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Determination of Sulfur in Bio-Samples by ICP-QMS/QMS with an ORC

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Abstract

A method for determination of sulfur was investigated using an inductively coupled plasma tandem quadrupole mass spectrometer (ICP-QMS/QMS) with an octopole reaction/collision cell (ORC). It helped to achieve a lower background equivalent concentration (BEC) and a lower detection limit (DL) when 10% HNO_3 with 10% ethanol was applied as the rinse solution. Sulfur measurement was carried out by shifting the measured mass from $^{32}S^+$ to $^{32}S^{16}O^+$ by reaction with O_2 gas. The introduction of H_2 together with O_2 as reaction gases provided a lower DL. The BEC and DL of ^{32}S were 0.83 ng g^{-1} and 0.03 ng g^{-1}, respectively. The validation of the present method was confirmed by determining sulfur in certified reference materials, NIST SRMs 2773, 2298, and 2299. The results of sulfur in amino-acids and protein indicate that determination of sulfur could be an effective technique for quantification of sulfur-containing amino acids and proteins.

Keywords: ICP-QMS/QMS; Sulphur; ORC; Detection limit; Certified reference material

Introduction

Sulfur is a major target element in metallomics research [1-3]. One of the reasons might be that the sulfur content in human-body is approximately 2%, while two sulfur-containing amino acids cysteine and methionine contribute to the contents of sulfur. Sulfur has four stable isotopes, i.e., ^{32}S, ^{33}S, ^{34}S, ^{36}S [4]. Due to the high abundances of ^{32}S and ^{34}S, respectively ca. 95% and 4%, they are usually analysed for metallomics purpose.

Inductively coupled plasma mass spectrometry (ICP-MS) is one of the most sensitive techniques for elemental measurement due to high temperature of the ICP for ionisation, relatively simple spectra than optical analysis, and wide linearity of the detector. However, the measurement of sulfur isotopes is often challenging for ICP-MS with a single quadrupole mass spectrometer (i.e., ICP-QMS) because of the polyatomic spectral interferences, especially $^{16}O_2^+$ on $^{32}S^+$.

Many researchers had tried to improve the detection limits of $^{32}S^+$ by ICP-QMS using O_2 as the reaction cell gas [5-15] to shift $^{32}S^+$ to $^{32}S^{16}O^+$ or Xe gas as the collision gas [15-18] to remove the interferences of $^{16}O_2^+$. High resolution (HR-) ICP-MS [6,19-25] providing a resolution over 1800 could separate the spectrum of $^{16}O_2^+$ from that of $^{32}S^+$, which can be calculated from the relative atomic masses of ^{16}O and ^{32}S, ca. 15.9949 and 31.9721, respectively [26]. In recent years, an alternative choice for sulfur measurement is an ICP-MS equipped with tandem quadrupole mass spectrometers (ICP-QMS/QMS) along with an octopole reaction/collision cell (ORC) [27-29]. In the measurement by ICP-QMS/QMS, the m/z of 32 was permitted to pass the first QMS and transferred to the ORC for reaction with oxygen gas, after which $^{32}S^+$ was shift to $^{32}S^{16}O^+$ and measured by the second QMS at the m/z of 48.

To the best of the present authors' knowledge, the best detection limits of ^{32}S obtained by ICP-QMS with O_2 as reaction cell gas [5] and with Xe as the collision gas [16] were 0.2 ng g^{-1} and 3.2 ng g^{-1}, respectively. The best detection limits obtained by HR-ICP-MS without [19] and with [20] a desolvation unit were 0.6 ng g^{-1} and 0.01 ng g^{-1}, respectively. The improvement of detection limit by using the desolvation unit could be attributed to the removal of oxygen introduction to the HR-ICP-MS, removing the tailing of $^{16}O_2^+$ which resulted in a relatively high background signal of $^{32}S^+$ [20]. The reported detection limit [27-29] obtained by ICP-QMS/QMS was in the range of 0.33 ng g^{-1} to 4.3 ng g^{-1}, which is comparable to the best performance obtained using other approaches but still higher than that obtained by HR-ICP-MS with using a desolvation unit. These facts might indicate that the background signals were not controlled sufficiently in the reports by ICP-QMS/QMS up to date. From the mechanism of spectral interference separation in the ICP-QMS/QMS with and ORC, the present authors speculated that the background signal of sulfur might be achieved at the same level as that obtained by HR-ICP-MS with using a desolvation unit

