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Abstract

Background: During monitoring of monthly medians of results from patients undertaken to assess analytical stability in routine laboratory performance, the medians for serum sodium for male and female patients were found to be significantly related.

Methods: Daily, weekly and monthly patient medians of serum sodium for both male and female patients were calculated from results obtained on samples from the population >18 years on three analysers in the hospital laboratory. The half-range of medians was applied as an estimate of the maximum bias. Further, the ratios between the two medians were calculated.

Results: The medians of both genders demonstrated dispersions over time, but they were closely connected in like patterns, which were confirmed by the half-range of the ratios of medians for males and females that varied from 0.36% for daily, 0.14% for weekly and 0.036% for monthly ratios over all instruments.

Conclusions: The tight relationship between the gender medians for serum sodium is only possible when raw laboratory data are used for calculation. The two patient medians can be used to confirm both and are useful as independent estimates of analytical bias during constant calibration periods. In contrast to the gender combined median, the estimate of analytical bias can be confirmed further by calculation of the ratios of medians for males and females.

Keywords: analytical bias; analytical stability; partitioning by gender; serum sodium; within-subject biological variation.

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Introduction

Serum sodium is one of the most tightly homeostatically regulated measurands in human blood. The required performance specifications of the analytical quality based on biological variation of the analyte are demanding because of low magnitude of fluctuations in concentrations over time. In consequence, it remains difficult to examine the concentration of this measurand with attainment of the desirable analytical performance specifications for imprecision and bias as well as analytical performance specifications for establishing common reference intervals [1, 2]. A report from two Belgian hospital laboratories on 5-day moving mean serum sodium results obtained on samples from patients, and followed for 13 years, was reported by Stepman et al. [3] with a maximum difference of approximately 4 mmol/L and long-term coefficients of variation (CV) of 5-day means of 0.6% and 0.9%. These estimates were of the same order as described by Lott et al. [4] who reported a CV of 0.82% for medians calculated on basis of samples collected from 200 to 2000 patients. The within-subject biological variation (CV_I) for serum sodium concentration is approximately 0.6% according to Minchinela et al. [5] based on the median of the large number of high-quality published estimates [6]. The reported CV [3, 4], above, as well as data reported ubiquitously in external quality assessment (EQA) schemes, considerably exceeded the desirable performance specifications of $CV_A < ½CV_I$, where CV_A is the analytical imprecision. Recently, we published the results of an investigation focusing on the range of monthly patient medians where the half-range was regarded as the numerical value of the maximum analytical bias, $|B_{MAX}|$ [7]. Our calculations of concentrations were based on raw data obtainable from the analysers rather than on the whole integers usually used to report serum sodium concentrations so that a sufficient number of significant figures after the decimal point would be generated for the computations of the quality terms. We discovered that serum sodium medians from male and female patients were closely related, and independent of the calibration of the analysers, since both medians seem to reflect the real *steady-state* distributions among patients.

The purpose of the current investigation was to explore the association between medians of serum sodium concentrations among male and female patients over time based on raw laboratory data and to assess the utility of the use of the two medians as independent estimates of analytical bias.

Materials and methods

Analysers and results on samples from patients

The clinical chemistry laboratory at Nordsjællands Hospital, University of Copenhagen, Hillerød, Denmark, generated 360,000 serum sodium results in 2015 where approximately 44% were requested by general practitioners. Serum sodium was examined on three Siemens Dimension Vista® 1500 instruments (Siemens Healthcare Diagnostics Inc., Newark, DE, USA), and the study included all results from patients >18 years of age with a Danish personal identification number. The study included only weekdays with more than 100 serum sodium results on each of the three analysers. Siemens Healthcare Diagnostics Inc. provided the reagents and calibrators. The routine procedures for serum sodium measurements were neither changed during the investigation nor during the subsequent assessment of the model. However, the results of the measurements were retained as raw data for the computations and calculations of medians used in the model. Imprecision at 141 mmol/L (instrument 1: 0.48%, instrument 2: 0.65%, instrument 3: 0.66%) was based on daily quality control.

