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Development of certified reference material of methamphetamine hydrochloride

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ABSTRACT
This work aimed to present the production of a Certified Reference Material (CRM) of methamphetamine hydrochloride, as an important tool to ensure the quality of forensic results. Methamphetamine is a synthetic drug derived from amphetamine, which potentially stimulates the central nervous system, and its prolonged use can cause excessive anxiety, euphoria, bipolar disorder, and psychosis, among other health damages. To produce this batch of CRM, homogeneity and transport stability studies were carried out by High-Performance Liquid Chromatography with Photodiode Array Detection (HPLC-PDA) using the results of chromatographic area corrected by the mass fraction of the sample in the analyzed solution. Evaluation of stability under storage conditions and characterization of the material were performed by ^{1}H qNMR, a ratio primary measurement procedure. The CRM showed neither considerable heterogeneity nor a tendency to instability under transport conditions (temperature of 50 °C up to 21 days) and storage conditions (20–25 °C). The certified purity value of methamphetamine hydrochloride was (999 ± 12) mg/g, equivalent to a mass fraction of (99.9 ± 1.2) g / (100 g), (k = 2).

Section: RESEARCH PAPER

Keywords: methamphetamine; certified reference material; metrological traceability; forensic chemistry

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1. INTRODUCTION

Methamphetamine is a synthetic drug derived from the amphetamine molecule. Amphetamine compounds are central nervous system stimulants, causing increased concentrations of the neurotransmitters dopamine, serotonin, and norepinephrine in the brain [1], [2]. This induces greater alertness, increased excitement, euphoria, excessive anxiety, and personality disorders [3]. Although some of these amphetamine compounds can be used to therapeutically treat narcolepsy, attention deficit hyperactivity disorder, and obesity, its abusive use causes irreversible damage [4].

Methamphetamine hydrochloride (N-methyl-1-phenylpropan-2-amine; hydrochloride, MA.HCl; Figure 1) is an unpredictable and lethal drug, more potent than amphetamine, due to the additional methyl moiety that makes it more lipophilic and, therefore, facilitates the crossing of the blood-brain barrier [5]. Methamphetamine on the illegal market is also known as ice, crank, meth, glass, speed, and crystal. Hydrochloride is its most common form due to the solubility of this compound in water and acids, and to the consequent potential to be used orally, injected, intravenously, and

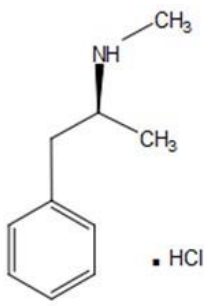

Figure 1. Chemical structure of methamphetamine hydrochloride.

intranasally [6], [7]. The United Nation Office on Drugs and Crime (UNODC) estimates that there are 27 million users of amphetamine-type stimulants globally, constituting the third largest group of users, after cannabis and opioids [8].

Identification of MA.HCl is extremely important in several types of crimes. Judicial processes resulting from seizure and repression operations in general require that the results of forensic analysis are reliable in order to avoid questioning due to possible analytical weaknesses.

The use of CRM by laboratories is a tool required by the ISO/IEC 17025 standard [9] to guarantee the quality of routine analysis, as well as to establish metrological traceability in calibration. CRMs are stable, homogeneous, and fully characterized regarding their composition, which are accompanied by a certificate or similar type of document declaring the specified value of a given property, and the associated measurement uncertainty [10]. CRMs can be used to provide measurements with quality assurance and metrological traceability to the International System of Units (SI), which means accuracy and comparability of results over time and space [9]-[13]. Laboratories accredited under ISO/IEC 17025 are required to establish the metrological traceability of their measurement results [9].The present work aimed at developing a CRM of MA.HCl following the requirements from ISO 17034 standard [11], as a tool to improve the robustness of the reports of forensic chemistry laboratories, as well as a strategical tool for the implementation of public security actions.