In the present work, the authors tried to establish a measurement method for sulfur using ICP-QMS/QMS, where optimisation of the operation conditions was carried out to get a better detection limit (DL). For such purpose, the m/z of the first QMS was set to 32 permitting the pass of $^{32}S^+$ and $^{16}O_2^+$ as the majority of the ions; H_2 was additionally used as the reaction gas along with $^{16}O_2$ to prevent the transfer of $^{16}O_2^+$ to $^{16}O_3^+$ in the ORC; the m/z of the second QMS was set to 48 for measuring the signal of sulfur as $^{32}S^{16}O^+$. In the present work, the precursor ions generating spectral interferences were also investigated, which may provide valuable information for ICP-QMS measurement.

The validity of the present method was confirmed by analysing three certified reference materials, NIST SRMs 2773, 2298, and 2299. The measurement of sulfur content was applied to the quantitation of two sulfur-containing amino acids, cystine and methionine, and a sulfur-containing protein.

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Experimental

Instrumentation

An ICP-QMS/QMS with an ORC (Agilent 8800s, Agilent Technologies, Japan) was applied to the measurement of sulfur isotopes and the spectral interferences. The typical operating conditions are summarised in Table 1. The operating condition for each parameter was daily optimised. A microwave digestion instrument (ETHOS 1, Milestone General K.K., Kawasaki, Japan) and TFM® digestion vessels were utilised for the digestion of the certified reference material (CRM) samples. The cleaning of digestion vessels was carried out using an automatic cleaning system (TraceClean system, Milestone General K.K.) and then cleaned with the microwave irradiation whose program is identical to that used for the digestion of the samples.

Chemicals and materials

An elemental standard solution of sulfur (as SO_4^{2-}, guaranteed by the Japan Calibration Service System, JCSS) was purchased from Kanto Chemical Co., Inc. (Tokyo, Japan). Ultrapur® grade of HNO_3 (13 mol L^{-1}) for digestion of the samples and making sample solutions was also purchased from Kanto Chemical Co., Inc. Pure water used throughout the present study was prepared using a Millipore purification system (Element, Nihon Millipore Kogyo, Tokyo, Japan). The validity of the present method was confirmed by analysing three CRMs, i.e., NIST SRMs 2773 (bio-diesel), 2298 (high octane gasoline), and 2299 (reformulated gasoline), issued by the National Institute of Standards and Technology (Gaithersburg, USA). The present method was applied to the analysis of three CRMs for sulfur-containing compounds, i.e., two amino acids (NMIJ CRM 6025-a, L-Cystine and NMIJ CRM 6023-a, L-Methionine) and a protein (NMIJ CRM 6202-a, human serum albumin), issued by the National Metrology Institute of Japan (Tsukuba, Japan).

Microwave acid digestion

In microwave acid digestion, 0.5 mL of the sample was taken for each sub-sample and the mass was precisely measured using an electronic balance. After that, 5 mL of Ultrapur® HNO_3 was added and subjected to the microwave irradiation process (ramp: 180°C for 30 min, hold: for 15 min; cool down: for 50 min; 200°C for 30 min, hold: for 15 min; cool down: for 50 min). After the microwave irradiation, pure water was added to each sample to achieve a 50 mL digested solution. At least two blank tests were carried out in each batch of acid digestion, where quantities of HNO_3 equivalent to the samples were added into empty digestion vessels and those were subjected to all of the operations in the acid digestion.