Traceability of medians of serum sodium

The target values of serum sodium medians for both males and females were determined by use of the certified NFKK Reference Serum X lot number: NFKK2002a (DEKS Rigshospitalet – Glostrup, Glostrup, Denmark) with an assigned concentration of 140.65 mmol/L (expanded uncertainty: 0.75 mmol/L) as reported by The Scandinavian Society of Clinical Chemistry [8]. According to the instructions, the Serum X was kept at –70 °C until use, where it was removed from the freezer and placed in the dark for 2 h at room temperature, then mixed gently for 10 min and measured within 2 h. The serum was analysed in triplicates among the daily patient samples on all three instruments and the medians were calculated with the calibrator then in use as with the serum.

Calculations

The raw results from the examinations on samples from patients were transferred from the analysers to the laboratory information system (LABKA, CSC Danmark A/S, Valby, Denmark) and a few minutes later to the Oracle database PKLABKA (CSC).

The medians of serum sodium during January to June 2016 were calculated and extracted from the database using the PL/SQL Developer (Allround Automations, Enchede, The Netherlands). Daily, weekly and monthly medians of patient results were calculated for each gender on each analyser and for the three analysers combined. All other computations were performed on Microsoft Excel 2010 and Microsoft Access 2010.

The model

The medians of serum sodium examination results for both males and females were calculated for each individual analyser and for the combination of all three analysers for every day during the working week as defined above, the working week and the working month.

The estimates were compared to the performance quality specifications for optimal, desirable and minimum quality of 0.12%, 0.23% and 0.35%, respectively, as suggested by Fraser et al. [1] derived from the median estimates of CV_I in the most recent biological variation database [5]. The half-ranges of medians, in millimoles per litre, were used as the expression for bias, or more correctly for Δbias as documented previously [7]. Additionally, the ratio between medians for males and females (ratio = median females/median males) was calculated for daily, weekly and monthly medians, and half-range in millimoles per litre for these ratios was also compared to the performance specifications. The medians as well as the ratios of medians were validated with the following numbers: '1' for half-range millimoles per liter <0.12%, '2' for half-range millimoles per liter <0.23%, '3' for half-range millimoles per liter <0.35% and '4' for larger half-range millimoles per liter.

Results

Calibration

The medians obtained with Reference Serum X as calibrator were Vista 1 – males 139.7 mmol/L and females 139.7 mmol/L, Vista 2 – males 140.2 mmol/L and females 140.3 mmol/L and Vista 3 – males 140.7 mmol/L and females 140.9 mmol/L. The combined mean concentrations obtained from the three analysers were 140.2 mmol/L for males and 140.2 mmol/L for females. There were 565 samples from males and 578 samples from females. The ratios between medians from males and females were 1.000 (Vista 1), 1.001 (Vista 2) and 1.001 (Vista 3). The mean of median results provided by the three analysers was 1.0006. Consequently, the target medians used in the model were considered equal for the two genders and combined to give 140.2 mmol/L.

Daily medians

Figure 1 shows the daily medians of serum sodium for the first 2 months of 2016 for males and females. The combined medians for all three Vista analysers are shown in Figure 1A and the individual medians obtained from the three analysers are shown in Figure 1B. Only the results for the first 2 months of 2016 are shown in order to facilitate interpretation, whereas detailed daily performance characteristics for serum sodium medians for the first 6 months of 2016 for males and females are listed in Table 1A and shown in Supplemental Figure 1A and B.

Weekly medians

Figure 2 provides the weekly medians for serum sodium for the first 6 months of 2016 for males and females. The