2. EXPERIMENTAL PROCESS

2.1. Chemicals and sample preparation

All solvents used were High-Performance Liquid Cromatography (HPLC) grade (Tedia, USA); maleic acid CRM 8792.0001 (certified purity: (999.9 ± 1.7) mg/g, $k = 2$) was from the Brazilian National Institute of Metrology, Quality and Technology (Inmetro, Duque de Caxias, RJ, Brazil); deuterium oxide (D_2O) was from Cambridge Isotope Laboratories (Andover, USA). The MA.HCl is a high-purity powder that meets the commercial standard; it is ground, homogenized, and bottled in 478 amber glass vials (50 mg), stored at 20 °C to 25 °C.

2.2. Instrumentation

HPLC-PDA. ACQUITY UPLC–PDA System (model Xevo TQ; Waters, MA, USA) was used for the homogeneity and transport stability studies, and preliminary determination of purity. Liquid chromatographic separation was performed using an Acquity UPLC BEH C8 and 18 columns (1.7 µm × 2.1 mm × 100 mm; Waters, Milford, MA, USA), with a flow rate of 0.3 mL/min, and an injection volume of 10 µL at 27.5 ºC column temperature, and wavelength detector (λ = 210 nm). Mobile phase A consisted of water with 0.1 % (v/v) Trifluoroacetic acid (TFA), mobile phase B was acetonitrile with 0.1 % (v/v) TFA. Gradient mode elution (0–1 min, 10 % B, 1–6 min, 10–40 % B, 6–10 min, 40–80 % B, 10–11.01 min, 80–10 % B, and 11.01–12 min, 10 % B).

Karl Fischer coulometric titration. The water content was determined using a Karl Fischer coulometer (model 852, Metrohm AG, Bleiche West, Switzerland) equipped with a generator electrode without a diaphragm, a current generator electrode (400 mA) and a platinum indicator electrode (10 µA). The results were processed with Tiamo 2.4 software, 2006 version (Metrohm).

NMR. Data acquisition was performed in a Nuclear Magnetic Resonance (NMR) spectrometer system Avance III HD equipped with an Ascend 500 magnet operating at 11.74 T (500 MHz for ^{1}H) (Bruker Daltonics, MA, USA), and a Prodigy cryoprobe (CPP TCI 500S1 H&F-C/N-D-05 Z) at 298 K. A simple delay-pulse-acquire sequence was used with 90° pulses that were calibrated for each acquisition with an offset at 4.4 ppm, acquisition time was 3.28 s, with 64 k points, 16 transient scans, relaxation delay of 57 s, resulting in a Free Induction Decay (FID) resolution at 0.31 Hz/pt. The ^{1}H NMR spectrum was referenced with the D_2O solvent signal at 4.8 ppm. Acquisition replicates (n = 3) of each tube were performed randomly. The spectra were processed with MestreNova 14.1.1 program, Mestrelab Research SL (Santiago de Compostela, Spain). Peak multiplicities were designated by the following abbreviations: s, singlet; d, doublet; t, triplet; dd, double doublet, and m, multiplet.

2.3. Sample preparation and measurement uncertainty

Sample solutions were gravimetrically prepared using calibrated analytical balances: Sartorius MSA 2.7S, 2.1 g capacity, resolution of 0.0001 mg, expanded uncertainty of 0.0017 mg ($k = 2$) at the measured load (Goettingen, Germany), Mettler Toledo XS 205, 220 g capacity, resolution of 0.01 mg, Mettler Toledo XS 1003 S, 1010 g capacity, resolution of 0.001 g, and Mettler Toledo UMX5, 5.1 g capacity, resolution of 0.0001 mg, expanded uncertainty of 0.0014 mg ($k = 2$) at the measured load (Greifensee, Switzerland).