Results and Discussion

Cleaning of the instrument for sulfur measurement

In order to achieve a lower detection limit (DL) for sulfur measurement, the instrument background should be well-controlled. In the present experiment, the instrument was repeatedly washed by introduction of three rinse solutions in turn, i.e., pure water, 10% HNO_3, and 10% HNO_3 with 10% ethanol. The washing was repeated until the background equivalent concentration (BEC) was lower than 2 ng g^{-1}.

The signal intensities of sulfur obtained with different rinse solution are plotted in Figure 1, where the washing procedure was carried out in the order of "pure water washing 1→10% HNO_3 washing 1→10% HNO_3 with 10% ethanol washing 1→pure water washing 2→".

For each set of washing procedure, it is noted that the signal intensity of sulfur obtained by 10% HNO_3 with 10% ethanol was much lower than that by 10% HNO_3, while the later one was slightly lower than that by pure water. These facts could be attributed to the matrix effect caused by ethanol and HNO_3, respectively. It can be seen that sulfur signal intensity increased in each washing with pure water (except for washing 1) from 0s to 60s, which could be attributed to the matrix transfer from 10% HNO_3 with 10% ethanol to pure water.

In Figure 1, it is notable that the signal intensity of sulfur obtained for "washing 1" of each rinse solution decreased to some extent with the increase of washing time. However, the signal intensity of sulfur after "washing 1" was respectively stable for pure water and 10% HNO_3 in each washing, which indicate that the residual sulfur was difficult to remove by washing with pure water or 10% HNO_3. By contrast, the signal intensity of sulfur apparently decreased in each washing of 10% HNO_3 with 10% ethanol, indicating the effective removal of residual sulfur in the instrument.

Instrument parameter	Operating condition
RF power (W)	1600
Plasma gas flow rate (L min^{-1})	18
Auxiliary gas flow rate (L min^{-1})	1.8
Carrier gas flow rate (L min^{-1})	0.9
Sampling depth (mm)	8.0
Cell gas (mL min^{-1})	O_2 0.3, H_2 1.0
Nebulizer	Micro flow 200
Selected mass at 1st QMS	32,34
Selected mass at 2nd QMS	48,50
Accumulation-time/mass (s)	3
Number of replicates	10

Table 1: Typical operating conditions of ICP-QMS/QMS.

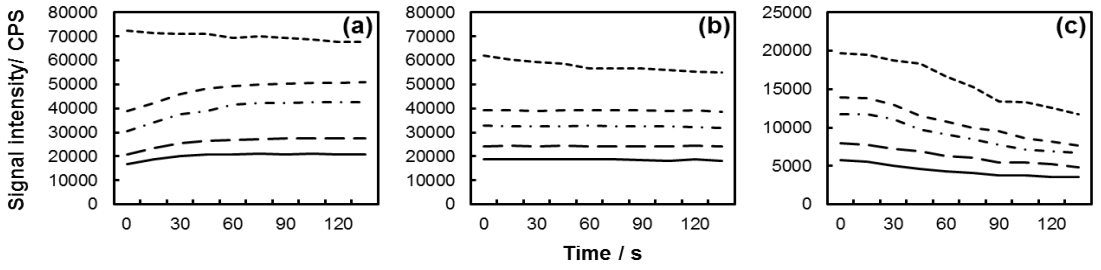

Figure 1: Washing profiles of sulfur obtained with three different rinse solutions. (1st QMS, *m*/*z*=32; 2nd QMS, *m*/*z*=48; reaction gas, O_2. ---------- washing 1; - - - - - - washing 2; - . - . - . - washing 3; — — — — washing 13; ———— washing 20. (a), pure water; (b), 10 % HNO3; (c), 10 % HNO_3 with 10 % ethanol).

Major precursor ions for the spectral interferences of sulfur isotopes

Figure 2 shows the mechanism of the ICP-QMS/QMS for removing the spectral interferences with $^{32}S^+$ measurement. Oxygen was solely used as the reaction gas in the researches using ICP-QMS/QMS published up to date [26-28]. In the present research, H_2 was used together with O_2 as the reaction gases.

