properties if non-robust plasma conditions are used.[3, 4]

In contrast to matrix effects caused by easily ionized elements, which can induce either analyte signal suppression or enhancement, inorganic acids basically produces signal suppression as compared to matrix-free solutions.

To eliminate, or at least to reduce inorganic acid matrix effects, several experimental strategies have been developed. These strategies include sample pretreatment for analyte-matrix separation,[5-9] alternative sample introduction systems,[10, 11] instrumental parameter optimization,[12] as well as the use of different calibration modalities.[13-19]

Most analyte–matrix separation methods and analyte-preconcentration methods are slow and tedious processes and can even require overnight treatments.[9] However, in many cases, analyte–matrix separation approaches can be carried out either off-line or on-line using flow injection or lab-on-valve (LOV)[20, 21] approaches based on sequential injection. Nevertheless, relatively large sample/reagent consumption is required in flow injection analysis and relatively complex systems are often needed.

The use of alternative sample introduction systems has also some disadvantages. Normally, the addition of new components, such as an electrothermal vaporizer[10] or a desolvation unit,[11] increases the cost of the system and complicates the adjustment of experimental conditions and, therefore, the analytical procedure itself becomes more complex. Moreover, instrumentation including these additional components is also more difficult to commercialize, since most customers prefer user-friendly instruments.

Compensation for matrix effects using proper calibration methods is also widely used in quantitative analysis by ICP-based techniques. Matrix matching calibration is one of the

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most common approaches. However, great care must be taken to prepare and handle calibration standards in order to ensure uncertainty and trueness when matrix matching calibration is used. This requires gravimetric and volumetric-based methods, carefully planned details of experimental procedures and extreme care to avoid errors such as those due to evaporation.[17-19] This procedure is time-consuming and several authors prefer to match only the acid concentration after acid digestion.[13-16] When matrix matching is not practical, other calibration methods can also be used to compensate for matrix effects. These include standard addition and internal standard approaches. With internal standardization, common analyte internal standardization[22] or interference standard (IFS)[23] methods, the selection of appropriate internal standards (or argon species in the case of the IFS method) is difficult, because in addition to energy, wavelength or mass, chemical stability and matrix concentration considerations, several unpredictable processes occurring in the sample introduction system and inside the plasma also need to be taken into account. When matrix complexity is such that matrix matching calibration and internal standardization are ineffective, the standard addition calibration offers a robust strategy for the compensation of matrix effects. However, this calibration method is slow, tedious and time-consuming as numerous solutions need to be prepared. To avoid such problems, standard addition calibration can be carried out on-line. On-line calibration combines the trueness of the classical standard addition calibration with the simplicity and speed of external calibration. For this reason, there is an increasing interest in systems offering easier calibration strategies. In general, these systems provide a simple, fast and easy way to analyze different kinds of samples using on-line calibration modalities. The various ways of performing on-line calibration using simultaneous nebulization can be found in the literature: (i) using a modified nebulizer[24, 25] or multinebulizer;[26-29] (ii) using two nebulizers[30] and/or spray chamber arrangements;[31, 32] and (iii) using two independent sample introduction systems.[33, 34]

Our research group has recently reported the successful removal of matrix effects caused by high concentration of easily ionized elements[27-30] and organic solvents[26] using multinebulization systems.

The aim of this work was to propose an easy method for compensation of inorganic acid matrix effects in ICP-OES and ICP-MS analyses. The method consists in the application of the on-line standard addition calibration using a *Flow Blurring*® multinebulizer-based introduction system. A standard sample introduction (SSI) system was also used

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throughout this work for comparison purposes. Analytical capabilities of both systems were firstly assessed by evaluating the analytical figures of merit obtained in the analysis of matrix-free solutions with the external calibration. Subsequently, the capability of the on-line standard addition calibration for acid effect compensation was evaluated and compared with that of traditional off-line calibration procedures performed with the SSI system. To this end, different kinds of samples (*i.e.,* synthetic acid samples and acid-digested samples – a real and a certified reference material of whole milk powder) were analyzed using the proposed (on-line) and the traditional off-line calibration methods in both ICP-OES and ICP-MS spectrometers. Results obtained from the different calibration methods were compared in terms of trueness and uncertainty.

2. Experimental

2.1. Equipment

An axially-viewed inductively coupled plasma optical emission spectrometer (model Vista AX, Varian Inc., Melbourne, Australia) and an inductively coupled plasma mass spectrometer (model 820-MS, Varian Inc., Melbourne, Australia) were used. When the ICP-MS was operated with the SSI system, an automatic sampler (model SPS3, Varian) was used. For both ICP-OES and ICP-MS instruments, quartz torches with 2.3 mm diameter injector tubes were employed. To avoid heating and also for easy accessibility, the sample introduction systems were always located outside the ICP torch compartment. Technical details of these spectrometers have been previously reported[35, 36] and the optimized operating conditions adopted in the work here described are shown in Table 1.

For ICP-OES analysis, several atomic and ionic emission lines corresponding to different elements contained in the samples were selected in order to cover a wide range of energy sum, E_{sum} (*i.e.*, excitation energy for atomic emission lines and the sum of excitation energy and ionization energy for ionic emission lines). Similarly, a range of masses corresponding to different isotopes were chosen for ICP-MS analysis (see Table S1 in ESI†).