2.4. Homogeneity study

Between-unit homogeneity was studied with the analyses of 3 true replicates of 10 units selected in a random stratified sampling scheme. Within-unit homogeneity was evaluated in 6 true replicates from a single unit. From each flask, 300 µg mL^{-1} solutions were prepared in triplicate, and each solution was injected three times into the HPLC system in a single injection sequence, as previously described. To prevent block effect or trend along the sequence, the first injection block (group) was analyzed in ascending filling order, the second in random order, and the third in descending order. Results were evaluated through the area of MA.HCl (analyte) corrected by the mass fraction of the solution, determined according to (1)

$$A_{\text{corrected}} = A_{\text{analyte}} / MF_{\text{solution}} , \quad (1)$$

where $A_{\text{corrected}}$ is the HPLC peak area corrected by mass fraction of the MA.HCl in the analyzed solution, A_{analyte} is the MA.HCl peak area (300 µg g^{-1} solution), and MF_{solution} is the mass fraction of MA.HCl in the solution. This result does not have a physical meaning, as it does not represent the concentration or mass fraction of MA.HCl in the sample. However, the variation of this relative parameter in the samples was used as a measure of the homogeneity of the material, as all samples were analyzed under repeatability conditions within the same chromatographic run sequence.

2.5. Short-stability study

The short-term stability study was performed at 50 °C (simulated transport temperature) for 28 days in an isochronous design. Stability was evaluated from 10 units selected by the stratified random approach. Every 7 days, 2 units were removed and kept at reference temperature (20–25 °C) for later analysis. At the end of the 28 days, the 8 flasks corresponding to 7, 14, 21, and 28 days of study were added to two others, which

remained at reference temperature. All CRM flasks were analyzed on the same day (300 µg mL^{-1} solution of MA.HCl) by HPLC-PDA. The evaluation of the results was based on the $A_{\text{corrected}}$ in an analogous way to the one presented for the study of homogeneity by (1).

2.6. Long-stability study

Long-term stability was evaluated under storage conditions (20–25 °C), during 6 months with monthly analysis (0, 1, 3, 5, and 6 months), by the classic design. The analysis was performed by ^{1}H quantitative nuclear magnetic resonance (^{1}H qNMR), using maleic acid CRM (999.9 ± 1.7) mg/g (k = 2), as an internal standard (IS). The samples and the IS were accurately weighted, targeting 10.0 mg and 9.4 mg, respectively, and dissolved in 1 mL of D_2O by vortexing. At each time point, two flasks were analyzed in 3 true replicates. The evaluation of the stability of MA.HCl under storage conditions was performed using linear regression.

2.7. Candidate CRM Characterization

The identification of related substances was previously determined by HPLC-PDA. For this, the columns C8 and C18 were evaluated, applying the chromatographic method previously described. The water content was determined with Karl Fischer coulometric titration using 6 replicates of 0.03 g (total of 6 flasks) by direct addition of samples into the titration vessel. Characterization was performed by ^{1}H qNMR, a ratio primary measurement procedure, using maleic acid CRM as the IS. The mass fraction of MA.HCl (w_A) in g/100 g was determined by qNMR using the (2):

$$w_A = \frac{I_A}{I_{IS}} \cdot \frac{M_A}{M_{IS}} \cdot \frac{N_{IS}}{N_A} \cdot \frac{m_{IS}}{m_A} \cdot w_{IS}\,, \tag{2}$$

where w is the mass fraction (g/100 g), I is the integral of the peak, M is the molar mass, N is the number of protons contributing to each quantified signal, and m is the weighted masses. The subscripts A and IS refer to analyte and internal standard, respectively.

2.8. Estimation of uncertainties

The CRM property value was the mass fraction determined with ^{1}H qNMR, and its uncertainty (u_{CRM}) was obtained by combining the uncertainties of the characterization study itself, homogeneity, short-term stability, and long-term stability assessments. The uncertainties were combined in a relative way, since the uncertainties of the homogeneity and the short-term stability were obtained using $A_{\text{corrected}}$ and not mass fraction, as used for characterization and long-term stability studies. The uncertainty estimations were performed according to the Eurachem/Citac Guide [14], ISO GUM [16], a supplement for Monte Carlo Simulation [17].