The 1st QMS and the 2nd QMS could be individually controlled: the instrument permits the mass scan by both QMS's. In the present work, mass scan was carried out for the 1st QMS followed by the 2nd QMS filtering at the *m*/*z* 48 for the measurement of $^{32}S^{16}O^+$. The flow rate of O_2 as reaction gas was optimised in advance. As the result, 0.3 mL min^{-1} of O_2 was found to be the optimum and applied in the following experiments. Mass scan of the 1st QMS was carried out for the mass range from 2 to 260, using a pair of blank (0.3 mol L^{-1} HNO_3) and standard (50 ng g^{-1} sulfur in 0.3 mol L^{-1} HNO_3) solutions. Since the signal intensities for the mass range lower than 15 and those for the mass range higher than 51 were very low and negligible, the results for the mass range from 16 to 50 are shown in Figure 3 for a clearer comparison.

The results in Figure 3(a) were obtained using O_2 as the reaction gas. Very high signals for *m*/*z* of 48 at the 2nd QMS were obtained when the *m*/*z* of the 1st QMS were 16, 32, 33, 40, and 48. The precursor ions at *m*/*z* of 16, 32, 33, and 48 could be attributed to the ions of $^{16}O^+$, $^{32}S^+$ (with $^{16}O_2^+$), $^{32}S^1H^+$, and $^{32}S^{16}O^+$, respectively. The precursor ion at the *m*/*z* of 40 has not been reported up to date. One of the possibilities of this precursor ion might be $^{80}Kr^{++}$, which could be the impurities in Ar gas used in ICP-QMS/QMS. A further experiment was carried out by setting the *m*/*z* of the 1st QMS and the 2nd QMS as 42 and 50, respectively. Signal of $^{84}Kr^{16}O^{++}$ was not observed. This result might indicate that either $^{84}Kr^{++}$ was not present in the ions passing through the 1st QMS or $^{84}Kr^{++}$ was not react with ^{16}O to form $^{84}Kr^{16}O^{++}$ ion. Therefore, it could be concluded that the precursor ion at the *m*/*z* of 40 in Figure 3(a) was not $^{80}Kr^{++}$. The present authors speculate that the precursor ion at the *m*/*z* of 40 was $^{40}Ar^+$ (maybe with minute $^{40}Ar_2^{++}$), which might transfer to $^{40}Ar_2{}^{16}O^{++}$ and be observed at the *m*/*z* of 48 at the 2nd QMS. The authors also carried out a measurement by an HR-ICP-MS to check whether the $^{40}Ar_2{}^{16}O^{++}$ ion was generated in the plasma. The $^{40}Ar_2{}^{16}O^{++}$ ion was not found in the HR-ICP-MS measurement. This fact indicated that the $^{40}Ar_2{}^{16}O^{++}$ ion was not generated in the plasma but generated in the ORC by the reaction with $^{16}O_2$. Another possibility of $^{40}Ar^+$ related interferences might be $^{16}O_3^+$ produced by asymmetric charge transfer. It should be noted that the ionization energies of Ar and O are 15.759 eV and 13.61806 eV, respectively [30]. Therefore, charge transfer from Ar^+ to O^+ is an endothermic reaction. Such kind of reactions is possible to happen in the ORC with enough collision energy [31].

Furthermore, it can be seen from Figure 3(b) that the precursor ions at the *m*/*z* of 16 and 40 were removed by using H_2 as the reaction gas together with O_2. The signal intensity obtained for the *m*/*z* of 32 slightly decreased when H_2 was additionally applied as the reaction gas.

In the measurement of ICP-QMS/QMS with an ORC, the 1st QMS could be set to permit the pass of ions with *m*/*z* of 32 and contributes to the removal of $^{16}O^+$ and $^{40}Ar^+$ generated in the plasma. However, $^{40}Ar^+$ signal could still be observed at the 2nd QMS, the reason for which is not clear up to now. The effect of H_2 on removal of $^{40}Ar^+$ was investigated and the results are plotted in Figure 4. As can be seen, apparent $^{40}Ar^+$ signal was observed when H_2 was not introduced as reaction gas. Introduction of 1 mL min^{-1} H_2 as the reaction gas was enough to remove the $^{40}Ar^+$ signal. Therefore, H_2 was used as the reaction gas along with O_2 in the present experiment to ensure the removal of $^{40}Ar^+$ related ions.