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2.2. Sample introduction systems

The FBMN-based system evaluated by this work consisted of a *Flow Blurring*® multinebulizer coupled to a spray chamber. The FBMN, already described in detail elsewhere,[26, 28] consists of two *Flow Blurring*® nebulization units (nozzles) joined together by a cylindrical PTFE body, as shown in Figure 1. The multinebulizer has a common nebulization gas inlet, and independent liquid inlets for each nozzle. The hydrodynamic principles and main features of the *Flow Blurring*® nebulization have been previously introduced.[37, 38] The FBMN was operated in two different commercial spray chambers: (i) a commercial cyclonic-type spray chamber (Model Tracey, 50 mL internal volume, Glass Expansion, Melbourne, Australia) for ICP-OES analysis; and (ii) a double pass spray chamber (Scott type, 110 mL internal volume, Glass Expansion) for ICP-MS analysis. This chamber was contained within a Peltier cooler device operated at 3°C to condensate excess solvent, thus minimizing oxides formation in the argon plasma. In all cases, the spray chamber-FBMN association is referred to as the FBMN-based system.

A concentric pneumatic nebulizer (model MicroMist (MM), Glass Expansion) coupled to the same abovementioned spray chambers depending on an ICP-based technique, was used as the standard sample introduction system. This SSI system was used as a reference system for comparison with the FBMN-based system.

For ICP-OES analysis, the liquid uptake rate was controlled *via* a multichannel peristaltic pump (model MCP, Ismatec, Glattbrugg, Switzerland). However, the peristaltic pump of the spectrometer was used in ICP-MS analysis for the controlling of the liquid uptake rate. In all cases, the same Tygon® peristaltic tubes (R-3607, id. 0.51 mm, Ismatec) were used.

The spray chamber waste was removed with the peristaltic pump of the spectrometers used in this study. Argon was always used as the nebulizing–carrier gas, and the nebulizing argon flow rates were also controlled by the spectrometers. In ICP-OES, the liquid uptake rate and nebulizing gas flow rate were optimized for both FBMN-based and SSI systems by simultaneously maximizing all the studied emission signals. A univariate optimization analysis was carried out at three different liquid flow rates (*i.e.*, 300, 400 and 500 μL min^{-1}) and at three different gas flow rates (*i.e.*, 0.60, 0.70 and 0.80 L min^{-1}). By contrast, in ICP-MS, they were optimized achieving the maximum

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ionic intensity for all elements and the formation of oxides and double-charged ions was kept to a minimum (Table 1).

2.3. Reagents and standards

Deionized water (18 MΩ cm) generated from a Milli-Q® Plus Total Water System (Millipore Corp., Bedford, MA, USA) was used to prepare all solutions. Prior to use, all glassware and polypropylene flasks were soaked in 10% v v^{-1} for 24 hours and rinsed with deionized water before use.

2.3.1. Solutions for ICP-OES analysis. Synthetic samples with 1.0 mg kg^{-1} of Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Na, Ni, Pb, Sb, Se, Sr and Zn were prepared in three different inorganic acids (*i.e.*, HNO_3, HCl and H_2SO_4). A set of solutions having increasing acid concentrations was prepared for each one. These sets consisted of five solutions having 0.1% (w w^{-1}), 1% (w w^{-1}), 5% (w w^{-1}), 10% (w w^{-1}) and 15% (w w^{-1}) acid concentration for HNO_3 and HCl media, and four solutions having 0.1% (w w^{-1}), 1% (w w^{-1}), 5% (w w^{-1}) and 10% (w w^{-1}) acid concentration for the H_2SO_4 medium. The synthetic samples were made using 1000 mg L^{-1} single-element stock solutions of each analyte (Tec-Lab, Hexis Científica, São Paulo, SP, Brazil), H_2SO_4 (98% w w^{-1}, Merck, Darmstadt, Germany) and HNO_3 and HCl were purified obtained by sub-boiling distillation (Milestone, Sorisole, Italy).

For external calibration, the same calibration standards were used with both the FBMN-based and SSI systems. Six calibration standards were prepared by appropriate dilution of the 1000 mg L^{-1} single-element stock solutions up to analyte concentrations of 0.4, 0.8, 1.2, 1.6 and 2.0 mg kg^{-1}. All calibration standards were prepared in 0.1% (w w^{-1}) nitric acid. A calibration blank containing the same HNO_3 concentration was also prepared.

For on-line standard addition calibration using the FBMN-based system, the same set of calibration standards and synthetic samples were used. However, in this case, calibration standards were spiked with 1.0 mg kg^{-1} of Y and synthetic samples were spiked with 1.0 mg kg^{-1} of In (see Section 2.6 for clarification).

For conventional standard addition calibration using the SSI system, the calibration standards were prepared by spiking the synthetic samples with the abovementioned stock solutions up to the desired added concentrations.

2.3.2. Solutions for ICP-MS analysis. Synthetic samples with 7.5 µg kg^{-1} of Ag, As, Cd, Co, Cu, Mn, Pb, Sb and Se were prepared in the same inorganic acids. For each

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inorganic acid, a set of four solutions having 0.1% (w w^{-1}), 1% (w w^{-1}), 5% (w w^{-1}) and 10% (w w^{-1}) acid concentration was prepared. These samples were also prepared from the abovementioned 1000 mg L^{-1} single-element stock solutions.

Calibration standards preparation was similar to that described for ICP-OES analysis with the different calibration methods, the only difference being the analyte concentration level. Six calibration standards having 1, 3, 6, 9, 12 and 15 μg kg^{-1} analyte concentrations, and a calibration blank, were prepared in 0.1% (w w^{-1}) HNO_3 for external calibration with the FBMN-based and SSI systems. For on-line standard addition calibration using the FBMN-based system, these calibration standards and the synthetic samples were spiked with 1.0 μg kg^{-1} of Y and 1.0 μg kg^{-1} of In, respectively (see Section 2.6 for clarification). Calibration standards for conventional standard addition calibration using the SSI system were prepared as for ICP-OES measurements.