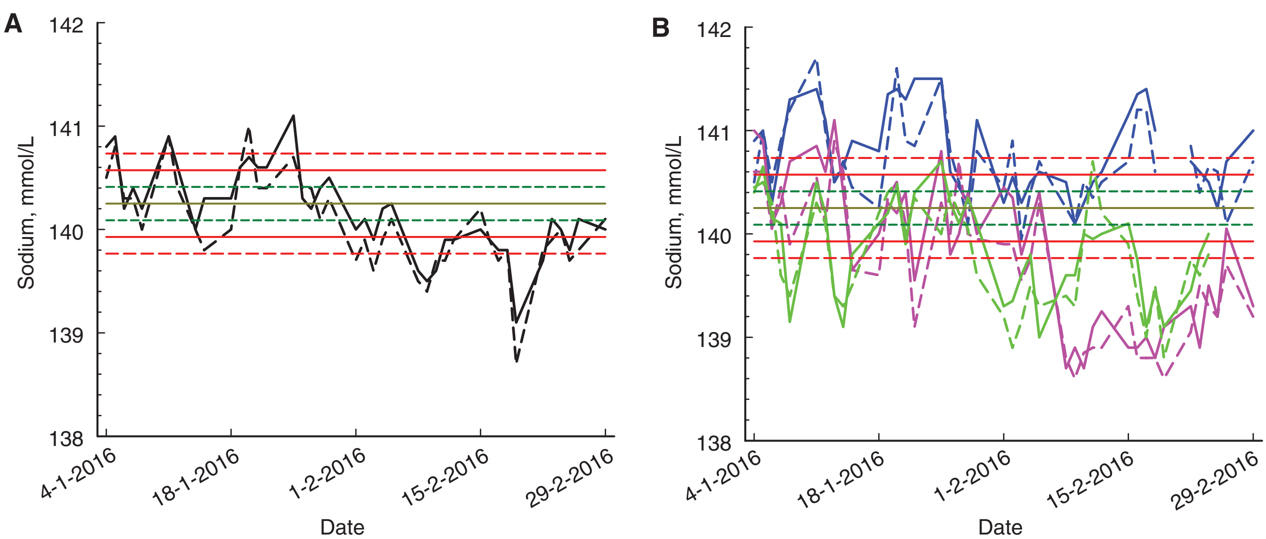

Figure 1: The daily median concentrations of serum sodium among males and females during the first 2 months of 2016.
(A) Combined daily medians derived from three analysers. Males (solid black line) and females (dotted black line). The horizontal lines are the true median (dark yellow = 140.2 mmol/L) and the three levels of ±acceptable bias: optimum (green dotted lines), desirable (red lines) and minimum quality (red dotted lines). (B) The individual daily medians obtained from three analysers. Males (solid line) and females (dotted line). Analyser 1 (blue lines), analyser 2 (purple lines) and analyser 3 (green lines). The horizontal lines are the true median (dark yellow = 140.2 mmol/L) and the three levels of ± acceptable bias: optimum (green dotted lines), desirable (red lines) and minimum quality (red dotted lines).

Table 1A: Detailed daily performance characteristics for serum sodium medians for males and females during the first 6 months of 2016.

	All analysers		Analyser 1		Analyser 2		Analyser 3	
Gender	Males	Females	Males	Females	Males	Females	Males	Females
Median, mmol/L	139.8	139.7	140.2	140.1	139.35	139.2	139.8	139.7
SD, mmol/L	0.50	0.50	0.77	0.81	0.81	0.83	0.48	0.53
CV, %	0.36	0.36	0.55	0.58	0.58	0.59	0.34	0.38
Minimum, n	369	439	102	106	106	105	102	101
Median, n	580	670	213.5	246	184	209	184	204
Maximum, n	759	898	372	416	343	393	317	372
Minimum, mmol/L	138.6	138.5	138.2	137.85	136.65	136.5	138.9	138.7
Maximum, mmol/L	141.1	141	141.5	141.7	141.1	140.9	141.2	140.9
Range, mmol/L	2.5	2.5	3.3	3.85	4.45	4.4	2.3	2.2
Half-range, mmol/L	1.25	1.25	1.65	1.925	2.225	2.2	1.15	1.1
Half-range, %	0.89	0.89	1.18	1.37	1.60	1.58	0.82	0.79
Classification	4	4	4	4	4	4	4	4

CV% calculated as 100*SD/median. Classification according to allowable bias Ref. [1].