Optimisation of H_2 flow rate for the measurement of sulfur

The signal intensities of sulfur in a pair of blank and standard solutions were investigated at different H_2 flow rates from 0 to 5 mL min^{-1}. The results of ^{32}S in the blank and standard solutions are plotted in Figure 5(a) and 5(b), while the (standard/blank) signal intensity ratio (S/B) is plotted in Figure 5(c).

It can be seen from Figure 5(a) to 5(c) that the signal intensities of $^{32}S^{16}O^+$ in both the blank solution and the standard one decreased gradually when the H_2 flow rate increased from 0 to 1.0 mL min^{-1}. By contrast, the S/B increased gradually and the maximum ratio was obtained at H_2 flow rate of 1.0 mL min^{-1}. These results might indicate that the application of H_2 as the reaction gas helped to supress the mass shift from $^{16}O_2^+$ to $^{16}O_3^+$ or help to suppress the formation of other spectral interferences induced by $^{16}O_2^+$. The signal intensities of $^{32}S^{16}O^+$ in the blank solution and the standard solution increased to some extent when the H_2 flow rate increased from 1.0 mL min^{-1} to 2.0 mL min^{-1}, while the S/B decreased. When the H_2 flow rate exceeded 2.0 mL min^{-1}, the signal intensities of $^{32}S^{16}O^+$ in the blank solution and the standard solution decreased gradually. At the same time, the S/B increased slightly when the H_2 flow rate increased from 2.0 mL min^{-1} to 3.0 mL min^{-1}, while the S/B was almost stable and independent of the H_2 flow rate when it was over 3.0 mL min^{-1}.

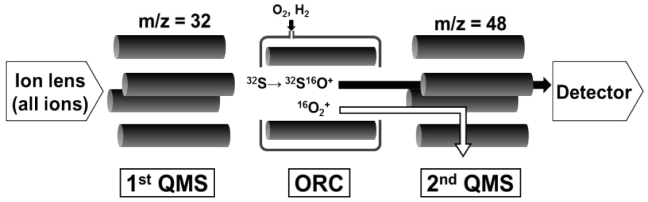

Figure 2: The mechanism of ICP-QMS/QMS for removing spectral interferences.

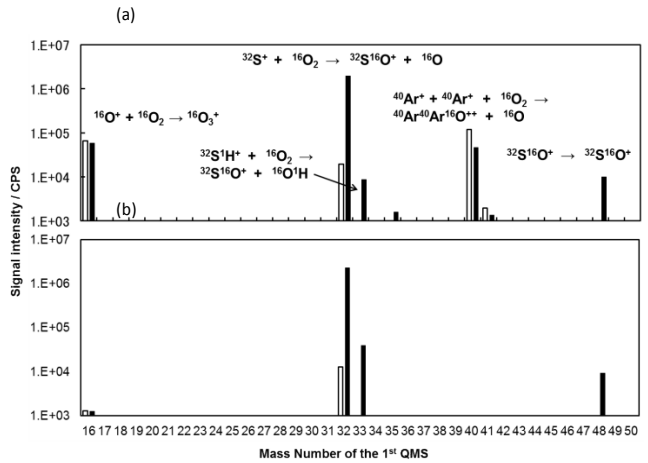

Figure 3: Mass spectrum observed by the 2nd QMS at 48 by scanning the mass range from 16 to 50 of the 1st QMS. (Open bar, 0.3 mol L^{-1} HNO_3; solid bar, 50 ng g^{-1} sulfur in 0.3 mol L^{-1} HNO_3. Reaction gas: (a) 0.3 mL min^{-1} of O_2; (b) 0.3 mL min^{-1} of O_2 and 1 mL min^{-1} of H_2