For both ICP-OES and ICP-MS measurements, when matrix matching calibration was carried out, potassium hydrogen phthalate (Merck, Darmstadt, Germany), sodium hydroxide (Merck) and phenolphthalein (Mallinckrodt Baker, Phillipsburg, NJ, USA) were used to determine the nitric acid concentration in the digested samples by titrimetric analysis.

To evaluate the trueness of the calibration methods, a real sample (Nestlé Brasil, São Paulo, SP, Brazil) and a certified reference material (NIST RM 8435, Gaithersburg, MD, USA) of whole milk powder were analyzed by both ICP-based techniques.

2.4. Digestion of whole milk powder

The whole milk powder samples (*i.e.*, a real sample and a certified reference material) were microwave-assisted acid-digested using a closed vessel cavity microwave digestion system (model Ethos 1600, Milestone). A 300 mg sample was weighted out in the reaction vessel and digestion reagents (*i.e.*, 3 mL hydrogen peroxide (30% w w^{-1}, Synth Labs, Diadema, SP, Brazil) and 8 mL purified HNO_3) were added. The mixture was allowed to react for 2 h prior to sealing the vessel. Three vessels were filled with samples and digestion reagents and one vessel, containing digestion reagents only, was used as a blank. After sealing and inserting the vessels in the microwave oven cavity, the digestion program shown in Table S2 in ESI† was applied. After digestion, the solutions were quantitatively transferred into cleaned polypropylene flasks and diluted to 50 g with deionized water. This sample dilution was used for determination of all the

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elements except Ca, K and Na. Additional dilution (*i.e.*, 0.5 g / 50 g using HNO_3 8% (w w^{-1})) was needed to analyze these elements.

2.5. Calibration strategies

Different calibration methods were compared in both ICP-OES and ICP-MS analysis depending on the analyzed sample (*i.e.*, matrix-free solutions, synthetic acid samples or whole milk powder).

2.5.1. Matrix-free solutions

For SSI and FBMN-based systems all figures of merit were estimated by analyzing matrix-free solutions using external calibration.

2.5.2. Synthetic samples

Synthetic samples containing different acids and acid concentrations were used for acid matrix effects evaluation. These samples were analyzed using external calibration and standard addition calibration. These calibration methods were performed with both sample introduction systems (*i.e.,* FBMN-based and SSI systems) and in both optical and mass spectrometers. With the FBMN-based system, external calibration was carried out in the traditional off-line manner. Namely, calibration standards and synthetic samples were sequentially nebulized through the two nebulization units of the FBMN. However, standard addition calibration was performed on-line. Namely, the synthetic sample solution was continuously nebulized through one of the nebulization units of the FBMN while calibration standards were sequentially nebulized through the other. In all cases, the results obtained with the FBMN-based system were compared to those obtained with the SSI system using off-line calibration.

Table 1 shows the liquid uptake rate conditions used with both sample introduction systems for the different calibration methods. As observed, the total liquid uptake rate in SSI and FBMN-based systems was always 400 µL min^{-1}. However, in the FBMN-based system, sample and standards uptake rates were different depending on the calibration method applied. For external calibration, sample and/or standards were sequentially nebulized at 400 µL min^{-1}. That is, 200 µL min^{-1} through each nebulization nozzle. For on-line standard addition calibration, the sample was nebulized at 200 µL min^{-1} through one nozzle and the standards were simultaneously nebulized at 200 µL min^{-1} through the second one.

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2.5.3. Whole milk powder

Whole milk powder samples were analyzed by the on-line standard addition calibration approach using the FBMN-based system and by matrix matching calibration using the SSI system. Matrix matching calibration is widely used for the analysis of digested samples, since acid concentration in the digested solutions can be easily matched in the calibration standards. However, acid concentration in the digested samples needs to be previously determined by titration procedures, given that it changes during the digestion process. In this work, nitric acid concentration was determined by titration with NaOH solution using a phenolphthalein indicator. Potassium hydrogen phthalate was used for NaOH solution standardization.

2.6. Relative transport efficiency

Relative transport efficiency (*fr*) evaluation is an essential requirement to perform on-line standard addition calibration with the use of multinebulizers.[24, 26] This parameter is needed to correct for underestimation or overestimation of the real analyte concentration in the sample due to possible differences in sample and calibration standards nebulization through the different multinebulizer nozzles. Numerous procedures for relative transport efficiency evaluation have been proposed by several authors,[24, 26, 33] including Bauer and Broekaert's method[24] applied in this work. This procedure is based on the use of two elements other than the analytes of interest. One of them, named "primary", is added to the sample and the other one, named "supplementary", is added to the standards. Relative transport efficiency can be determined from the emission line intensity measurements of these primary and supplementary elements during the standard addition calibration procedure used for sample analysis.

In this work, indium and yttrium were selected as primary and supplementary elements, respectively. Samples and standards were spiked with these elements up to concentrations indicated in Sections 2.3.1. and 2.3.2., and the correction method was applied to both ICP-OES and ICP-MS analyses. Extension of the procedure to ICP-MS analysis was done by considering signals from isotopes, rather than from emission lines, of the selected primary and supplementary elements. The reader may refer to Bauer and Broekaert[24] for further details of the correction procedure application.

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DOI: 10.1039/C4JA00079J

3. Results and discussion

3.1. Analytical figures of merit

As a first step of this study, analytical figures of merit were obtained in order to compare the analytical capabilities of both SSI and FBMN-based systems in ICP-OES and ICP-MS measurements. Thus, aqueous (matrix-free) calibration standards were used to evaluate sensitivity, precision and limits of detection obtained with both introduction systems. Results of this evaluation are summarized in Figure S1, Tables S3 and S4 in ESI†.