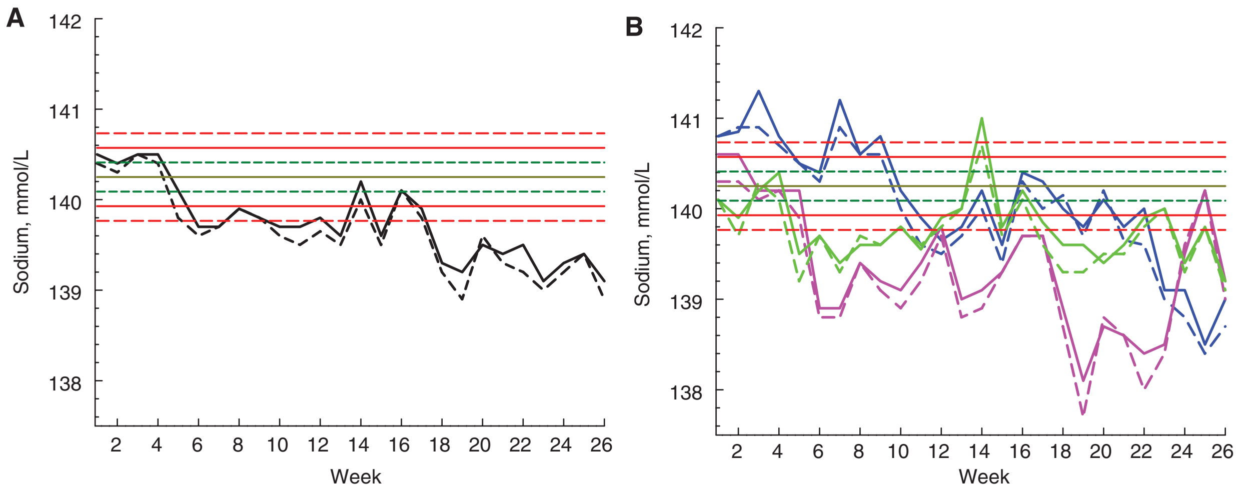

Figure 2: The weekly median concentrations of serum sodium among males and females during the first 6 months of 2016.
(A) Combined weekly medians derived from three analysers. Males (solid black line) and females (dotted black line). The horizontal lines are the true median (dark yellow = 140.2 mmol/L) and the three levels of ± acceptable bias: optimum (green dotted lines), desirable (red lines) and minimum quality (red dotted lines). (B) The individual weekly medians obtained from three Vista instruments. Males (solid line) and females (dotted line). Analyser 1 (blue lines), analyser 2 (purple lines) and analyser 3 (green lines). The horizontal lines are the true median (dark yellow = 140.2 mmol/L) and the three levels of ±acceptable bias: optimum (green dotted lines), desirable (red lines) and minimum quality (red dotted lines).

combined medians for all three Vista analysers are shown in Figure 2A, and the individual medians obtained from the three analysers are shown in Figure 2B. Detailed weekly performance characteristics for serum sodium medians for the first 6 months of 2016 for males and females are listed in Table 1B.

Monthly medians

Figure 3 provides the monthly medians for serum sodium for the first 6 months of 2016 for males and females. The combined medians for all three Vista analysers are shown in Figure 3A, and the individual medians obtained from the three analysers are shown in Figure 3B. Detailed weekly performance characteristics for serum-sodium medians for the first 6 months of 2016 for both males and females are listed in Table 1C.

Ratio between medians from males and females

Figure 4 shows the ratios of medians between males and females for serum sodium. The daily ratios during the

Table 1B: Detailed weekly performance characteristics for serum sodium medians for males and females during the first 6 months of 2016.

	All analysers		Analyser 1		Analyser 2		Analyser 3	
Gender	**Males**	**Females**	**Males**	**Females**	**Males**	**Females**	**Males**	**Females**
Median, mmol/L	139.7	139.6	140.15	140	139.25	139.15	139.8	139.7
SD, mmol/L	0.43	0.45	0.69	0.71	0.68	0.71	0.38	0.37
CV, %	0.31	0.32	0.49	0.51	0.49	0.51	0.27	0.26
Minimum, n	1303	1532	336	382	323	398	338	447
Median, n	2775	3237	1012	1174	890	1046	835	992
Maximum, n	3136	3684	1286	1553	1057	1227	1090	1255
Minimum, mmol/L	139.1	138.9	138.5	138.4	138.1	137.7	139.2	139.1
Maximum, mol/L	140.5	140.5	141.3	140.9	140.6	140.3	141	140.7
Range, mmol/L	1.4	1.6	2.8	2.5	2.5	2.6	1.8	1.6
Half-range, mmol/L	0.7	0.8	1.4	1.3	1.3	1.3	0.9	0.8
Half-range, %	0.50	0.57	1.00	0.89	0.90	0.93	0.64	0.57
Classification	4	4	4	4	4	4	4	4

CV% calculated as 100*SD/median. Classification according to allowable bias Ref. [1].

