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Method for determination of levoglucosan in snow and ice at trace concentration levels using ultra-performance liquid chromatography coupled with triple quadrupole mass spectrometry

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ABSTRACT

A method is developed for determination of levoglucosan at trace concentration levels in complex matrices of snow and ice samples. This method uses an injection mixture comprising acetonitrile and melt sample at a ratio of 50/50 (v/v). Samples are analyzed using ultra-performance liquid chromatography system combined with triple tandem quadrupole mass spectrometry (UPLC-MS/MS). Levoglucosan is analyzed on BEH Amide column (2.1 mm × 100 mm, 1.7 um), and a Z-spray electrospray ionization source is used for levoglucosan ionization. The polyether sulfone filter is selected for filtrating insoluble particles due to less impact on levoglucosan. The matrix effect is evaluated by using a standard addition method. During the method validation, limit of detection (LOD), linearity, recovery, repeatability and reproducibility were evaluated using standard addition method. The LOD of this method is 0.11 ng mL^{-1}. Recoveries vary from 91.2% at 0.82 ng mL^{-1} to 99.3% at 4.14 ng mL^{-1}. Repeatability ranges from 17.9% at a concentration of 0.82 ng mL^{-1} to 2.8% at 4.14 ng mL^{-1}. Reproducibility ranges from 15.1% at a concentration of 0.82 ng mL^{-1} to 1.9% at 4.14 ng mL^{-1}. This method can be implemented using less than 0.50 mL sample volume in low and middle latitude regions like the Tibetan Plateau.

1. Introduction

Biomass burning emissions contribute to about half of the carbonaceous aerosols all over the world [1]. The chemical composition inventory can provide detail source identification of the carbonaceous aerosols. Monosaccharide anhydrides (MAs) such as levoglucosan can be adopted as specific molecular tracers for biomass burning aerosols, because they can only be generated by the degradation of cellulose and hemicellulose when the burning temperature is higher than 300 °C [2]. MAs can remain stable for long periods of time, with only negligible degradation in sediment conditions [3,4], which further extends applicability of MAs in historical biomass burning studies.

Snow and ice samples from high latitude/altitude glaciers can provide important information about past fire regimes [3,5,6]. Levoglucosan and its isomers mannosan and galactosan can be used as ideal markers in biomass burning studies of snow and ice [3,5–7]. Several methods have been developed for determination of MAs in snow and ice samples [3,5,7,8]. The gas chromatography based methods need extreme dehydration conditions, which requires a long time for sample preparation [9]. The extreme dehydration conditions reduced the recovery and precision for handling trace concentration of levoglucosan in aqueous samples [5,7]. The high-performance liquid chromatography (HPLC) based method was used as an alternative to overcome these issues. The HPLC with triple quadrupole tandem mass spectrometry (HPLC-ESI-MS/MS) method with low LOD and high recovery ensured accurate results for detecting levoglucosan in Arctic and Antarctic ice [3,4,6]. However, samples from middle and low latitude regions (e.g. the Tibetan Plateau (TP)) usually contain much more complex organic components like the glycose and sugar alcohols besides MAs [5,7]. The method for polar ice showed very poor performance for levoglucosan due to matrix interferences when applied to samples from Tibetan glaciers [8]. A HPLC method with an estimated LOD of 10 ng mL^{-1} was reported for the Tibetan ice cores [8]. However, evidence showed that the levoglucosan concentration was at about 1 ng mL^{-1} level even in regions strongly affected by biomass burning emissions [5,7]. Due to the large quantity of insoluble particles in samples from low and middle latitude

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glaciers [10], direct injection without any pretreatment in previous methods [3,8] is harmful to the HPLC system and chromatographic columns. Accurate quantification of levoglucosan in middle and low latitude glacier snow and ice samples can provide important information for understanding regional biomass burning regimes, which is critical for understanding the relationship of biomass burning, climate change and human activities. Therefore, it is necessary to develop a rapid and effective method for determination of levoglucosan at trace concentration levels in complex matrix snow and ice for regions like the TP.

