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

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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 HNO₃ and HCl (with acid concentrations of up to 15% (w w⁻¹)) and H₂SO₄ (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

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

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

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

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

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

26 The use of alternative sample introduction systems has also some disadvantages.
27 Normally, the addition of new components, such as an electrothermal vaporizer¹⁰ or a
28 desolvation unit,¹¹ increases the cost of the system and complicates the adjustment of
29 experimental conditions and, therefore, the analytical procedure itself becomes more
30 complex. Moreover, instrumentation including these additional components is also more
31 difficult to commercialize, since most customers prefer user-friendly instruments.

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

1 most common approaches. However, great care must be taken to prepare and handle
2 calibration standards in order to ensure uncertainty and trueness when matrix matching
3 calibration is used. This requires gravimetric and volumetric-based methods, carefully
4 planned details of experimental procedures and extreme care to avoid errors such as
5 those due to evaporation.¹⁷⁻¹⁹ This procedure is time-consuming and several authors
6 prefer to match only the acid concentration after acid digestion.¹³⁻¹⁶ When matrix
7 matching is not practical, other calibration methods can also be used to compensate for
8 matrix effects. These include standard addition and internal standard approaches. With
9 internal standardization, common analyte internal standardization²² or interference
10 standard (IFS)²³ methods, the selection of appropriate internal standards (or argon
11 species in the case of the IFS method) is difficult, because in addition to energy,
12 wavelength or mass, chemical stability and matrix concentration considerations, several
13 unpredictable processes occurring in the sample introduction system and inside the
14 plasma also need to be taken into account. When matrix complexity is such that matrix
15 matching calibration and internal standardization are ineffective, the standard addition
16 calibration offers a robust strategy for the compensation of matrix effects. However, this
17 calibration method is slow, tedious and time-consuming as numerous solutions need to
18 be prepared. To avoid such problems, standard addition calibration can be carried out
19 on-line. On-line calibration combines the trueness of the classical standard addition
20 calibration with the simplicity and speed of external calibration. For this reason, there is
21 an increasing interest in systems offering easier calibration strategies. In general, these
22 systems provide a simple, fast and easy way to analyze different kinds of samples using
23 on-line calibration modalities. The various ways of performing on-line calibration using
24 simultaneous nebulization can be found in the literature: (i) using a modified
25 nebulizer^{24, 25} or multinebulizer,²⁶⁻²⁹ (ii) using two nebulizers³⁰ and/or spray chamber
26 arrangements;^{31, 32} and (iii) using two independent sample introduction systems.^{33, 34}
27 Our research group has recently reported the successful removal of matrix effects
28 caused by high concentration of easily ionized elements²⁷⁻³⁰ and organic solvents²⁶
29 using multinebulization systems.

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

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

12 13 **2. Experimental**

14 15 **2.1. Equipment**

16 An axially-viewed inductively coupled plasma optical emission spectrometer (model
17 Vista AX, Varian Inc., Melbourne, Australia) and an inductively coupled plasma mass
18 spectrometer (model 820-MS, Varian Inc., Melbourne, Australia) were used. When the
19 ICP-MS was operated with the SSI system, an automatic sampler (model SPS3, Varian)
20 was used. For both ICP-OES and ICP-MS instruments, quartz torches with 2.3 mm
21 diameter injector tubes were employed. To avoid heating and also for easy accessibility,
22 the sample introduction systems were always located outside the ICP torch
23 compartment. Technical details of these spectrometers have been previously reported³⁵,
24 ³⁶ and the optimized operating conditions adopted in the work here described are shown
25 in Table 1.

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

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 $\mu\text{L min}^{-1}$) 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

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

3 **2.3. Reagents and standards**

4 Deionized water (18 M Ω cm) generated from a Milli-Q[®] Plus Total Water System
5 (Millipore Corp., Bedford, MA, USA) was used to prepare all solutions. Prior to use, all
6 glassware and polypropylene flasks were soaked in 10% v v⁻¹ for 24 hours and rinsed
7 with deionized water before use.