3.1.1. Sensitivity

Figure S1 in ESI† shows the relative sensitivity obtained with both introduction systems in ICP-OES and ICP-MS measurements. Relative sensitivity is defined as the ratio between the sensitivity values obtained with the FBMN-based system and those obtained with the SSI system. Therefore, a relative sensitivity value higher than one means better sensitivity with the FBMN-based system. It can be observed that higher sensitivity was obtained with the FBMN-based system for all emission lines and isotopes evaluated, the difference in sensitivity being slightly more pronounced in ICP-OES than in ICP-MS analysis.

3.1.2. Precision

Table S3 in ESI† shows the precision, expressed as RSD (%), obtained for both systems. Precision was evaluated at three different analyte concentration levels: (i) 0.4, 1.2, and 2.0 mg kg^{-1} for ICP-OES; and (ii) 1, 6 and 12 μg kg^{-1} for ICP-MS measurements. It is noted that overall, the FBMN-based system provides more precise results than the SSI system in ICP-OES, especially at the highest concentration level. Precision in ICP-MS was also equal or even higher regarding the FBMN-based system for most of the isotopes evaluated, without any appreciable trend with regard to analyte concentration level. Averaging over the whole set of emission lines evaluated, RSD values of 1.5%, 2.1% and 1.1% were obtained in ICP-OES for the FBMN-based system at 0.4, 1.2 and 2.0 mg kg^{-1} concentration levels, respectively; compared to a 1.6%, 2.2% and 2.3% RSD values obtained for the SSI system at the same concentration levels. Average values in ICP-MS were 5%, 4% and 4% for the FBMN-based system and 4%, 5% and 4% for the SSI system, at 1, 6 and 12 μg kg^{-1}, respectively. It is noted that higher precision was always obtained in ICP-OES for the two introduction systems evaluated.

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3.1.3. Limits of detection

Table S4 in ESI† shows the limit of detection based on 3 times the standard deviation of the determination of 10 blanks. As observed, lower LOD values were obtained with the FBMN-based system for all emission lines and isotopes evaluated. ICP-OES limits of detection ranged from 0.03 μg kg^{-1} for SrII (407.771 nm) to 33 μg kg^{-1} for SeI (196.026 nm) regarding the FBMN-based system, and from 0.05 to 48 μg kg^{-1} for the same pair of emission lines with the SSI system. ICP-MS values ranged from 2 ng kg^{-1} for Mn (55 amu) to 45 ng kg^{-1} for Se (77 amu) with the FBMN-based system, and from 3 to 61 ng kg^{-1} for the same pair of isotopes with the SSI system.

3.2. Matrix effects evaluation

Matrix effects induced by inorganic acids were evaluated from the analysis of synthetic solutions having different concentrations in HNO_3, HCl and H_2SO_4. Preliminarily, samples were analyzed using both FBMN-based and SSI systems through external calibration. Subsequently, a second analysis was performed by using on-line standard addition calibration for the FBMN-based system and traditional standard addition calibration for the SSI system. Discussion on matrix effects is based on the trueness and uncertainty of the results obtained. Herein, trueness is reported as the percent recovery of a known added amount of analyte in the synthetic sample matrix; uncertainty was evaluated in the manner already described elsewhere.[30] In all cases, the concentration of analytes in the synthetic samples was near the centroid of the calibration graph in order to fulfill the condition for minimum uncertainty.[39] All results shown are the mean of five replicates. The emission lines and isotopes studied are presented on increasing E_{sum} values (Table S1 in ESI†).

3.2.1. External calibration

Figures S2 and S3 in ESI† show the percent recovery values obtained with the FBMN-based and SSI systems, respectively, when external calibration was applied. Information shown in these figures is summarized in Table 2 wherein, for the sake of simplification, only averaged recovery values over all the emission lines evaluated are shown. Due to isobaric interferences caused by $^{40}Ar^{35}Cl^+$ on $^{75}As^+$ determination and $^{40}Ar^{37}Cl^+$ on $^{77}Se^+$ determination, recovery values for these elements were not considered in the average recovery calculation for HCl matrices with ICP-MS.

3.2.1.1. ICP-OES evaluation. Table 2 shows that recovery values were found to be dependent on both the inorganic acid tested and the acid concentration for the two

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introduction systems evaluated. As expected, lower recovery values were obtained at increasing acid concentration, indicating a signal reduction due to matrix effect caused by acids. It is noted that matrix effects start to appear at 10% (w w^{-1}) acid concentration in HNO_3 and HCl matrices and at a much lower concentration -only 1% (w w^{-1})- in a H_2SO_4 matrix. Inorganic acid induced matrix effects, including the marked effect observed for H_2SO_4, have already been reported by other authors. These are known to be due to changes originated in the nebulization process due to the different physical properties of the acids (*i.e.*, surface tension, density, viscosity, and volatility) and/or to variations in plasma atomization and excitation conditions.[1, 40] Plasma-related matrix effects can be avoided, or at least minimized, by using robust conditions. Plasma conditions were monitored in this study by using the MgII (280.270 nm) / MgI (285.213 nm) intensity ratio approach. It has been reported that MgII / MgI ratio values higher than 8 can be used to indicate robust conditions in a radially viewed plasma mode. However, this value decreases by approximately 4 when an axially viewed mode is used, even if maintaining the same robust ICP operating conditions.[41] According to this work, MgII / MgI ratio was found to fluctuate between 5.5 and 5.7 for all acid concentrations tested and sample introduction systems used, indicating operation at robust conditions. Therefore, it can be inferred that matrix effects observed in this work are mainly related to nebulization/aerosol transport processes, rather than originating in the plasma. This assumption is also supported when considering the results shown in Figures S2 and S3 in ESI†. It is noted that signal suppression induced by a given acid at a given concentration is independent of the nature (*i.e.*, atomic or ionic) or E_{sum} value of the emission line evaluated, which also suggests non-plasma-related matrix effects.