The uncertainty due to between-unit (bu) homogeneity was calculated with (3) [18]:

$$u'_{\text{bu}} = \sqrt{\frac{MS_{\text{within}}}{n_r}} \cdot \sqrt[4]{\frac{2}{dfMS_{\text{within}}}}, \tag{3}$$

where u'_{bu} is the uncertainty due to between-unit homogeneity, MS_{within} is the mean square within groups, n_r is the number of replicates, and $dfMS_{\text{within}}$ is the degrees of freedom of the mean square within groups. Equation (3) is applied for calculating between-unit homogeneity when $MS_{\text{within}} > MS_{\text{between}}$ [16].

The uncertainty due to within-unit (wu) homogeneity was calculated with (4) [18]:

$$S_{\text{wu}} = \sqrt{\frac{MS_{\text{between}} - MS_{\text{within}}}{n_{\text{r}}}}\,, \tag{4}$$

where S_{wu} is the within-unit component of variance from a homogeneity study, expressed as a standard deviation (which can be used as a component u_{wu} of the uncertainty for the certified value), MS_{between} is the mean square between aliquots, and MS_{within} is the mean square within aliquots.

The short- and long-term stability uncertainties (u_{sts} and u_{lts}, respectively) were estimated using (5) [18]:

$$u_{\text{sts}} = u_{\text{lts}} = s_{b1}\, t\,, \tag{5}$$

where s_{b1} is the slope uncertainty in g/(100 g day^{-1}) or in g/(100 g week^{1}) and t is the time in days or weeks.

The combined standard uncertainty of the CRM property value (u_{CRM}) in g/(100 g) was estimated with (6):

$$u_{\text{CRM}} = \sqrt{u^2_{\text{C(W}_\text{A})} + u'^2_{\text{bu}} + u^2_{\text{sts}} + u^2_{\text{lts}}}\,. \tag{6}$$

Both stability uncertainties (u_{sts} and u_{lts}) were considered for calculating u_{CRM}. The expanded uncertainty of the certified property value (U_{CRM}) was calculated with (7), using a coverage factor (k) of 2, for a confidence level of approximately 95 %:

$$U_{\text{CRM}} = k \cdot u_{\text{CRM}}\,. \tag{7}$$

In (6), $u_{\text{C(W}_\text{A})}$ denotes the combined standard uncertainty contribution from the characterization of the property value of the MA.HCl. The $u_{\text{C(W}_\text{A})}$ was determined with ^{1}H NMR and was estimated with (8) according to GUM [16]:

$$u_{\text{C}}(w_{\text{A}}) = \sqrt{u^2_{\frac{\text{I}_\text{A}}{\text{I}_\text{IS}}} + u^2_{\text{M}_\text{A}} + u^2_{\text{M}_\text{IS}} + u^2_{\text{m}_\text{IS}} + u^2_{\text{m}_\text{A}} + u^2_{\text{W}_\text{IS}}}\,. \tag{8}$$

3. RESULTS AND DISCUSSION

3.1. Homogeneity study

The homogeneity results showed no trend across filling order (Figure 2) or chromatographic injection sequence (Figure 3).

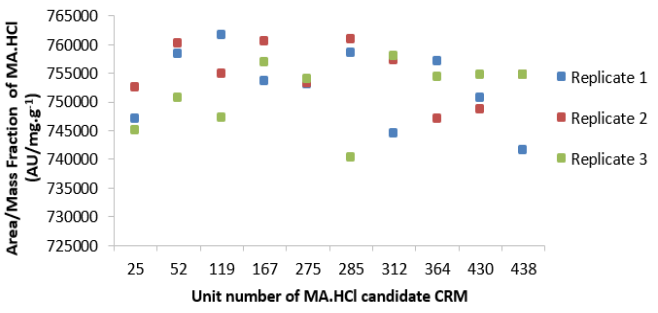

Figure 2. Trend graph of homogeneity between MA.HCl units and replicates by bottling order.