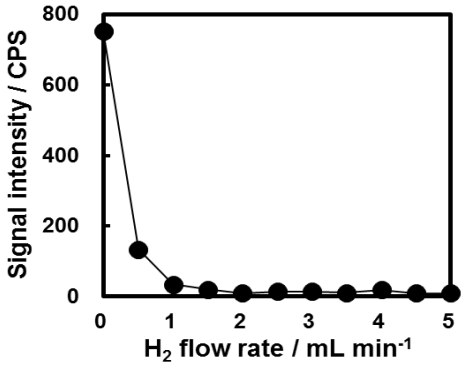

Figure 4: $^{40}Ar^+$ signal intensity observed at different flow rate of H_2 as the ORC gas. (1st QMS, *m*/*z*=32; 2nd QMS, *m*/*z*=40; O_2 flow rate, 0.3 mL min^{-1}).

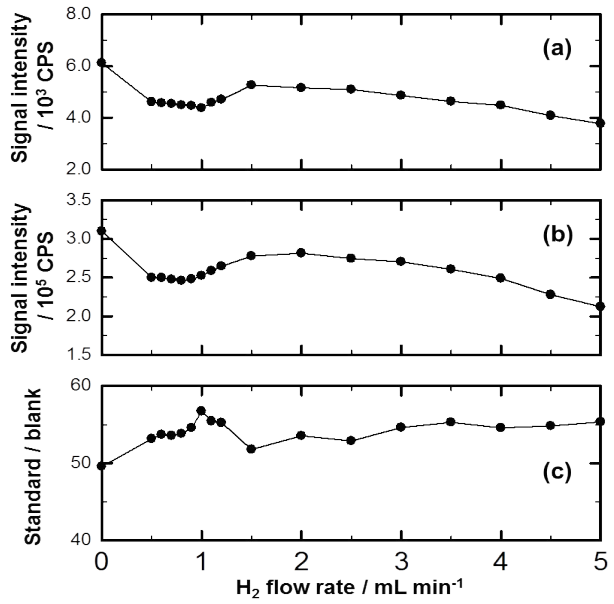

Figure 5: Signal intensities of $^{32}S^{16}O^+$ in the blank and standard solutions and their ratio observed at different H_2 flow rates. ((a) Blank solution, 0.3 mol L^{-1} HNO_3; (b) standard solution, 50 ng g^{-1} sulfur in 0.3 mol L^{-1} HNO_3; (c) standard to blank signal intensity ratio. 1st QMS, *m*/*z*=32; 2nd QMS, *m*/*z*=48).

As it can be seen in Figure 5(c), the maximum S/B was achieved at the H_2 flow rate of 1.0 mL min^{-1}. This condition provided the best detection limit for sulfur measurement and was applied to the following experiments. The DL(3σ) and BEC of ^{32}S were 0.03 ng g^{-1} and 0.83 ng g^{-1}, respectively. The calibration curve obtained with 0 ng g^{-1}, 50 ng g^{-1}, 100 ng g^{-1}, and 150 ng g^{-1} sulfur in 0.3 mol L^{-1} HNO_3 gave a correlation factor with R^2=0.9999.

A comparison of the present DL and BEC with those reported with various techniques is summarised in Table 2. As can be seen in Table 2, the present DL is comparable with the best performance reported in Reference [20] obtained by HR-ICP-MS with the assist of a desolvation unit to remove the $^{16}O_2^+$ interference. The present method provides better DL and BEC than other techniques without using a desolvation unit. The reason could be attributed to the effective removal of spectral interferences by the QMS/QMS system with the ORC using H_2 and O_2 as the reaction gases. The 1st QMS selecting *m*/*z* of 32 permitted the pass of $^{16}O_2^+$ and $^{32}S^+$ while blocked $^{16}O^+$ and reduced the possibility of transference from $^{16}O^+$ to $^{16}O_3^+$ in the ORC. The introduction of H_2 as the reaction gas might further reduced the possibility of transference from $^{16}O_2^+$ to $^{16}O_3^+$ in the ORC and/or the formation of other spectral interferences induced by $^{16}O_2^+$. It is noted that the DL in the present work was much lower than those reported in References [27-29] based on the ICP-QMS/QMS technique. These results might indicate that the measurements in References [27-29] were carried out with a relatively higher blank signal, i.e., a higher BEC, as mentioned in Reference [27].