In this study, a method based on UPLC-MS/MS for determination of levoglucosan in snow and ice is reported. The preparation process and instrument conditions are specific for complex matrix samples from low and middle latitude glaciers.

2. Material and methods

2.1. Chemicals

HPLC gradient grade acetonitrile (ACN) was obtained from Fisher Scientific (U.S.A.). HPLC gradient grade methanol for standard stock solutions was obtained from J.T.Baker (U.S.A.). HPLC grade ammonium hydroxide (10%) was obtained from Mreda (U.S.A.). Ultrapure water was obtained from a Milli-Q ultrapure water system (U.S.A.). Standard levoglucosan (1,6-anhydro-β-D-glucopyranose, 99%) was obtained from Sigma-Aldrich (St. Louis, U.S.A.), mannosan (1,6-anhydro-β-D-mannopyranose, 98%) was obtained from TRC (Toronto, Canada), and glactosan (1,6-anhydro-β-D-galactopyranose 97%) was obtained from J&K (Pforzheim, Germany). Individual standard stock solutions were prepared using methanol at a concentration of 1000 μg mL^{-1}, and progressively diluted by ultrapure water for use. Standard stock solutions were stored in dark conditions at a temperature of 4 °C.

2.2. Sample preparation

A total of 61 snow samples were collected from different Tibetan glaciers. Fresh snow samples were compacted in pre-cleaned PET bottles and were kept frozen at a temperature of −20 °C before analysis [7]. Ice samples were obtained from the Zangsegangri ice core. Ice core sections were stored in a freeze storeroom at a temperature of −20 °C. Previous studies indicated that samples stored under these conditions displayed no apparent degradation of levoglucosan for at least several years [3,6]. Sample preparation was carried out in a cold ultraclean room at −18 °C. The outer part of each sample was scraped using a pre-cleaned scalpel, and one portion of the inner part was used for levoglucosan analysis. Fifty ice samples were selected at different depths for levoglucosan analysis in this study. Samples were melted at a room temperature (about 15 °C) in a fume cupboard before analysis, and shaken for 5 min. A sample volume of 0.50 mL of each sample was extracted and filtered by polyether sulfone (PES) filter. The filtrate was collected in a 2.00 mL sample vial, and 0.50 mL ACN was added to each sample before analysis.

2.3. Instrumentation

Sample analysis was performed by a Waters Acquity UPLC system (USA) in reversed phase mode. The autosampler was thermostatically controlled at a temperature of 15 °C. A BEH VanGuard Pre-column (2.1 mm × 5 mm, 1.7 um, Waters, USA) was used to protect the chromatography column. For the chromatographic analysis, 5.00 uL of each sample was injected onto a BEH Amide column (2.1 × 100 mm, 1.7 um, Waters, USA). The column temperature was set to 40 °C. The mobile phase comprised ultrapure water with 0.1% NH_3H_2O (mobile A) and ACN (mobile B). Gradient elution was employed at a flow rate of 0.20 mL min^{-1}, and the gradient program was shown in Table 1. The retention time of levoglucosan was 1.41 min, and the analytical process lasted 7.00 min in total (Fig. 1).

Table 1
Detailed gradient flow program for the UPLC system.

Time (min)	Mobile A/mobile B	Flow rate (mL min^{-1})	Curve
initial	65/35	0.20	6
0.25	65/35	0.20	6
0.50	50/50	0.20	9
7.00	50/50	0.20	6

The Acquity triple quadrupole mass spectrometer (TQD) equipped with a Z-spray electrospray ionization (ESI) source was used for determination of levoglucosan in this study. Data were collected in negative ion mode by multiple reactions monitoring (MRM), and the ESI source block temperature was 150 °C. The optimal MS conditions of the mass spectrometers were as follows: source voltage 3.00 kV; source desolvation temperature 500 °C; source gas flow desolvation 800 L h^{-1}; cone gas 50 L h^{-1}. The ion transition *m/z* 161/101 was used for quantification of levoglucosan in samples. The data were collected and analyzed by Masslynx 4.1 software developed by Waters company.