8 **2.3.1. Solutions for ICP-OES analysis.** Synthetic samples with 1.0 mg kg⁻¹ of Al, As,
9 Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Na, Ni, Pb, Sb, Se, Sr and Zn were prepared
10 in three different inorganic acids (*i.e.*, HNO₃, HCl and H₂SO₄). A set of solutions
11 having increasing acid concentrations was prepared for each one. These sets consisted
12 of five solutions having 0.1% (w w⁻¹), 1% (w w⁻¹), 5% (w w⁻¹), 10% (w w⁻¹) and 15%
13 (w w⁻¹) acid concentration for HNO₃ and HCl media, and four solutions having 0.1% (w
14 w⁻¹), 1% (w w⁻¹), 5% (w w⁻¹) and 10% (w w⁻¹) acid concentration for the H₂SO₄
15 medium. The synthetic samples were made using 1000 mg L⁻¹ single-element stock
16 solutions of each analyte (Tec-Lab, Hexis Científica, São Paulo, SP, Brazil), H₂SO₄
17 (98% w w⁻¹, Merck, Darmstadt, Germany) and HNO₃ and HCl were purified obtained
18 by sub-boiling distillation (Milestone, Sorisole, Italy).

19 For external calibration, the same calibration standards were used with both the FBMN-
20 based and SSI systems. Six calibration standards were prepared by appropriate dilution
21 of the 1000 mg L⁻¹ single-element stock solutions up to analyte concentrations of 0.4,
22 0.8, 1.2, 1.6 and 2.0 mg kg⁻¹. All calibration standards were prepared in 0.1% (w w⁻¹)
23 nitric acid. A calibration blank containing the same HNO₃ concentration was also
24 prepared.

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

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

32 **2.3.2. Solutions for ICP-MS analysis.** Synthetic samples with 7.5 μ g kg⁻¹ of Ag, As,
33 Cd, Co, Cu, Mn, Pb, Sb and Se were prepared in the same inorganic acids. For each

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3 1 inorganic acid, a set of four solutions having 0.1% (w w⁻¹), 1% (w w⁻¹), 5% (w w⁻¹) and
4 10% (w w⁻¹) acid concentration was prepared. These samples were also prepared from
5
6 2 10% (w w⁻¹) acid concentration was prepared. These samples were also prepared from
7 3 the abovementioned 1000 mg L⁻¹ single-element stock solutions.

8 4 Calibration standards preparation was similar to that described for ICP-OES analysis
9 5 with the different calibration methods, the only difference being the analyte
10 6 concentration level. Six calibration standards having 1, 3, 6, 9, 12 and 15 µg kg⁻¹ analyte
11 7 concentrations, and a calibration blank, were prepared in 0.1% (w w⁻¹) HNO₃ for
12 8 external calibration with the FBMN-based and SSI systems. For on-line standard
13 9 addition calibration using the FBMN-based system, these calibration standards and the
14 10 synthetic samples were spiked with 1.0 µg kg⁻¹ of Y and 1.0 µg kg⁻¹ of In, respectively
15 11 (see Section 2.6 for clarification). Calibration standards for conventional standard
16 12 addition calibration using the SSI system were prepared as for ICP-OES measurements.

17 13 For both ICP-OES and ICP-MS measurements, when matrix matching calibration was
18 14 carried out, potassium hydrogen phthalate (Merck, Darmstadt, Germany), sodium
19 15 hydroxide (Merck) and phenolphthalein (Mallinckrodt Baker, Phillipsburg, NJ, USA)
20 16 were used to determine the nitric acid concentration in the digested samples by
21 17 titrimetric analysis.

22 18 To evaluate the trueness of the calibration methods, a real sample (Nestlé Brasil, São
23 19 Paulo, SP, Brazil) and a certified reference material (NIST RM 8435, Gaithersburg,
24 20 MD, USA) of whole milk powder were analyzed by both ICP-based techniques.

21 2.4. Digestion of whole milk powder

22 22 The whole milk powder samples (*i.e.*, a real sample and a certified reference material)
23 23 were microwave-assisted acid-digested using a closed vessel cavity microwave
24 24 digestion system (model Ethos 1600, Milestone). A 300 mg sample was weighted out in
25 25 the reaction vessel and digestion reagents (*i.e.*, 3 mL hydrogen peroxide (30% w w⁻¹,
26 26 Synth Labs, Diadema, SP, Brazil) and 8 mL purified HNO₃) were added. The mixture
27 27 was allowed to react for 2 h prior to sealing the vessel. Three vessels were filled with
28 28 samples and digestion reagents and one vessel, containing digestion reagents only, was
29 29 used as a blank. After sealing and inserting the vessels in the microwave oven cavity,
30 30 the digestion program shown in Table S2 in ESI[†] was applied. After digestion, the
31 31 solutions were quantitatively transferred into cleaned polypropylene flasks and diluted
32 32 to 50 g with deionized water. This sample dilution was used for determination of all the

1 elements except Ca, K and Na. Additional dilution (*i.e.*, 0.5 g / 50 g using HNO₃ 8% (w
2 w⁻¹)) was needed to analyze these elements.