Whichever the origin of these matrix effects, Table 2 shows that they are almost independent of the introduction system used. For instance, by considering only the recovery data obtained for those acid concentrations inducing matrix effects (*i.e.*, 10% (w w^{-1}) and 15% (w w^{-1}) for nitric and hydrochloric acids; and 1% (w w^{-1}), 5% (w w^{-1}) and 10% (w w^{-1}) for sulfuric acid), the average recovery values ranged from 89 to 75%, 87 to 79% and 92 to 73%, for nitric, hydrochloric and sulfuric acids, respectively, using FBMN-based system. Similar recovery values, from 91 to 81%, 92 to 81% and 92 to 74%, respectively, were observed when using the SSI system.

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On the other hand, uncertainty values associated with the recovery values were always found to increase when increasing the acid concentration, without any noteworthy trend related to the acid tested or the introduction system used, as observed in Table 2.

3.2.1.2. ICP-MS evaluation. Overall, results obtained for ICP-MS were quite similar to those observed for ICP-OES. As expected, recovery values decreased at increasing acid concentration indicating signal suppression induced by the acid matrix. In the case of ICP-MS, however, matrix effects were found to be stronger compared to ICP-OES, being significant at an even lower acid concentration (*i.e.,* 5% (w w^{-1})) in HNO_3 and HCl matrices. This effect is represented in Table 2. As shown, considering only the recovery values for acid concentrations inducing matrix effects, recovery values ranging from 81 to 64%, 81 to 72% and 79 to 47%, for nitric, hydrochloric and sulfuric acid, respectively, were obtained with the FBMN-based system, and comparable values were obtained with the SSI system. Acid matrix effects have been reported to be more severe in ICP-MS than in ICP-OES.[42] Notwithstanding, as in the case of ICP-OES, these effects are, highly dependent on the experimental conditions used. ICP-OES and ICP-MS spectrometers in this work were operated with a different spray chamber and, as reported by several authors, the type of spray chamber (*i.e.*, double-pass or cyclonic) also plays a critical role in signal reduction induced by the presence of acid.[43-46]

Contrary to ICP-OES, uncertainty values associated with the obtained recovery values were independent not only of the acid tested and the introduction system used but also of the acid concentration. As noted, higher uncertainty values were obtained in ICP-MS measurements compared to ICP-OES, ranging from 3 to 8%.

3.2.2. Standard addition calibration

Figures S4 and S5 in ESI† show the percent recovery values obtained with the FBMN-based and the SSI systems when on-line and conventional standard addition calibration, respectively, were applied. Results shown in these figures are also summarized in Table 2.

3.2.2.1. ICP-OES evaluation. Table 2 shows how both conventional and on-line standard addition calibrations improved recovery values compared to external calibration. Averaged recovery values ranged from 98 to 102% in all solutions tested for the two introduction systems, without any appreciable trend when increasing acid concentration. Likewise, Figures S4 and S5 in ESI† reveal that, for all emission lines

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evaluated, recovery values always match 100%. Uncertainty values (Table 2) were similar for all conditions studied, being 5% in almost all cases.

3.2.2.2. ICP-MS evaluation. Similar results were obtained using this technique, with recovery values ranging from 97 to 106% without any acid concentration dependence (Table 2). Uncertainty values, ranging from 6 to 9%, were also higher than in ICP-OES with this calibration. This behavior can be observed in Figures S4 and S5 in ESI† for all isotopes evaluated.

3.3. Certified reference material and real sample analysis

Results shown in Section 3.2. demonstrate that both on-line and off-line standard addition calibration are useful for acid matrix effect compensation. However, the on-line procedure using the FBMN-based system offers several practical advantages, such as handling simplicity, reduction in the total analysis time and reagent/sample consumption. An alternative calibration method, extensively used for analysis of acid-digested samples with conventional sample introduction systems, is matrix matching calibration. For this reason, a comparative study between on-line standard addition and matrix matching calibration was also carried out. In this study, a real sample and a sample of certified reference material of whole milk powder were analyzed in ICP-OES and ICP-MS using both calibration procedures (*i.e.*, on-line standard addition calibration with the FBMN-based system and matrix matching calibration using the SSI system). Thus, both samples were microwave-assisted acid-digested as described in Section 2.4. The digested solutions were subsequently titrated in order to obtain the final acid concentration for the matching of the acid content in the standards for external calibration (see Table S5 in ESI†). As in the preceding section, the calibration methods evaluated were compared in terms of trueness (*i.e.*, recovery) and uncertainty of the obtained results.

3.3.1. Analysis of a certified reference material (CRM)

Table 3 shows the results obtained for the analysis of a whole milk powder CRM. Certified values are also included. In this case the different analytes in the sample were determined by either ICP-OES or ICP-MS based on their concentration levels. In general, satisfactory results were obtained with both calibration methods. As observed, the values established were consistent with certified concentration intervals for all analytes determined by ICP-OES or ICP-MS. Recovery values ranging from 93 to 106% and from 95 to 104% were obtained using the SSI system and the FBMN-based

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system, respectively. Uncertainty values obtained with the two calibration methods were found to be similar and ranged from 7 to 26%.