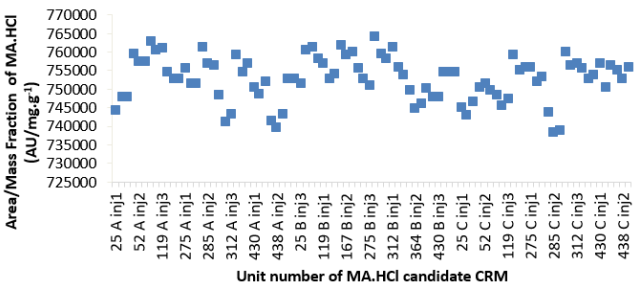

Figure 3. Trend graph of homogeneity between MA.HCl units and replicates by injection order.

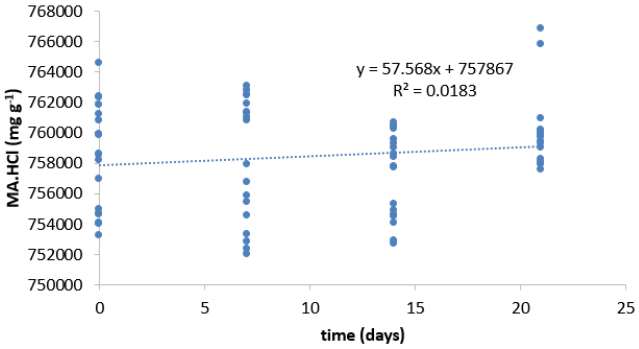

Figure 4. Results for the short-term stability study of MA.HCl candidate CRM at 50 °C.

In the homogeneity assessment, the one-way analysis of variance for the 11 flasks analyzed in triplicates resulted in uncertainty associated with between-unit heterogeneity of 2.01×10^3 (3) and an uncertainty associated within-unit heterogeneity of 3.61×10^3 (4), both in terms of chromatographic corrected area.

For the assessment of within-unit homogeneity, one unit of MA.HCl was selected, from which six replicates were prepared and injected in triplicate. The results were analyzed by one-way ANOVA (Table 1). In the study of within-unit homogeneity, the MS_{between} (weighing replicates; 4.19×10^7) was greater than the MS_{within} (injection replicates; 2.83×10^6). The analytical variation was much smaller than the variation between aliquots. Furthermore, the variation between aliquots (2.09×10^8) was even greater than the between-unit homogeneity uncertainty (2.01×10^3), as well as greater than the uncertainty associated with the balance indication (0.0017). Since the purity of the CRM candidate is very high (the batch showed only 0.01 mg/g of impurities), it is not expected that the difference between replicates was caused by heterogeneity inside the flask, but rather by variations in the weighing of the samples attributable to the operator. Therefore, any actual lack of homogeneity is covered by the between-unit homogeneity uncertainty, which is also assessed using three aliquots per vial, and there is no need to incorporate an additional component that would artificially inflate the material's uncertainty due to analytical limitations. In addition, the repeatability of the HPLC-PDA method was high with a relative standard deviation (RSD) from 0.14 to 0.29 %, so any minor differences in chromatographic area results would be noticed. Thus, the value of within-unit heterogeneity was not considered for calculating the u_{CRM}. The uncertainty related to the homogeneity for CRM of MA.HCl was 2.01×10^3, equivalent to 0.27 % of the mean value of the area ratio results (7.53×10^5).

3.2. Short- and long-term stability studies

The short-term stability study was carried out to evaluate the CRM stability under transport conditions (50 °C) for 28 days by HPLC-PDA, using an isochronous design. All flasks were analyzed at the end of the study. The evaluation of the results was based on the $A_{\text{corrected}}$ as applied in the homogeneity study. The results of the short-term stability study are shown in Figure 4. A trend in the measurand response was observed when the results of the area corrected were plotted in order of study time. After removing the last study point (28 days), the curve slope was considered insignificant (t_{b1} value smaller than t_{crit}, 1.144 < 1.995), and therefore this material proved stable under transport conditions (50 °C, 21 days). Using Equation (5), based on the value of $s_{b1} = 5.03 \times 10^1$ (regression analysis) and on the 21-day period, the short-term stability uncertainty (u_{sts}) was 1.06×10^3, equivalent to 0.14 % of the mean value of the area ratio results (7.58×10^5).