3 **2.5. Calibration strategies**

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

7 **2.5.1. Matrix-free solutions**

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

10 **2.5.2. Synthetic samples**

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

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

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1 2.5.3. Whole milk powder

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

11 2.6. Relative transport efficiency

12 Relative transport efficiency (f_r) evaluation is an essential requirement to perform on-
13 line standard addition calibration with the use of multinebulizers.^{24, 26} This parameter is
14 needed to correct for underestimation or overestimation of the real analyte concentration
15 in the sample due to possible differences in sample and calibration standards
16 nebulization through the different multinebulizer nozzles. Numerous procedures for
17 relative transport efficiency evaluation have been proposed by several authors,^{24, 26, 33}
18 including Bauer and Broekaert's method²⁴ applied in this work. This procedure is based
19 on the use of two elements other than the analytes of interest. One of them, named
20 "primary", is added to the sample and the other one, named "supplementary", is added
21 to the standards. Relative transport efficiency can be determined from the emission line
22 intensity measurements of these primary and supplementary elements during the
23 standard addition calibration procedure used for sample analysis.

24 In this work, indium and yttrium were selected as primary and supplementary elements,
25 respectively. Samples and standards were spiked with these elements up to
26 concentrations indicated in Sections 2.3.1. and 2.3.2., and the correction method was
27 applied to both ICP-OES and ICP-MS analyses. Extension of the procedure to ICP-MS
28 analysis was done by considering signals from isotopes, rather than from emission lines,
29 of the selected primary and supplementary elements. The reader may refer to Bauer and
30 Broekaert²⁴ for further details of the correction procedure application.

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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.

1 3.1.3. Limits of detection

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

10 3.2. Matrix effects evaluation

11 Matrix effects induced by inorganic acids were evaluated from the analysis of synthetic
12 solutions having different concentrations in HNO₃, HCl and H₂SO₄. Preliminarily,
13 samples were analyzed using both FBMN-based and SSI systems through external
14 calibration. Subsequently, a second analysis was performed by using on-line standard
15 addition calibration for the FBMN-based system and traditional standard addition
16 calibration for the SSI system. Discussion on matrix effects is based on the trueness and
17 uncertainty of the results obtained. Herein, trueness is reported as the percent recovery
18 of a known added amount of analyte in the synthetic sample matrix; uncertainty was
19 evaluated in the manner already described elsewhere.³⁰ In all cases, the concentration of
20 analytes in the synthetic samples was near the centroid of the calibration graph in order
21 to fulfill the condition for minimum uncertainty.³⁹ All results shown are the mean of
22 five replicates. The emission lines and isotopes studied are presented on increasing E_{sum}
23 values (Table S1 in ESI[†]).

24 3.2.1. External calibration

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

32 **3.2.1.1. ICP-OES evaluation.** Table 2 shows that recovery values were found to be
33 dependent on both the inorganic acid tested and the acid concentration for the two