3.3.2. Analysis of a real sample

A commercial whole milk powder sample was acquired from a supermarket in São Carlos, SP, Brazil. The sample was microwave-assisted acid-digested in the same manner as the previous CRM and was analyzed using the proposed calibrations. Thereafter, the digested solutions were spiked with analytes at two different concentration levels to evaluate trueness from recovery assays. Spiked concentrations of 0.5 and 1.0 mg kg^{-1} were used for ICP-OES analysis, and of 4 and 7 µg kg^{-1} for ICP-MS analysis. Recovery values were calculated based on the difference between the analyte concentrations found after and before spiking the sample. For those analytes which concentrations were found to be below the limits of quantification (LOQ), recovery values were calculated using exclusively the analyte concentration found after spiking the sample.

Table 4 shows the results of this evaluation whereby concentration values of several analytes are below the LOQ. LOQ values for matrix matching calibration with the SSI system and on-line standard addition calibration with the FBMN-based system are included in this table. LOQ values for matrix matching calibration were evaluated by using calibration standards containing 8% (w w^{-1}) nitric acid concentration. Thus, the nitric acid concentration in the calibration standards was similar to that in the analyzed sample (Table S5 in ESI†). For on-line standard addition calibration, LOQ values were evaluated by sequentially nebulizing calibration standards containing 0.1% (w w^{-1}) nitric acid through one of the nebulizer nozzles, while continuously nebulizing a blank sample through the other nozzle. Since a blank milk powder sample (free-from analytes) was not available, 8% (w w^{-1}) HNO_3 was used as a blank sample. As observed, the LOQ values were similar for both calibrations. However, it is worth mentioning that the calibration standard uptake rate in the FBMN-based system was half of that used in the SSI system (*i.e.*, 200 µL min^{-1} in FBMN-based system compared to 400 µL min^{-1} in SSI system).

Table 4 results show that in general the analyte concentrations of both calibrations are fairly consistent. In addition, recovery values obtained from the two recovery assays were close to 100% for both calibration methods and for both spectrometric techniques.

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4. Conclusions

The sample introduction system based on the use of a *Flow Blurring*® multinebulizer has been successfully applied to the analysis of samples having high inorganic acid concentrations. The use of this system for on-line standard addition calibration has proved to be an efficient calibration procedure to compensate acid matrix effects in both ICP-OES and ICP-MS analyses, leading to a similar trueness and uncertainty as off-line standard addition and matrix matching calibrations. Compared to off-line standard addition calibration, however, the on-line procedure is faster, easier to handle and greatly reduces the reagent/sample consumption. Moreover, since calibration standards used in on-line standard addition calibration do not need matrix matching (*i.e.*, acid concentration in standards as low as 0.1% (w w^{-1}) is usually required), titration procedures after sample digestion is avoided, therefore offering an added advantage over the more commonly used matrix matching calibration procedure. The aforementioned experimental and economic benefits show the potential for the proposed system to become an excellent choice for direct analysis of digested samples by ICP-OES and ICP-MS techniques.

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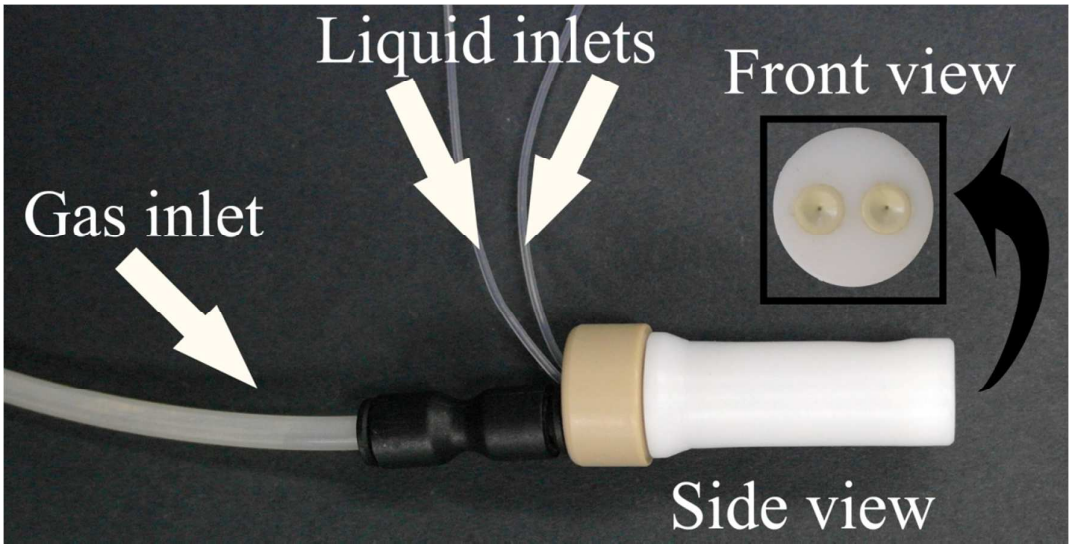

Figure 1. Photograph of the *Flow Blurring*® multinebulizer (FBMN) and its front view with the two nebulization units.

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Table 1. ICP-OES and ICP-MS experimental parameters.