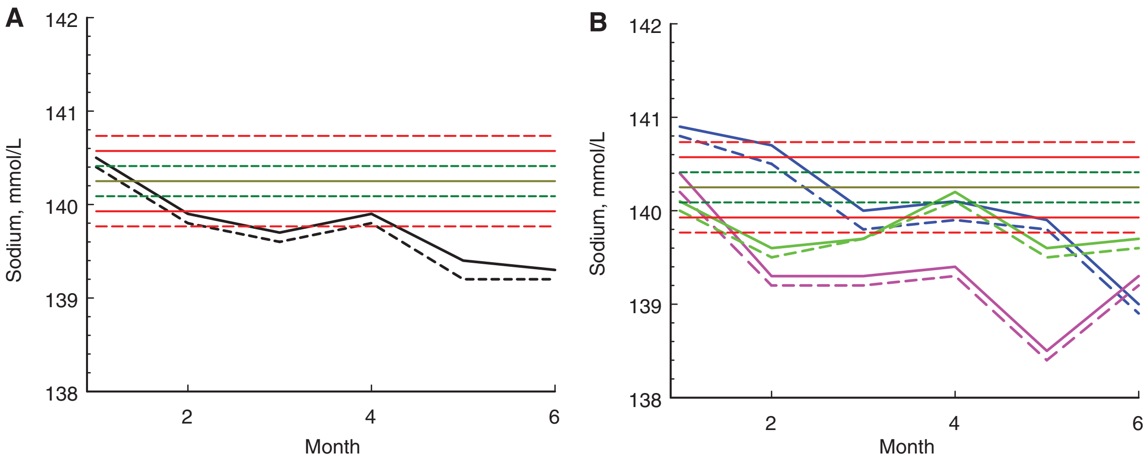

Figure 3: The monthly median concentrations of serum sodium among male and female patients during the first 6 months of 2016. (A) Combined monthly medians derived from three analysers. Males (solid black line) and females (dotted black line). The horizontal lines are the true median (dark yellow = 140.2 mmol/L) and the three levels of ±acceptable bias: optimum (green dotted lines), desirable (red lines) and minimum quality (red dotted lines). (B) The individual weekly medians obtained from three analysers. Males (solid line) and females (dotted line). Analyser 1 (blue lines), analyser 2 (purple lines) and analyser 3 (green lines). The horizontal lines are the true median (dark yellow = 140.2 mmol/L) and the three levels of ±acceptable bias: optimum (green dotted lines), desirable (red lines) and minimum quality (red dotted lines).

Table 1C: Detailed monthly performance characteristics for serum sodium medians for males and females during the first 6 months of 2016.

	All analysers		Analyser 1		Analyser 2		Analyser 3	
Gender	**Males**	**Females**	**Males**	**Females**	**Males**	**Females**	**Males**	**Females**
Median, mmol/L	139.8	139.7	140.05	139.85	139.3	139.2	139.7	139.65
SD, mmol/L	0.43	0.45	0.67	0.66	0.61	0.57	0.26	0.26
CV, %	0.31	0.32	0.48	0.47	0.43	0.41	0.19	0.18
Minimum, n	10760	12299	3571	4222	3224	3555	3352	3783
Median, n	11503	13489	4228	4902	3744	4322	3569	4041
Maximum, n	12209	13993	4973	5592	3965	4716	3927	4691
Minimum, mmol/L	139.3	139.2	139	138.9	138.5	138.4	139.6	139.5
Maximum, mmol/L	140.5	140.4	140.9	140.8	140.4	140.2	140.2	140.1
Range, mmol/L	1.2	1.2	1.9	1.9	1.9	1.8	0.6	0.6
Half-range, mmol/L	0.6	0.6	0.95	0.95	0.95	0.9	0.3	0.3
Half-range, %	0.43	0.43	0.68	0.68	0.68	0.65	0.21	0.21
Classification	4	4	4	4	4	4	2	2