1 introduction systems evaluated. As expected, lower recovery values were obtained at
2 increasing acid concentration, indicating a signal reduction due to matrix effect caused
3 by acids. It is noted that matrix effects start to appear at 10% (w w⁻¹) acid concentration
4 in HNO₃ and HCl matrices and at a much lower concentration -only 1% (w w⁻¹)- in a
5 H₂SO₄ matrix. Inorganic acid induced matrix effects, including the marked effect
6 observed for H₂SO₄, have already been reported by other authors. These are known to
7 be due to changes originated in the nebulization process due to the different physical
8 properties of the acids (*i.e.*, surface tension, density, viscosity, and volatility) and/or to
9 variations in plasma atomization and excitation conditions.^{1, 40} Plasma-related matrix
10 effects can be avoided, or at least minimized, by using robust conditions. Plasma
11 conditions were monitored in this study by using the MgII (280.270 nm) / MgI (285.213
12 nm) intensity ratio approach. It has been reported that MgII / MgI ratio values higher
13 than 8 can be used to indicate robust conditions in a radially viewed plasma mode.
14 However, this value decreases by approximately 4 when an axially viewed mode is
15 used, even if maintaining the same robust ICP operating conditions.⁴¹ According to this
16 work, MgII / MgI ratio was found to fluctuate between 5.5 and 5.7 for all acid
17 concentrations tested and sample introduction systems used, indicating operation at
18 robust conditions. Therefore, it can be inferred that matrix effects observed in this work
19 are mainly related to nebulization/aerosol transport processes, rather than originating in
20 the plasma. This assumption is also supported when considering the results shown in
21 Figures S2 and S3 in ESI[†]. It is noted that signal suppression induced by a given acid at
22 a given concentration is independent of the nature (*i.e.*, atomic or ionic) or E_{sum} value of
23 the emission line evaluated, which also suggests non-plasma-related matrix effects.
24 Whichever the origin of these matrix effects, Table 2 shows that they are almost
25 independent of the introduction system used. For instance, by considering only the
26 recovery data obtained for those acid concentrations inducing matrix effects (*i.e.*, 10%
27 (w w⁻¹) and 15% (w w⁻¹) for nitric and hydrochloric acids; and 1% (w w⁻¹), 5% (w w⁻¹)
28 and 10% (w w⁻¹) for sulfuric acid), the average recovery values ranged from 89 to 75%,
29 87 to 79% and 92 to 73%, for nitric, hydrochloric and sulfuric acids, respectively, using
30 FBMN-based system. Similar recovery values, from 91 to 81%, 92 to 81% and 92 to
31 74%, respectively, were observed when using the SSI system.

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3 1 On the other hand, uncertainty values associated with the recovery values were always
4 2 found to increase when increasing the acid concentration, without any noteworthy trend
5 3 related to the acid tested or the introduction system used, as observed in Table 2.

6 4 **3.2.1.2. ICP-MS evaluation.** Overall, results obtained for ICP-MS were quite similar
7 5 to those observed for ICP-OES. As expected, recovery values decreased at increasing
8 6 acid concentration indicating signal suppression induced by the acid matrix. In the case
9 7 of ICP-MS, however, matrix effects were found to be stronger compared to ICP-OES,
10 8 being significant at an even lower acid concentration (*i.e.*, 5% (w w⁻¹)) in HNO₃ and
11 9 HCl matrices. This effect is represented in Table 2. As shown, considering only the
12 10 recovery values for acid concentrations inducing matrix effects, recovery values ranging
13 11 from 81 to 64%, 81 to 72% and 79 to 47%, for nitric, hydrochloric and sulfuric acid,
14 12 respectively, were obtained with the FBMN-based system, and comparable values were
15 13 obtained with the SSI system. Acid matrix effects have been reported to be more severe
16 14 in ICP-MS than in ICP-OES.⁴² Notwithstanding, as in the case of ICP-OES, these
17 15 effects are, highly dependent on the experimental conditions used. ICP-OES and ICP-
18 16 MS spectrometers in this work were operated with a different spray chamber and, as
19 17 reported by several authors, the type of spray chamber (*i.e.*, double-pass or cyclonic)
20 18 also plays a critical role in signal reduction induced by the presence of acid.⁴³⁻⁴⁶

21 19 Contrary to ICP-OES, uncertainty values associated with the obtained recovery values
22 20 were independent not only of the acid tested and the introduction system used but also
23 21 of the acid concentration. As noted, higher uncertainty values were obtained in ICP-MS
24 22 measurements compared to ICP-OES, ranging from 3 to 8%.

25 23 **3.2.2. Standard addition calibration**

26 24 Figures S4 and S5 in ESI[†] show the percent recovery values obtained with the FBMN-
27 25 based and the SSI systems when on-line and conventional standard addition calibration,
28 26 respectively, were applied. Results shown in these figures are also summarized in Table
29 27 2.

30 28 **3.2.2.1. ICP-OES evaluation.** Table 2 shows how both conventional and on-line
31 29 standard addition calibrations improved recovery values compared to external
32 30 calibration. Averaged recovery values ranged from 98 to 102% in all solutions tested for
33 31 the two introduction systems, without any appreciable trend when increasing acid
34 32 concentration. Likewise, Figures S4 and S5 in ESI[†] reveal that, for all emission lines

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

3 **3.2.2.2. ICP-MS evaluation.** Similar results were obtained using this technique, with
4 recovery values ranging from 97 to 106% without any acid concentration dependence
5 (Table 2). Uncertainty values, ranging from 6 to 9%, were also higher than in ICP-OES
6 with this calibration. This behavior can be observed in Figures S4 and S5 in ESI[†] for all
7 isotopes evaluated.