Parameter	Varian Vista AX	Varian 820-MS
RF applied power (kW)	1.3	1.4
Outer gas flow rate (L min^{-1})	15	18
Intermediate gas flow rate (L min^{-1})	1.5	1.8
Number of replicates	5	5
Dwell time (ms)	-	20
Viewing mode	Axial	-
SSI system		
Nebulizer	MicroMist	MicroMist
Spray chamber	Cyclonic-type	Scott-type
Spray chamber temperature (°C)	-	3
External calibration		
Gas flow rate (L min^{-1})	0.70	1.05
Sheath gas flow rate (L min^{-1})	-	0.10
Standard/sample uptake rate (µL min^{-1})	400	400
Conventional standard addition calibration		
Gas flow rate (L min^{-1})	0.70	1.05
Sheath gas flow rate (L min^{-1})	-	0.10
Spiked sample uptake rate (µL min^{-1})	400	400
FBMN-based system		
Nebulizer	FBMN	FBMN
Spray chamber	Cyclonic-type	Scott-type
Spray chamber temperature (°C)	-	3
External calibration		
Gas flow rate (L min^{-1})	0.70	1.05
Sheath gas flow rate (L min^{-1})	-	0.10
Standard/sample uptake rate (µL min^{-1})	400	400
On-line standard addition calibration		
Gas flow rate (L min^{-1})	0.70	1.05
Sheath gas flow rate (L min^{-1})	-	0.10
Total liquid uptake rate (µL min^{-1})	400	400
Standard uptake rate (µL min^{-1})	200	200
Sample uptake rate (µL min^{-1})	200	200

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Table 2. Mean recovery values obtained in the analysis of synthetic acid samples by ICP-OES and ICP-MS using external and standard addition calibrations with the FBMN-based and the SSI systems.

		Mean recovery (%)							
		FBMN-based system				SSI system			
		ICP-OES		ICP-MS		ICP-OES		ICP-MS	
Acid	Concentration (w w^{-1})	E.C.[a]	On-line S.A.[b]	E.C.[a]	On-line S.A.[b]	E.C.[a]	S.A.[b]	E.C.[a]	S.A.[b]
HNO_3	0.1	100.2±0.8	101±5	102±5	97±8	100.1±0.9	101±5	100±3	101±8
	1	100.2±1.1	99±5	100±5	98±7	100.1±1.0	101±5	100±2	100±7
	5	99.4±1.1	101±5	81±6	98±7	99.4±1.3	100±5	86±3	102±7
	10	88.9±1.5	100±5	64±4	106±8	91±3	100±5	71±3	99±8
	15	75±4	101±4	-	-	81±3	100±5	-	-
HCl	0.1	100.2±1.1	102±5	102±5	105±9	100.4±1.3	100±5	100±5	104±8
	1	99.8±0.9	99±5	101±5	104±8	99.6±1.1	101±5	101±4	101±6
	5	100±2	101±5	81±5	103±8	100.6±1.1	101±5	81±7	105±6
	10	87±2	101±4	72±5	104±7	92±3	99±5	68±8	97±6
	15	79±2	100±4	-	-	81±3	98±5	-	-
H_2SO_4	0.1	99.4±1.2	100±5	100±6	102±7	99.5±1.1	100±5	100±5	100±6
	1	92±2	100±5	79±6	98±8	92±2	100±5	75±6	101±6
	5	84±3	100±5	63±6	99±7	84±3	100±6	52±7	101±7
	10	73±4	100±5	47±7	101±8	74±3	100±5	41±6	103±8

[a]External calibration. The uncertainty values are the mean uncertainty of all emission lines and isotopes. For each emission line and isotope, uncertainty was estimated as the standard deviation of the interpolated concentration.[39]
[b]Standard addition. The uncertainty values are the mean uncertainty of all emission lines and isotopes. For each emission line and isotope, uncertainty was estimated as the standard deviation of the extrapolated concentration.[39]

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Table 3. Analysis of a whole milk powder CRM using matrix matching and on-line standard addition calibrations in ICP-OES and ICP-MS.

		SSI system		FBMN-based system	
		Matrix matching calibration		On-line standard addition calibration	
Emission line (nm)	Certified value[a]	Found value[a]	Recovery[b]	Found value[a]	Recovery[b]
CaII (396.847)	9220±490	9201±1117	100±12	9027±1480	98±16
KI (766.491)	13630±470	13924±1136	102±8	14222±1865	104±14
MgII (280.270)	814±76	862±126	106±15	806±188	99±23
NaI (588.995)	3560±400	3453±253	97±7	3630±510	102±14
SrII (407.771)	4.35±0.50	4.1±1.1	94±25	4.4±0.8	101±18
ZnI (213.857)	28.0±3.1	26±7	93±26	27±3	95±11
Isotope (amu)	Certified value[a]	Found value[a]	Recovery (%)[b]	Found value[c]	Recovery (%)[b]
Cu (63)	0.46±0.08	0.48±0.09	104±18	0.45±0.07	98±15
Mn (55)	0.17±0.05	0.17±0.02	98±12	0.17±0.02	102±14
Pb (208)	0.11±0.05	0.11±0.02	104±19	0.109±0.013	99±12

[a]In mg kg^{-1} ± confidence interval at 95% (n = 3).
[b]In % ± confidence interval at 95% (n = 3).

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Table 4. Analysis and recovery values at different concentration levels of a commercial whole milk powder sample using matrix matching and on-line standard addition calibrations in ICP-OES and ICP-MS.