The long-term stability study (storage conditions at 20–25 °C for 6 months) was evaluated using classical design. The samples were individually analyzed by qNMR on pre-determined periods (0, 1, 3, 5, and 6 months). Linear regression of data showed that the slope of the curve was not significantly different from zero, (t_{b1} value smaller than t_{crit}, 0.756 < 2.003), therefore this material proved stable at 20–25 °C for 6 months. The results from all acquisitions were considered to assess long-term stability. In the third month of the long-term stability study (103 days), a set of measurement data above the mean line (linearized fit) was observed. However, this data dispersion was accounted for in the value of s_{b1}, and consequently, in the uncertainty associated with the batch instability, which was determined by the product of s_{b1} by the time interval between characterization and the expiry date of the certificate.

Figure 5 shows the results of the long-term stability study of the MA.HCl candidate CRM. The long-term stability uncertainty (u_{lts}) was estimated as 5.1 mg g^{-1} which is equivalent to 0.51 % according to Equation (5), considering s_{b1} as 0.0053 (regression analysis) and t as the storage shelf-life of 967 days (approximately 3 years).

Table 1. Uncertainty combination data obtained for the characterization of MA.HCl by ^{1}H qNMR.

Signal	W_A (mg/g)	$u_{(WA)}$ (mg/g)	$u_{c(WA)}$ (mg/g)
7.39 ppm	998.60	0.87	0.92
2.88 ppm	998.98	0.92	
Average	998.79		

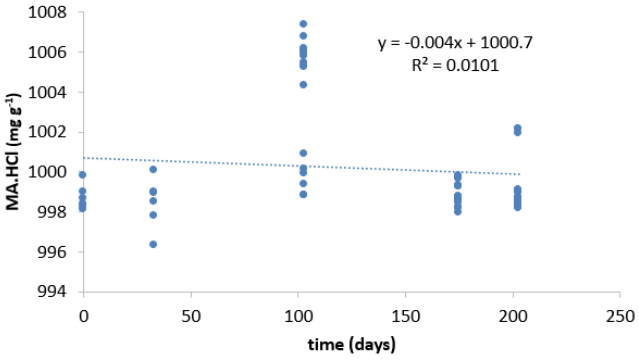

Figure 5. Results for the long-term stability study of MA.HCl candidate CRM.

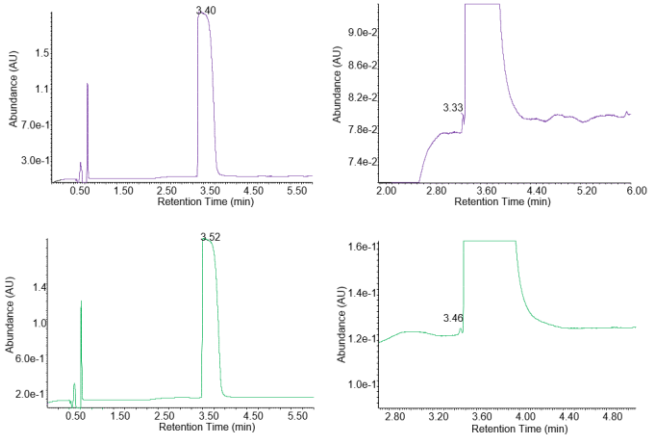

Figure 6. HPLC-PDA chromatograms of test-related substances of candidate MA.HCl CRM (at 1000 µg mL^{-1}) columns C8 (a) and columns C18 (b), magnification (c), unknown impurities (t_R = 3.33 min) with C8 column, magnification (d), unknown impurities (t_R = 3.46 min) with C18 column.tudy of MA.HCl candidate CRM.

3.3. Characterization

The related substances were evaluated by HPLC-PDA and the water content by Karl Fischer coulometric titration. Characterization was performed by ^{1}H qNMR, a potential ratio primary method of measurement, using maleic acid CRM as an IS.