Validity of the method for measurement of sulfur

In order to confirm the validity of the present method, each content of sulfur in three CRMs, NIST SRMs 2773 (bio-diesel), 2298 (high octane gasoline), and 2299 (reformulated gasoline), was measured after acid digestion.

The observed values of sulfur contents in these CRMs are plotted in Figure 6 in comparison to the certified values, along with the expanded uncertainty of each value. It can be seen that the observed value for each CRM agreed with its certified one considering the uncertainty. Because the CRMs were analysed after microwave acid digestion (sample 0.5 g, solution 50 g), the concentration of sulfur in the sample solution of NIST SRM 2298 was approximately 45 ng g^{-1}. These results showed that the present method is valid for measuring sulfur at 50 ng g^{-1} with the expanded uncertainty of approximately 2%.

Quantitation of sulphur-containing amino acids and sulfur containing proteins by measuring sulfur contents

The present method was applied to the quantitation of sulfur-containing amino acids (NMIJ CRM 6025-a, L-Cystine and NMIJ

Reference Number	Instrument	Technique	Analyte	DL/ng g^{-1}	BEC/ng g^{-1}
[5]	Elan DRC	O_2 reaction	$^{32}S^{16}O^+$	0.2	4.8
[6]	Elan DRC-II	O_2 reaction	$^{32}S^{16}O^+$	4.3	NA[a]
[7]	HP 4500	O_2 reaction	$^{32}S^{16}O^+$	35	NA[a]
[9]	Thermo X7	O_2 reaction	$^{32}S^{16}O^+$	11	NA[a]
[10]	Elan DRC-2	O_2 reaction	$^{32}S^{16}O^+$	30	NA[a]
[12]	Agilent 7500ce	O_2 reaction	$^{32}S^{16}O^+$	3.4	NA[a]
[14]	Agilent 7500a	O_2 reaction	$^{32}S^{16}O^+$	13	84
[15]	Agilent 7500ce	O_2 reaction	$^{32}S^{16}O^+$	0.7	NA[a]
[24]	Elan DRC-plus	O_2 reaction	$^{32}S^{16}O^+$	10	NA[a]
[15]	Agilent 7500ce	Xe collision	$^{32}S^+$	10.9	NA[a]
[16]	Agilent 7500c	Xe collision	$^{32}S^+$	3.2	NA[a]
[17]	Agilent 7500ce	Xe collision	$^{32}S^+$	45	NA[a]
[18]	Micromass	He, H_2, Xe reaction/collision	$^{32}S^+$	48	NA[a]
[6]	Element	HR (4500)	$^{32}S^+$	14	NA[a]
[19]	Elemental Axiom	HR (6000)	$^{32}S^+$	0.6	NA[a]
[20]	Element	HR (4000), desolvation	$^{32}S^+$	0.01	NA[a]
[24]	Element XR	HR (4000)	$^{32}S^+$	1	NA[a]
[25]	Element XR	HR (4500)	$^{32}S^+$	0.7	NA[a]
[27]	Agilent 8800	QMS/QMS, O_2 reaction	$^{32}S^{16}O^+$	1.2	NA[a]
[28]	Agilent 8800	QMS/QMS, O_2 reaction	$^{32}S^{16}O^+$	0.33	NA[a]
[29]	Agilent 8800	QMS/QMS, O_2 reaction	$^{32}S^{16}O^+$	4	NA[a]
Present work	Agilent 8800	QMS/QMS, H_2, O_2 reaction	$^{32}S^{16}O^+$	0.03	0.83

Table 2: The DLs and BECs for measuring ^{32}S by various techniques. [a]: Not available.