	SSI system				FBMN-based system			
	Matrix matching calibration				On-line standard addition calibration			
			Spike recovery (%)[c]				Spike recovery (%)[c]	
Emission line (nm)	LOQ[a] (µg kg^{-1})	Found value (mg kg^{-1})[c]	0.5 mg kg^{-1}	1.0 mg kg^{-1}	LOQ[b] (µg kg^{-1})	Found value (mg kg^{-1})[c]	0.5 mg kg^{-1}	1.0 mg kg^{-1}
AlI (396.152)	11	<LOQ	95±3	102±2	15	<LOQ	100±8	97±4
AsI (188.980)	113	<LOQ	111±10	100±2	135	<LOQ	103±8	101±6
BaII (455.403)	0.2	1.6±0.4	102±3	104±2	0.3	2.1±0.3	105±7	103±6
CaII (396.847)	11	3188±230	93±3	98±6	15	2679±774	102±7	99±8
CdII (226.502)	4	<LOQ	97±2	93±2	6	<LOQ	100±6	103±6
CoII (238.892)	14	<LOQ	101±3	95±2	19	<LOQ	104±10	104±6
CrII (267.716)	5	<LOQ	98±3	95±2	7	<LOQ	104±8	94±6
CuI (324.754)	5	<LOQ	97±3	102±2	7	<LOQ	108±11	99±6
FeII (238.204)	6	<LOQ	98±2	95±2	8	<LOQ	100±5	104±6
KI (766.491)	11	10499±2439	95±5	106±6	16	8060±2321	104±7	97±10
LiI (670.783)	0.3	<LOQ	94±3	93±3	0.4	<LOQ	105±11	96±6
MgII (280.270)	3	575±123	97±3	98±2	4	398±109	95±7	98±9
MgI (285.213)	12	607±134	98±3	98±2	18	471±134	103±4	94±6
MnII (257.610)	0.8	<LOQ	101±3	98±2	1.1	<LOQ	103±7	100±6
NaI (588.995)	27	3124±762	91±7	92±4	41	3351±924	103±3	94±7
NiII (216.555)	34	<LOQ	110±4	90±3	44	<LOQ	107±11	97±6
PbII (220.353)	134	<LOQ	92±11	96±2	199	<LOQ	100±8	103±6
SbI (217.582)	143	<LOQ	98±6	96±3	189	<LOQ	106±11	105±8
SeI (196.026)	195	<LOQ	107±4	97±4	223	<LOQ	105±8	103±6
SrII (407.771)	0.14	3.3±0.7	100±1	97±2	0.2	2.9±1.3	105±6	96±6
ZnI (213.857)	4	20±5	95±4	96±2	6	12±3	99±8	92±6
Isotope (amu)	LOQ[a] (ng kg^{-1})	Found value (µg kg^{-1})[c]	4 µg kg^{-1}	7 µg kg^{-1}	LOQ[b] (ng kg^{-1})	Found value (µg kg^{-1})[c]	4 µg kg^{-1}	7 µg kg^{-1}
Ag (107)	93	209±42	105±8	106±9	135	292±70	100±11	103±10
As (75)	81	<LOQ	113±6	104±7	144	<LOQ	93±6	94±13
Cd (114)	15	<LOQ	106±2	98±2	22	<LOQ	97±6	97±7
Co (59)	14	43±4	106±8	100±8	20	40±3	96±5	94±10
Cu (63)	43	670±137	94±6	104±4	73	833±84	99±7	95±19
Mn (55)	14	451±56	94±7	91±6	23	321±48	104±5	100±13
Pb (208)	52	<LOQ	101±5	93±8	75	<LOQ	95±6	95±4
Sb (121)	66	<LOQ	103±3	99±4	104	<LOQ	97±7	102±9
Se (77)	203	261±37	102±6	102±4	323	308±32	101±6	100±10

[a]Limit of quantification with external calibration using calibration standards with 8% (w w^{-1})HNO_3.
[b]Limit of quantification with on-line standard addition calibration using calibration standards with 0.1% (w w^{-1}) HNO_3 and a blank of 8% (w w^{-1}) HNO_3.
[c]Uncertainty values are the standard deviations of the results obtained from the analysis of three digested samples.

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Multinebulizer based on *Flow Blurring*® nebulization principle for the analysis of acid digested samples using on-line standard addition calibration in ICP-OES and ICP-MS.

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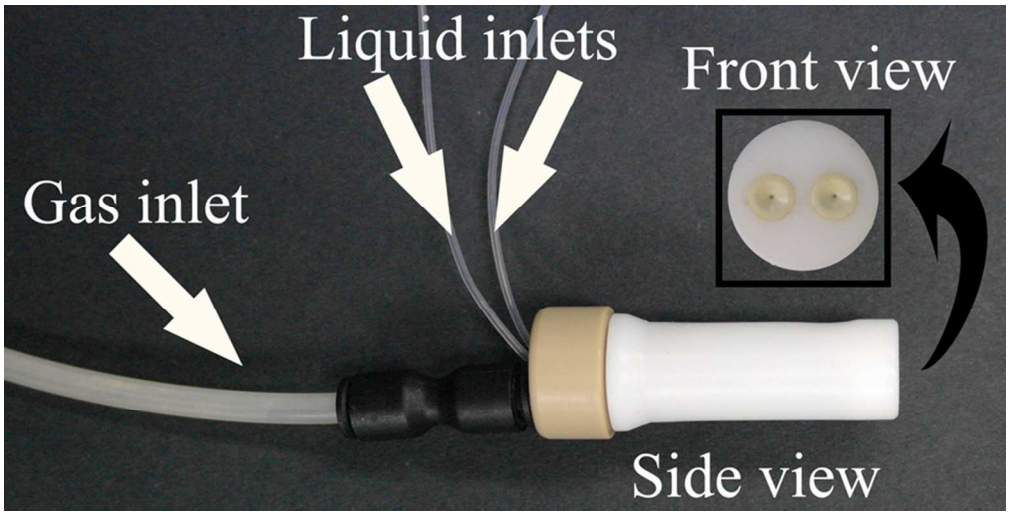

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