2.4. Method validation

The method was validated following recommendations of ICH and some recent scientific publications relating to the analytical process [3,9,11–14]. During the method validation, LOD, linearity, recovery, repeatability and reproducibility were evaluated using standard additions method. Special attention was paid to evaluating the “matrix effect”, because different Tibetan glaciers might have inconsistent matrix conditions and we did not get a commercial applicable isotope labeled levoglucosan for internal calibration. A snow sample (named KKSL-G) reported with no levoglucosan in our previous study [7] was used as real matrix procedural blanks. The standard addition method was used for evaluating the matrix effect in this study [15], and levoglucosan standard solutions at known concentrations were added into samples after filtering.

3. Results and discussion

3.1. Optimization of the instrumental performance

The ESI-MS conditions were optimized by infusing single standard of three isomers in both positive and negative ionization mode. No signal was recorded under different ion source parameters in positive mode. Highly abundant analytes signals were detected in negative mode, and ion transitions of the three isomers were selected using single standard solutions by direct infusion at a concentration of 100 ng mL^{-1} into the ion source of the mass spectrometer (161/71 and 161/101 for levoglucosan, 161/59 and 161/101 for galactosan, 161/85 and 161/101 for mannosan). The effect of various ESI-MS parameters such as ESI source temperature (100–200 °C), source voltage (2.5–4.5 kV), source desolvation temperature (300–650 °C) and desolvation gas flow rate (600–1000 L h^{-1}) was studied.

C18 columns have usually been used for HPLC determination of levoglucosan in snow/ice [3,8]; however, very poor chromatographic response intensity was observed when the Acquity BEH C18 column (Waters, 2.1 × 100 mm, 2.1 × 75 mm and 2.1 × 50 mm,

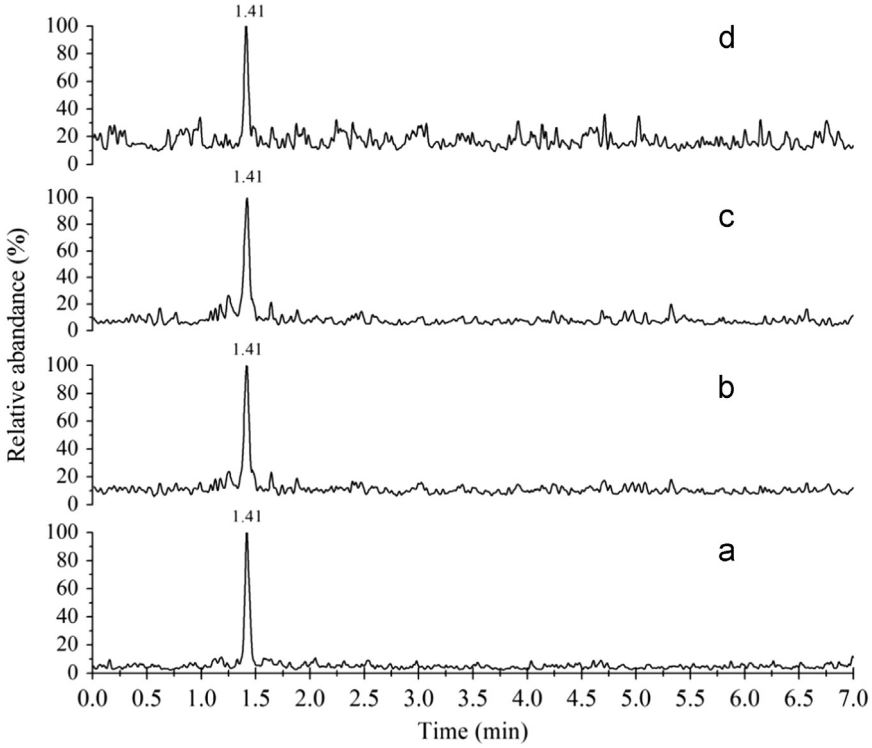

Fig. 1. Chromatogram for levoglucosan under the optimal experimental conditions. (a) Standard solution at a concentration of 2.00 ng mL^{-1}; (b–d) Chromatogram for the Zangsegangri ice core sample T405_01, b is MRM; c is in transition 161/101; d is in transition 161/71.