CV% calculated as 100*SD/median. Classification according to allowable bias Ref. [1].

first 2 months of 2016 are shown in Figure 4A, and the weekly ratios during the first 6 months of 2016 are shown in Figure 4B, whereas the monthly medians are shown in Figure 4C. The performance characteristics of ratios between the patient medians of serum sodium in males and females for the first 6 months of 2016 are presented in Table 2. Table 2A provides the characteristics for daily ratios of medians (also showed in Supplemental Figure 2). Table 2B documents the characteristic for weekly ratios of medians, and the characteristics for monthly ratios of medians are shown in Table 2C.

Discussion

Importance of using raw data for serum sodium concentrations to calculate patient medians

The estimates of the medians of serum sodium concentrations calculated from patient data had apparent low uncertainties due to the narrow distributions of routine measurements [7].

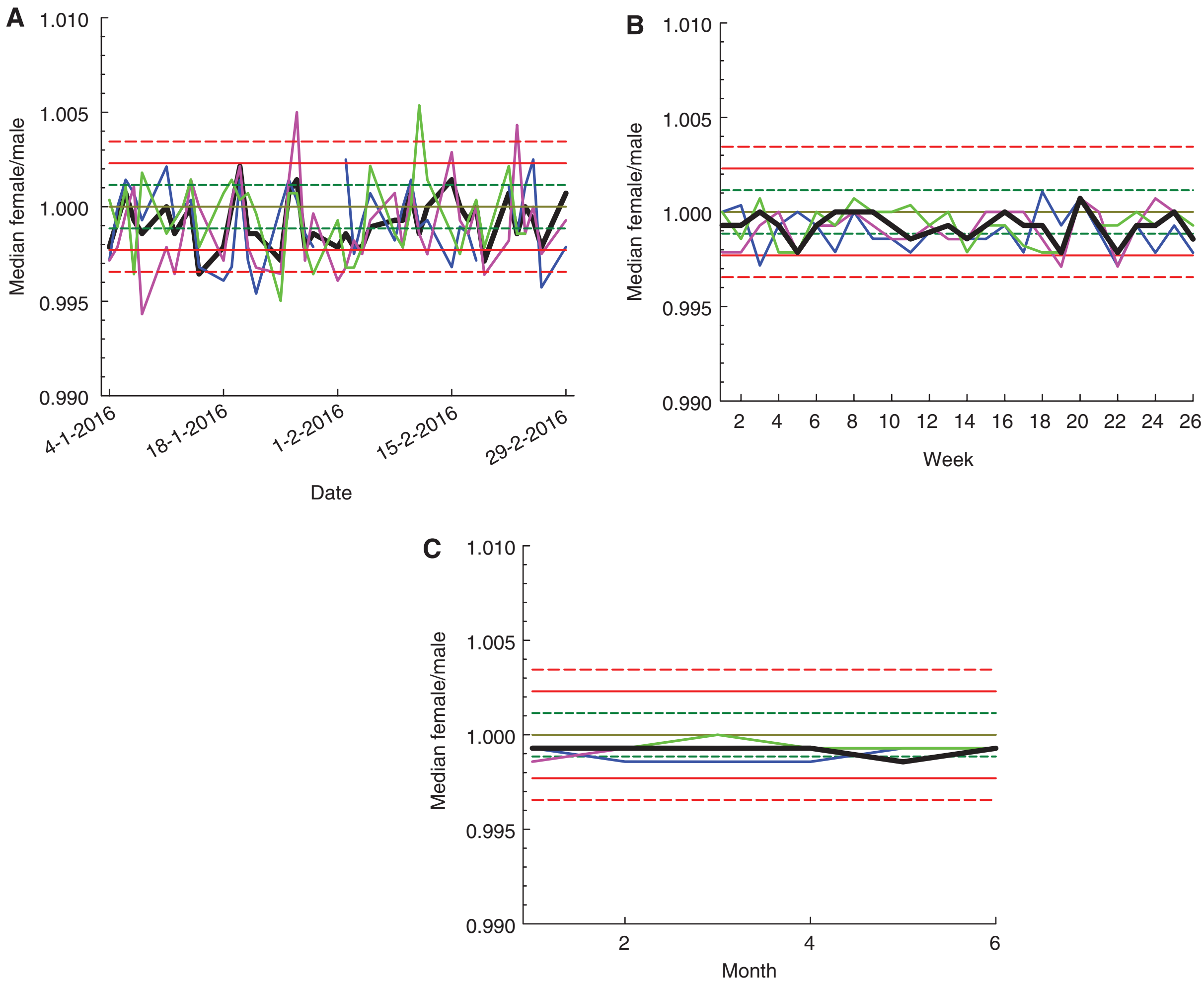

Figure 4: Ratios between median concentrations of serum sodium from females and males measured with three Vista instruments. (A) Daily ratios between medians during the first 2 months of 2016. Combined results (black lines), analyser 1 (blue lines), analyser 2 (purple lines) and analyser 3 (green lines). The horizontal lines are the true median (dark yellow = 1.000) and the three levels of ± acceptable bias: optimum (green dotted lines), desirable (red lines) and minimum quality (red dotted lines). (B) Weekly ratios between medians during 6 months of 2016. Combined results (black lines), analyser 1 (blue lines), analyser 2 (purple lines) and analyser 3 (green lines). The horizontal lines are the true median (dark yellow = 1.000) and the three levels of ±acceptable bias: optimum (green dotted lines), desirable (red lines) and minimum quality (red dotted lines). (C) Monthly ratios between medians during 6 months of 2016. Combined results (black lines), analyser 1 (blue lines), analyser 2 (purple lines) and analyser 3 (green lines). The horizontal lines are the true median (dark yellow = 1.000) and the three levels of ±acceptable bias: optimum (green dotted lines), desirable (red lines) and minimum quality (red dotted lines).