The water mass fraction determined by Karl Fischer coulometric titration was 0.40 mg/g of MA.HCl, with an expanded uncertainty (u_{water}) of 0.35 mg/g for k = 2.

The HPLC-PDA analyses showed a low-intensity peak detected close to the main component peak (1000 µg mL^{-1} solution of MA.HCl) as shown in Figure 6. However, the impurity signal intensity was very close to the chromatogram noise, in the order of 0.01 mg/g, a value lower than the material target uncertainty (u_{CRM}) of 1.5 mg/g. Both columns C8 and C18 presented good method repeatability, with approximately 0.2 % RSD (n = 10), respectively.

The structural identification of MA.HCl was confirmed by ^{1}H NMR analysis. The ^{1}H NMR spectrum (500 MHz, D_2O) of the MA.HCl CRM candidate showed the following signals

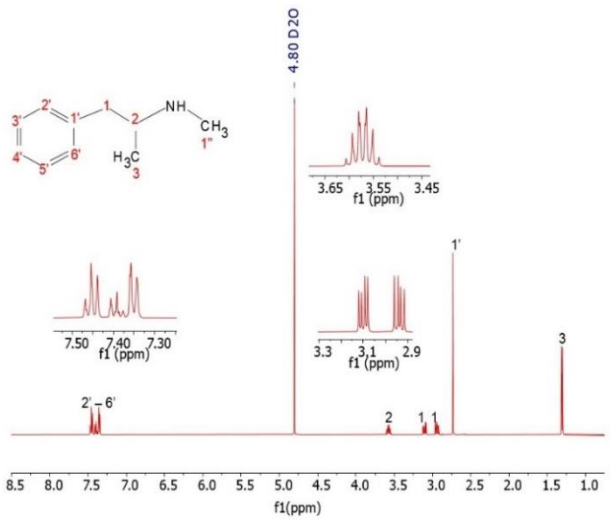

Figure 7. 500 MHz ^{1}H NMR spectrum for MA.HCl candidate CRM in D_2O, were f1 corresponds to the chemical shift.

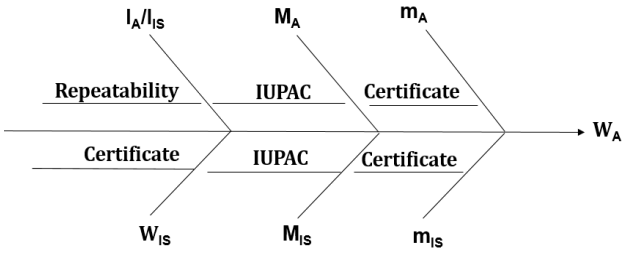

Figure 8. Ishikawa diagram illustrating the uncertainty sources affecting MA.HCl mass fraction.

(Figure 7): δ 1.27 ppm (d, 3H); δ 2.70 ppm (s, 3H); 2.90 ppm (dd, 1H); 3.07 ppm (dd, 1H); 3.53 ppm (m, 1H); 7.44 ppm - 7.31 ppm (m, 5H).

The purity of the IS in mg/g (999.9 ± 1.7, k = 2) was included in Equation (2), so that the final result would be in this unit. The signals used for quantitative analysis were 6.4 ppm for maleic acid, and 2.88 ppm (ddd, 2H + s, 3H) and 7.39 ppm (m, 5H) for MA.HCl. The quantification of MA.HCl was performed by the average of these two signals.

To estimate the measurement uncertainty of the qNMR determination (u_{WA}), the classic approach of the GUM [16] was used, considering all sources of uncertainty of the input quantities of the measurand according to Equation (2) (Figure 8). The results of the mass fraction and measurement uncertainty are shown in Table 2. The mass fraction obtained using the NMR peak at 2.88 ppm presented a slightly higher uncertainty, and this was considered for the characterization of the batch ($u_{\mathrm{C(W_A)}}$). The uncertainty budget detailing all parts of the process, and showing the sources of uncertainty to the characterization of MA.HCl by quantitative ^{1}H NMR (qNMR) using the peak at 2.88 ppm, is shown in Table 3.