1.7 um) was introduced in the UPLC system in this study. MAs are strongly hydrophilic compounds, and previous studies even reported that MAs could not be sufficiently retained on alkyl-bonded silica columns [12]. Due to extensive column bleeding, the carbohydrate column was not compatible with the mass spectrometer ion source for levoglucosan analysis reported in previous aerosol studies [11]. Polar compounds have been proven to achieve higher retention and selectivity on the BEH Amide stationary phase compared with BEH hydrophilic interaction chromatography (HILIC) stationary phase in the UPLC system [16]. Previous study indicated that BEH amide columns were with good performances for dealing with MAs in aqueous matrix samples [12]. Therefore, the Acquity BEH Amide column (2.1 mm × 150 mm, 1.7 um) was chosen for analysis of levoglucosan in snow and ice samples in this study.

Pure water matrix injection is harmful to the Amide column due to the severe depletion of the amide group by water. However, a higher proportion of ACN can apparently dilute the concentration of levoglucosan in samples. An injection mixture comprising ACN and melt sample at a ratio of 50/50 (v/v) was used. This ratio not only yields a good chromatographic peak of levoglucosan, but also protects the BEH amide stationary phase. Furthermore, 50% ACN can also prevent the potential microbial decomposition of levoglucosan in melted samples, noting the large number of bacteria reported in Tibetan glaciers [10]. Result of repeated tests showed that levogluocsan was stable and displayed negligible degradation under the 50% ACN during storage at a temperature of 4 °C for longer than one week.

The recommended mobile phase for the Acquity BEH Amide column includes a high ACN ratio. The rotation time becomes longer when a higher ratio of ACN is used. On the other hand, a higher ratio of ACN in the mobile phase can also lead to a broader chromatographic peak of levoglucosan. Different ratios of ACN/water (30/70, 32.5/67.5, 35/65, 37.5/62.5, 40/60, 50/50, 60/40, 70/30) were tested as mobile phases. The best signal to noise (S/N) was obtained using a mobile phase of 35% ACN, with $S/N=263$ at a concentration of 10.00 ng mL^{-1} for levoglucosan standard solution. However, when the isocratic program of 35% ACN was applied to Tibetan glacier samples, it showed poor levoglucosan separation. Considering the depletion of the BEH amide stationary phase and the impact of other unknown polar organic compounds on levoglucosan, a gradient method was used to achieve a better result (Table 1). The S/N under this gradient program was 287 at a target concentration of 10.00 ng mL^{-1} (3 injections), was 56 at a concentration of 2.00 ng mL^{-1} (Fig. 1a), and was 73 at a concentration of 3.02 ng mL^{-1} for a Tibetan ice sample (Fig. 1b–d).

Comparative experiments showed that signal intensity increased when temperature increased from 25 to 40 °C, and then decreased with increasing temperature. Thus, the column temperature was chosen as 40 °C in this study.

Experimental results showed that the signal intensity increased a little with increasing flow rate of the mobile phase, but the retention time increased with lower flow rates. When the ratio of ACN is lower than 50% in the mobile phase, a lower flow rate is helpful to protect the BEH amide column. Previous studies also indicated that a lower flow rate could reduce matrix effects [17]. Finally, a flow rate of 0.20 mL min^{-1} was used in this study.