When median concentrations are calculated from routinely reported results of examinations using whole integers only, changes can only be expressed as +1 mmol/L or –1 mmol/L. However, this interval appears to be much too large to be applied to stable medians of serum sodium examination results and less useful to estimate the small ratios of medians between genders. Thus, our estimate of the monthly medians would be 140 mmol/L and minor changes would only be estimated as 139 or 141 mmol/L, e.g. all the medians provided in Table 1 would be 139 or 140 mmol/L. Consequently, we used the raw serum sodium examination results available from the analysers so as to obtain sufficient number of significant figures after the decimal points to obtain a detailed assessment of any small changes in medians over time.

Significance of separating medians for male and female patients

The median serum sodium concentrations among males and females were similar as regards the daily medians, very close for weekly medians and nearly identical for

Table 2: Performance characteristics of the ratios between serum sodium concentration medians from males and females for the first 6 months of 2016.

	All analysers	Analyser 1	Analyser 2	Analyser 3
(A) Daily medians				
Median	0.99928	0.99876	0.99928	0.99929
SD	0.00120	0.00203	0.00231	0.00226
CV, %	0.120	0.203	0.231	0.226
Minimum	0.99644	0.99428	0.99350	0.99392
Maximum	1.00360	1.00432	1.00501	1.00572
Range	0.00716	0.01004	0.01151	0.01179
Half-range, %	0.36	0.50	0.57	0.59
Classification	4	4	4	4
(B) Weekly medians				
Median	0.99928	0.99910	0.99928	0.99929
SD	0.00072	0.00103	0.00101	0.00095
CV, %	0.072	0.103	0.101	0.095
Minimum	0.99784	0.99714	0.99710	0.99785
Maximum	1.00072	1.00107	1.00072	1.00072
Range	0.00287	0.00393	0.00362	0.00287
Half-range, %	0.14	0.20	0.18	0.14
Classification	2	2	2	2
(C) Monthly medians				
Median	0.99928	0.99893	0.99928	0.99929
SD	0.00029	0.00039	0.00029	0.00029
CV, %	0.029	0.039	0.029	0.029
Minimum	0.99857	0.99857	0.99858	0.99928
Maximum	0.99929	0.99929	0.99928	1.00000
Range	0.00072	0.00072	0.00071	0.00072
Half-range, %	0.036	0.036	0.035	0.036
Classification	1	1	1	1