The mass fraction of the MA.HCl determined with ^{1}H qNMR was (998.8 ± 1.8) mg/g, for k = 2. The HPLC-PDA analysis results and the water content were compatible with the purity by qNMR.

3.4. CRM certified value and estimation of uncertainties

The certified value is the one with the highest confidence in its accuracy and for which all known or potential sources of error were researched and considered. The characterization value of the MA.HCl CRM was determined by ^{1}H qNMR.

In order to calculate the expanded uncertainty, contributions from standard uncertainty due to homogeneity, short-term stability, long-term stability, and characterization were evaluated. To do this, the combined standard uncertainty and expanded uncertainty for the certified reference material were calculated according to Equation (6) and Equation (7), including the uncertainty of the MA.HCl mass fraction determined by ^{1}H qNMR (W_A) according to Equation (8). The calculated combined standard uncertainty was 6.0 mg/g. The budget for the uncertainty estimation of the certified value is presented in Table 4.

Table 2. Uncertainty combination data obtained for the characterization of MA.HCl by ^{1}H qNMR.

Signal	W_A (mg/g)	$u_{(WA)}$ (mg/g)	$u_{c(WA)}$ (mg/g)
7.39 ppm	998.60	0.87	0.92
2.88 ppm	998.98	0.92	
Average	998.79		

Table 3. The uncertainty budget for the characterization study of MA.HCl by ^{1}H qNMR using the signal at 2.88 ppm.

Sources of uncertainty	Value	Type	Distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty component
I_A/I_{IS} (repeatability)	1.3515	A	Normal	0.0005	739.1853	0.3359
M_A	185.6920	B	Rectangular	0.0067	5.3798	0.0361
M_{IS}	116.0719	B	Rectangular	0.0025	-8.6066	0.0214
m_{IS}	11.6866	B	Normal	0.0006	85.4808	0.0470
m_A	10.1162	B	Normal	0.0006	-98.7505	0.0543
W_{IS}	999.9	B	Normal	0.8	0.9991	0.8492

Table 4. The uncertainty budget calculation for the uncertainty estimation of the certified value for the MA.HCl CRM.

Sources of uncertainty	Value	Standard uncertainty	Uncertainty component
Characterization	998.79	0.92	0.0009
Homogeneity	753.0×10^3	2.0×10^3	0.0027
Short-term stability	758.5×10^3	1.1×10^3	0.0014
Long-term stability	1000.2	5.1	0.0051
Certified value (mg/g)	999	$u_{CRM} = 6$	$U_{CRM} = 12$

The certified value with its expanded uncertainty for a confidence level of approximately 95 % and a coverage factor $k = 2$ was MA.HCl mass fraction: (999 ± 12) mg/g or (99.9 ± 1.2) g/100 g.

4. CONCLUSIONS

The first batch of the CRM of MA.HCl produced by Inmetro was finalized and complied with all the requirements. The certified value with its expanded uncertainty (U_{CRM}) for a confidence level of approximately 95 % and coverage factor $k = 2$, was (99.9 ± 1.2) g/100 g. This material will be an important tool for forensic laboratories to ensure the metrological traceability of measurement and the quality of the forensic results.

AUTHORS' CONTRIBUTION

Conceptualization, Silvia R. P. Lopes, Eliane C. P. Rego and Bruno C. Garrido; methodology, Silvia R. P. Lopes, Wagner Wollinger, Eliane C. P. Rego and Bruno C. Garrido; investigation, Silvia R. P. Lopes; formal analysis, Silvia R. P. Lopes and Bruno C. Garrido; writing – original draft, Silvia R. P. Lopes; writing – review and editing, Silvia R. P. Lopes, Wagner Wollinger, Eliane C. P. Rego and Bruno C. Garrido; Resources, Wagner Wollinger, Eliane C. P. Rego and Bruno C. Garrido; project administration, Bruno C. Garrido. All authors have read and agreed to the published version of the manuscript.

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