8 **3.3. Certified reference material and real sample analysis**

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

26 **3.3.1. Analysis of a certified reference material (CRM)**

27 Table 3 shows the results obtained for the analysis of a whole milk powder CRM.
28 Certified values are also included. In this case the different analytes in the sample were
29 determined by either ICP-OES or ICP-MS based on their concentration levels. In
30 general, satisfactory results were obtained with both calibration methods. As observed,
31 the values established were consistent with certified concentration intervals for all
32 analytes determined by ICP-OES or ICP-MS. Recovery values ranging from 93 to
33 106% and from 95 to 104% were obtained using the SSI system and the FBMN-based

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

3 **3.3.2. Analysis of a real sample**

4 A commercial whole milk powder sample was acquired from a supermarket in São
5 Carlos, SP, Brazil. The sample was microwave-assisted acid-digested in the same
6 manner as the previous CRM and was analyzed using the proposed calibrations.
7 Thereafter, the digested solutions were spiked with analytes at two different
8 concentration levels to evaluate trueness from recovery assays. Spiked concentrations of
9 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
10 analysis. Recovery values were calculated based on the difference between the analyte
11 concentrations found after and before spiking the sample. For those analytes which
12 concentrations were found to be below the limits of quantification (LOQ), recovery
13 values were calculated using exclusively the analyte concentration found after spiking
14 the sample.

15 Table 4 shows the results of this evaluation whereby concentration values of several
16 analytes are below the LOQ. LOQ values for matrix matching calibration with the SSI
17 system and on-line standard addition calibration with the FBMN-based system are
18 included in this table. LOQ values for matrix matching calibration were evaluated by
19 using calibration standards containing 8% (w w⁻¹) nitric acid concentration. Thus, the
20 nitric acid concentration in the calibration standards was similar to that in the analyzed
21 sample (Table S5 in ESI[†]). For on-line standard addition calibration, LOQ values were
22 evaluated by sequentially nebulizing calibration standards containing 0.1% (w w⁻¹)
23 nitric acid through one of the nebulizer nozzles, while continuously nebulizing a blank
24 sample through the other nozzle. Since a blank milk powder sample (free-from analytes)
25 was not available, 8% (w w⁻¹) HNO₃ was used as a blank sample. As observed, the LOQ
26 values were similar for both calibrations. However, it is worth mentioning that the
27 calibration standard uptake rate in the FBMN-based system was half of that used in the
28 SSI system (*i.e.*, 200 µL min⁻¹ in FBMN-based system compared to 400 µL min⁻¹ in SSI
29 system).

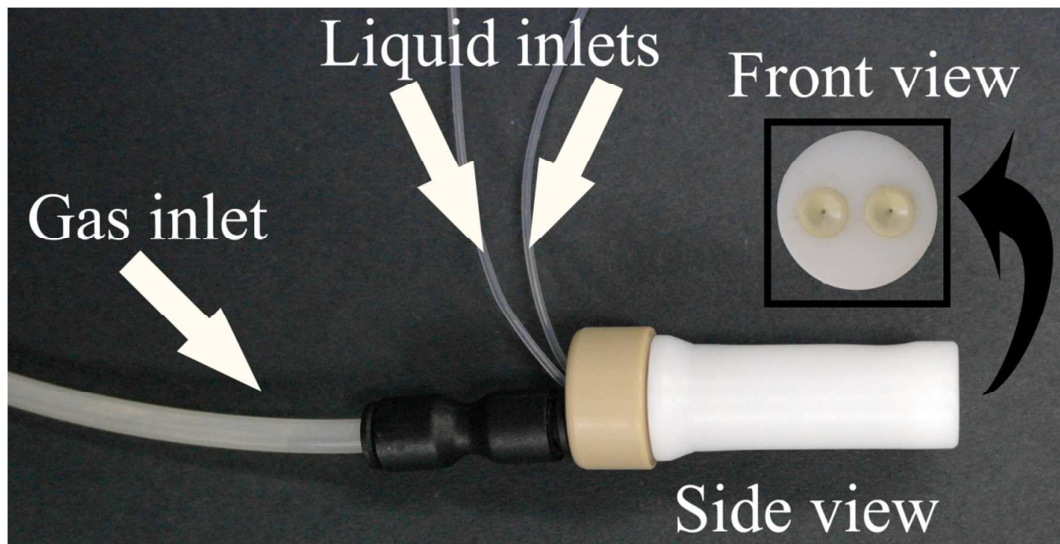
30 Table 4 results show that in general the analyte concentrations of both calibrations are
31 fairly consistent. In addition, recovery values obtained from the two recovery assays
32 were close to 100% for both calibration methods and for both spectrometric techniques.
33

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.