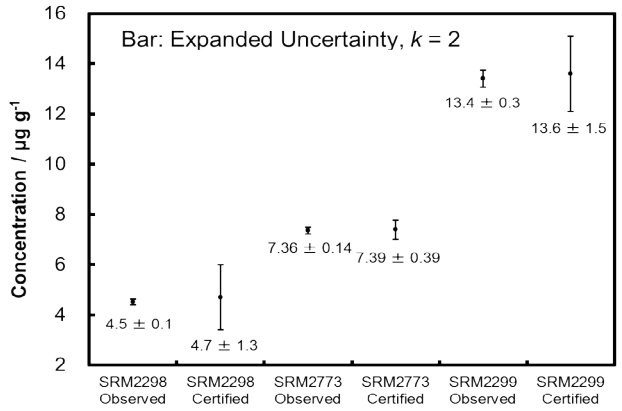

Figure 6: A comparison of observed and certified values of sulfur in three CRMs. The value following "±" indicates the expanded uncertainty with the coverage factor 2.

Sample code	Observed value[a]	Certified value[a]	Unit
NMIJ CRM 6025-a	0.982 ± 0.021	0.998 ± 0.003	kg kg^{-1}
NMIJ CRM 6023-a	0.991 ± 0.022	0.999 ± 0.002	kg kg^{-1}
NMIJ CRM 6202-a	1130 ± 23	1098 ± 31	μmol kg^{-1}

Table 3: Observed and certified values of sulfur-containing amino acids and protein. [a]: The value following "±" indicates the expanded uncertainty with the coverage factor 2.

CRM 6023-a, L-Methionine) and a protein (NMIJ CRM 6202-a, human serum albumin). The amino acid samples were dissolved in 0.1 mol L^{-1} HCl. The protein sample was digested with Ultrapur® HNO_3 in the same way as that used for the NIST SRMs. The samples were further diluted to obtain the analysis solutions containing approximately 50 ng g^{-1} of S.

The results are summarized in Table 3 along with the certified values. It can be seen that the observed values were in agreement with the certified values considering the measurement uncertainty. This fact indicates that the measurement of S content could be applied to the quantitation of sulfur-containing compounds.

Conclusion

ICP-QMS/QMS with an ORC system was investigated to establish a method for the measurement of sulfur in bio-samples. Washing procedure using 10% HNO_3 with 10% ethanol helped to obtain a lower BEC and a lower DL for sulfur measurement. The interference of $^{16}O_2^+$ with the measurement of $^{32}S^+$ could be effectively removed by setting the *m*/*z* of the 1st QMS as 32 to permit the pass of $^{16}O_2^+$ and $^{32}S^+$, while the $^{32}S^+$ reacted with O_2 gas and transferred to $^{32}S^{16}O^+$ in the ORC and then measured at the *m*/*z* of 48 in the 2nd QMS. The introduction of H_2 gas in the ORC helped to remove $^{40}Ar^+$ related interferences with the measurement of $^{32}S^+$. The DL and BEC of ^{32}S in the present work were 0.03 ng g^{-1} and 0.83 ng g^{-1}, respectively. The DL was comparable with that obtained by an HR-ICP-MS with the assist of a desolvation unit and better than those obtained with other techniques. This result could be attributed to the fact that the measurement of $^{32}S^+$ in the present work was shifted to $^{32}S^{16}O^+$ and the transfer from $^{16}O_2^+$ to $^{16}O_3^+$ was effectively suppressed by the introduction of H_2; i.e., the measurement by ICP-QMS/QMS with an ORC did not suffer from $^{16}O_2^+$ signal tailing as that observed in HR-ICP-MS. The validity of the present method was confirmed by analysing sulfur in three NIST SRMs, for which the observed values agreed with their certified values. The results of analysis of sulfur-containing amino acids and protein showed that the measurement of sulfur content could be applied to the quantitation of these compounds.

The analysis in the present work was designed for the quantitation of total sulfur in the sample, which is effective for the quantitation of sulfur-containing compounds of high purity for metrological purpose. Hyphenation of ICP-QMS/QMS with separation techniques such as high pressure liquid chromatography could provide further information for the species of sulfur in the sample.

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