CV% calculated as 100*SD/median. Classification according to allowable bias Ref. [1].

monthly medians (Figures 1–3) indicating a similar distribution among the two genders. By using median instead of mean concentrations, we eliminated the problems of confounding the estimates with extreme examination results values, provided most of the concentrations lie within the reference interval. The half-range values for daily ratios of medians among males and females were of the same order as the monthly medians. The half-range values for monthly ratios of medians among males and females were below 0.05%, indicating a very strong relationship between the gender medians, independent of the ongoing analytical performance. Initially, we combined the gender medians with a common median of 140.2 mmol/L, but our results (Table 2C) indicated that the median among males was 0.1% above the median of females.

These estimates were only possible to calculate when we used raw data with further significant figures.

Relation to performance specifications for analytical bias

We estimated the analytical quality based on the respective medians obtained from male and female patients as well as on the ratio of medians. The half value of the range of medians was used as an estimate of the maximum bias. Additionally, we compared our data to the three levels of performance specifications defined by Fraser et al. as optimum, desirable and minimum quality [1]. For serum sodium the three levels were 0.12%, 0.23% and 0.35%, respectively, calculated on basis of the biological within-subject and between-subject variation data available from Minchinela et al. [5]. Application of the three levels enables an overview of the current quality similar to the information provided by routinely used ‘internal quality control’ schemes (Figures 1–4).

Usefulness of medians stratified for gender

Owing to the stability of the distributions of serum sodium, the medians obtained from males and females and their ratios appeared suitable to validate the stability of the analytical performance because the two medians of gender are not very different. The distribution of the serum sodium results was independent of gender. The importance of the serum sodium medians by gender is that they are two independent estimates of the ongoing analytical bias, so they can be used in combination, when the male median can be used for detecting any bias and the female median can be used for confirmation of this. If only the combined patient median is used, then there is no confirmation of a bias that might require correction, so the advantage of using both gender medians is the increased utility of using the two independent estimates together. The medians will be useful as long as the characteristics of the patient groups used to derive these remain unchanged, and they will thereby provide a guarantee of long-term analytical quality. The range of weekly ratio of medians for all analysers was below 0.003 (Table 2B), and thus the performance specification for ‘minimum quality’ (<0.35%) were attained, suggesting that it would be possible to maintain the weekly analytical bias within ‘minimum quality’. Additionally, the range of monthly ratios of medians for all analysers (Table 2C) were within ‘optimum quality’ analytical performance specifications (<0.12%).

It is seen from Figure 1B that, for each analyser, both gender medians are closely related, whereas the ‘mean values' for the individual analysers vary differently for the different analysers; in consequence, a correction using a factor will provide improved analytical quality over simple acceptance of the calibration in use. The three analysers should be corrected individually. The discrepancies between the gender medians and the calibrations in use are further accentuated in Figures 2B and 3B. In case of major differences between the gender medians on an analyser, the possibility of error must be considered, and trouble-shooting should be undertaken followed by correction of any faults.

Trueness

This investigation attempted to estimate the trueness of serum sodium examinations based on triplicate measurements, three different analyzers and calculations of medians based on results from samples from 578 females and 565 males. However, the approach was insufficient for a useful estimate of the trueness, but a target value of the median, as the 140.2 mmol/L estimated here, could be useful for long-term performance stability of serum sodium examinations. In addition, when EQA challenges with traceable target values are measured, the patient medians can be assessed and the long-term stability can be assured until next EQA challenge. It may be speculated that, within geographical areas, the medians of patients from selected ethnic groups investigated in hospitals of comparable size and with same ratio of samples from inpatients and outpatient will be similar and these medians can be used to assess the performances of a larger group of hospital laboratories.

Conclusions

A. Raw data from the analysers with more significant figures than the usually reported integers for serum sodium were needed for a reliable estimation of medians of patient results.
B. The medians of serum sodium among males and females were similar.
C. The medians of serum sodium among males and females appeared as useful tools for two independent estimates of the analytical quality of serum sodium examinations.
D. The analytical quality of serum sodium can be further assessed by the ratio of medians between males and females.

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