The excellent separation capacity of the BEH Amide column can provide potential separation of three isomers. Good chromatographic performance was obtained for single standard solutions of three isomers. However, the response intensity was very low for mixed standards even at a concentration of 100 ng mL^{-1} (about 20 times lower than that for a single standard). A similar phenomenon was reported in Antarctic ice samples [3]. Considering the extremely low concentration of the MAs in snow/ice samples, we finally concentrated on increasing the instrumental sensitivity of levoglucosan at the cost of the chromatographic separation of the three isomers. This is acceptable because levoglucosan accounting for more than 90% of total MAs in environmental conditions [2,3], mannosan and galactosan were reported only minor contributors

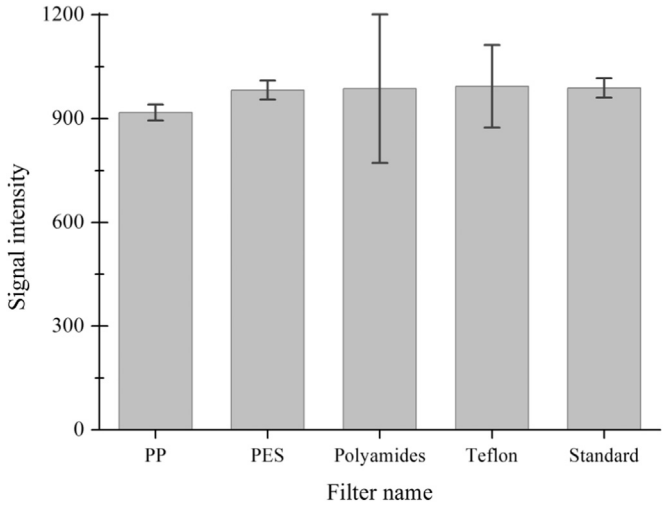

Fig. 2. Comparative experimental results of four water system Millipore filters by adding levoglucosan at a concentration of 4.14 ng mL^{-1} into procedural blanks, based on 6 injections.

to the total MAs in the TP ice [8].

3.2. Extraction of levoglucosan in samples

Although previous studies have indicated that the filtration process might absorb and contaminate the samples [3], filtration was necessary for sample preparation when using the UPLC system due to the large quantity of insoluble particles in samples from Tibetan glaciers [10]. In this study, comparative experiments were conducted with four commercially available 0.22 um water system Millipore filters: Teflon filter, Polyamides filter, Polypropylene (PP) filter and PES filter (6 injections). Results showed that the PP filter could absorb levoglucosan significantly. However, repeatability tests (6 injections) showed a relative standard deviation (RSD) of 21.1% for the Polyamides filter, 12.2% for the Teflon filter and 3.2% for the PES filter at a concentration of 4.14 ng mL^{-1}(Fig. 2). All of the samples were filtered using 0.22 um PES filters.

3.3. Matrix effect

Co-eluting compounds originating from the matrix can significantly impact the signal intensity [15,17]. Series of known levoglucosan standard solutions were added into authentic samples from three different glaciers after filtration for evaluating the matrix effect. The absolute matrix effects were investigated using the standard addition method [15]. Good linearity was obtained from standard addition samples, with $R^2 > 0.995$ (Table 2). Therefore, we can be confident that the impact of the matrix effect is limited for samples from different Tibetan glaciers.

Table 2
Absolute matrix effects (%) based on areas and areas ratio for levoglucosan in Tibetan glacier snow and ice samples with the UPLC system.

Sample series	Sample type	Adding concentration	Matrix effects ± RSD (%)
CPG06 (0.77 ng mL^{-1})	Snow	0.50	93.7 ± 11.6 (n=3)
		1.00	97.1 ± 7.6 (n=3)
		2.00	99.6 ± 4.0 (n=3)
ZSGR0403 (BLD)	Ice	0.50	81.1 ± 14.4 (n=3)
		1.00	94.2 ± 6.1 (n=3)
		2.00	97.6 ± 3.5 (n=3)
ZQP_S3(1.11 ng mL^{-1})	Snow	0.50	96.9 ± 6.6 (n=3)
		1.00	98.0 ± 4.4 (n=3)
		2.00	99.2 ± 2.7 (n=3)

3.4. Method validation

Results show that there are no apparent chromatographic peaks of levoglucosan in procedural blanks, and the response intensity is 44 ± 8 (based on 18 injections). Method LOD was evaluated by standard addition at a known concentration into the procedural blanks. The RSD was 0.037 ng mL^{-1} at a target concentration of 1.00 ng mL^{-1} (based on 6 injections). The LOD of this method was quantified as three times the averaged RSD, yielding a concentration of 0.11 ng mL^{-1}. The absolute mass LOD is 0.55 pg (0.11 ng mL^{-1} × 5 uL injection) in this study, compared with 0.3 pg (3 pg mL^{-1} × 100 uL injection) reported by Gambaro et al. (2008).