1 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

2

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

		Mean recovery (%)							
		FBMN-based system				SSI system			
Acid	Concentration (w w ⁻¹)	ICP-OES		ICP-MS		ICP-OES		ICP-MS	
		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 ₂ SO 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

^aExternal 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

^bStandard 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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1 Table 3. Analysis of a whole milk powder CRM using matrix matching and on-line standard addition calibrations in
 2 ICP-OES and ICP-MS.

Emission line (nm)	Certified value ^a	SSI system		FBMN-based system	
		Matrix matching calibration		On-line standard addition calibration	
		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

^aIn mg kg⁻¹ ± confidence interval at 95% (n = 3).

^bIn % ± confidence interval at 95% (n = 3).

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

Emission line (nm)	SSI system				FBMN-based system			
	Matrix matching calibration		Spike recovery (%) ^c		On-line standard addition calibration		Spike recovery (%) ^c	
	LOQ ^a ($\mu\text{g kg}^{-1}$)	Found value (mg kg^{-1}) ^c	0.5 mg kg^{-1}	1.0 mg kg^{-1}	LOQ ^b ($\mu\text{g kg}^{-1}$)	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 ($\mu\text{g kg}^{-1}$) ^c	4 $\mu\text{g kg}^{-1}$	7 $\mu\text{g kg}^{-1}$	LOQ ^b (ng kg^{-1})	Found value ($\mu\text{g kg}^{-1}$) ^c	4 $\mu\text{g kg}^{-1}$	7 $\mu\text{g kg}^{-1}$
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

^aLimit of quantification with external calibration using calibration standards with 8% (w w⁻¹)HNO₃.

^bLimit of quantification with on-line standard addition calibration using calibration standards with 0.1% (w w⁻¹) HNO₃ and a blank of 8% (w w⁻¹) HNO₃.

^cUncertainty values are the standard deviations of the results obtained from the analysis of three digested samples.

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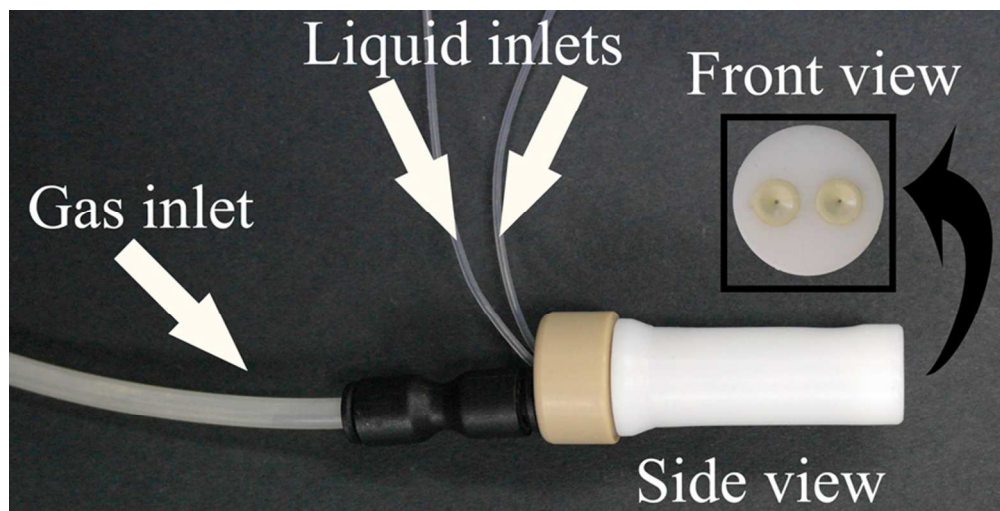
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3 Multinebulizer based on *Flow Blurring*[®] nebulization principle for the analysis of acid digested
4 samples using on-line standard addition calibration in ICP-OES and ICP-MS.
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80x40mm (300 x 300 DPI)