Results of three consecutive measurements show that recovery is 91.2% at a concentration of 0.82 ng mL^{-1}, and 99.3% at a concentration of 4.14 ng mL^{-1}. Repeatability of the method was evaluated by RSD, and varies from 17.9% at a concentration of 0.82 ng mL^{-1} to 2.8% at a concentration of 4.14 ng mL^{-1}. Reproducibility of the method was assessed by analyzing the same concentration over three consecutive days (three replications per day). RSD is 15.1% at 0.82 ng mL^{-1}, and 1.9% at 4.14 ng mL^{-1}. Three consecutive measurements of the selected samples from the Zangsegangri ice core also show high repeatability; RSD is 17.5% at a concentration of 1.49 ng mL^{-1} and 8.2% at a concentration of 3.41 ng mL^{-1} in authentic ice samples.

The linearity was evaluated based on matrix matched calibration curve, and daily calibration was performed. The target concentration of levoglucosan for the calibration curve varied from 0.25 to 4.00 ng mL^{-1} at five concentration levels (0.25, 0.50, 1.00, 2.00, 4.00 ng mL^{-1}), covering typical concentrations of levoglucosan in the snow/ice samples reported in previous studies. Good linearity was obtained, with an R^2 value of 0.9993. The intercept of the calibration curve is 39, indicating that the background is much lower than the LOD. The coefficient of variation for the daily calibration curves was only 4.6% during the experimental period, which indicates that the matrix effect impact is small and has no apparent influences on snow and ice samples [18].

Two snow samples, which had been analyzed in our previous study [7], are used for validating this method. A Muztagh Ata glacier snow sample was reported with levoglucosan concentration of 1.93 ng mL^{-1} in previous study, and it is 1.97 ng mL^{-1} using this method. A Beijing snowfall sample was reported with 1.65 ng mL^{-1} of MAs in total, and it is 1.60 ng mL^{-1} using this method.

3.5. Levoglucosan in Tibetan glacier samples

Levoglucosan concentration varied from below LOD to 7.56 ng mL^{-1}, and the average value was 0.85 ng mL^{-1} in the Tibetan glacier samples (Table 3). Levoglucosan concentration has been reported with an average value of 0.11 ng mL^{-1} in ice samples from polar regions [3,4,6]. The concentration reached

Table 3
Concentration of levoglucosan (ng mL^{-1}) in snow and ice samples on the TP.

Glacier name	Levoglucosan concentration	Average	Sample number	Sample type
Dasuopu	BLD to 1.56	0.31	11	Snow
Muji	0.32 to 2.78	1.14	12	Snow-pit
Demula	BLD to 1.13	0.28	6	Snow
Zuoqiupu	BLD to 6.07	1.41	17	Snow
Cuopugou	BLD to 3.95	1.01	15	Snow-pit
Zangsegangri	BLD to 7.56	0.71	50	Ice core

Notes: BLD means below limit of detection.

0.75 ng mL^{-1} in a Ushkovsky ice core, due to the strong influence of wildfires over Siberia [5]. Results indicated that Tibetan glaciers are more seriously contaminated by biomass burning emissions when compared with high latitude regions.

4. Conclusions

A UPLC-MS/MS method for rapid determination of levoglucosan in snow and ice samples has been validated in this study. This method is suitable for samples from Tibetan glaciers, and can be applied to other low and middle latitude snow and ice samples with complex matrices. Result indicates that Tibetan glaciers are evidently affected by biomass burning emissions. This method will facilitate further studies of biomass burning records on Tibetan glaciers.

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