The sodium correction factor for dogs undergoing treatment for a hyperglycemic crisis is a 1.6-mEq/L decrease in sodium per 100-mg/dL increase in glucose

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OBJECTIVE
To determine the sodium correction factor for clinical use in hyperglycemic diabetic dogs.

SAMPLE
Retrospective analysis of 76 hospitalization episodes from 67 different dogs presenting to the University of Georgia Veterinary Teaching Hospital between January 1, 2015, and January 1, 2023.

METHODS
For each hospitalization episode, paired blood sodium and glucose concentration measurements were recorded from the time of presentation until glucose concentration was ≤ 201 mg/dL. Therapies administered, primary diagnosis, and concurrent diseases were also recorded for each episode. A linear mixed model was used to determine the sodium correction factor per 100-mg/dL increase in glucose. Piecewise linear mixed models were also constructed for blood glucose measurements ≤ 400 mg/dL and > 400 mg/dL to explore potential correction factor differences between low and high glucose concentrations.

RESULTS
A sodium correction factor of a 1.6-mEq/L (95% CI, 1.3 to 1.9 mEq/L) decrease in sodium concentration per 100-mg/dL increase in blood glucose concentration was calculated. Differences in the correction factor between conditions of low and high glucose concentrations could not be determined due to a small sample size of blood glucose values > 400 mg/dL. Most dogs received similar treatments throughout the study period, including balanced isotonic crystalloids (97% [74/76]), electrolyte supplementation (84% [64/76]), and regular insulin (97% [74/76]). Almost all patients (93% [71/76]) had 1 or more concurrent diseases.

CLINICAL RELEVANCE
A sodium correction factor of 1.6 mEq/L (decrease in sodium per 100-mg/dL increase in glucose) is recommended for clinical use in hyperglycemic diabetic dogs.

Keywords: sodium, hyperglycemia, dilutional hyponatremia, correction factor, diabetes mellitus

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is > 400 mg/dL. Most of the proposed sodium correction factors have been based on theoretical models,\(^\text{6,11}\) although a few studies have been performed of healthy human subjects\(^\text{10,14}\) and human patients with DKA.\(^\text{21}\) Despite the range of proposed factors and variety of research models, 2 recent literature reviews\(^\text{5,12}\) both concluded that a correction factor of 1.6 mEq/L was best for clinical use in hyperglycemic humans. A sodium correction factor of 1.6 mEq/L is also frequently cited in veterinary literature, although no studies have been performed to validate its use in dogs or cats.\(^\text{1,3,6–9}\)

The goal of this study was to determine the sodium correction factor for hyperglycemic diabetic dogs. We hypothesized that 1.6 mEq/L would be the appropriate sodium correction factor for hyperglycemic diabetic dogs undergoing in-patient fluid and insulin therapy.

Methods

Study population

Medical records from the University of Georgia Veterinary Teaching Hospital between January 1, 2015, and January 1, 2023, were searched for keywords relating to diabetic ketosis without acidosis (DK), DKA, HHS, or hyperglycemia. Dogs were included in the study if they presented with a blood glucose concentration ≥ 239 mg/dL, were hospitalized for treatment of their hyperglycemia, had documented resolution of their hyperglycemia into a clinically desirable range for a diabetic dog (blood glucose concentration ≤ 201 mg/dL), and had a minimum of 2 paired blood sodium/glucose concentration measurements (including both initial hyperglycemia and subsequent resolution). Dogs were excluded from the study if they had incomplete records or had a severe sodium derangement (blood sodium concentration < 125 or > 165 mEq/L) at admission leading to treatment with specialized fluids (eg, 5% dextrose or hypertonic saline) aimed at altering blood sodium concentration. Dogs could be included in the study more than once if they had multiple hospitalization episodes that fit the study inclusion criteria.

Medical records review

Patient data collected from each medical record included signalment, body weight, fluid types administered, electrolyte supplementation, type of insulin therapy (regular or long-acting) and administration route (IV continuous rate infusion or IM), diagnosis as recorded in the medical record (hyperglycemic diabetic, DK, DKA, HHS), and concurrent diseases. Paired blood sodium and glucose (Na/Glu) values were recorded from the time of admission until the blood glucose concentration was ≤ 201 mg/dL. Any subsequent changes in sodium and glucose concentrations during the hospitalization episode were not evaluated. The date and time of bloodwork measurements were also recorded.

All blood sodium and concurrent glucose measurements were obtained from a single biochemical analyzer (pHOX Ultra; NOVA Biomedical). For those glucose measurements that were above the working range of the instrument (> 500 mg/dL) or weren’t read by the machine due to calibration issues, glucose concentrations were obtained from a concurrently run alternative analyzer in the following order of preference: (1) clinical pathology analyzer (Cobas c501; Roche), (2) after-hours chemistry analyzer (Vetscan VS2; Zoetis), and (3) handheld analyzer (AlphaTRAK2; Abbott Animal Health). The machine on which the glucose concentrations were measured was recorded for each value. When a handheld analyzer value was used, the contemporaneous PCV was also recorded, if available. The clinical pathology and NOVA analyzers undergo daily quality control testing (QC), and QC must be reviewed and deemed acceptable or results are not run or released. Each rotor for the after-hours chemistry analyzer must pass an internal QC check during the sample run. No QC data were available for the handheld analyzer.

Calculation of the sodium correction factor and statistical analysis

All analyses were performed using commercial statistics software (SAS, version 9.4; SAS Institute Inc). A significance threshold of .05 was used. A linear mixed model with sodium concentration as the dependent variable and glucose concentration as the independent variable was used to determine the slope for each hospitalization episode, then the population average slope.\(^\text{20}\) The population average slope was then multiplied by 100 to determine the change in sodium concentration per 100-mg/dL increase in glucose. The sodium correction factor was defined as the change in sodium concentration per 100-mg/dL increase in glucose. Model assumptions (normality and homoscedasticity of model residuals) were evaluated via inspection of conditional residual Q-Q and residual plots. The Satterthwaite degrees of freedom method and restricted maximum likelihood estimation were used.

The corrected sodium concentration was calculated serially at each time point for each episode using the following formula: measured sodium + (1.6 [glucose at each time point – final glucose]/100). The difference (Δ) between the corrected sodium at each data point and the final measured sodium was calculated. For episodes with > 2 data points, the Δ values were compared using the Wilcoxon matched pairs signed rank test. The goal of Δ analysis was to evaluate the accuracy of the correction factor and determine whether that accuracy was improved by serial recalculation of the corrected sodium. Separate piecewise linear mixed models were also constructed for blood glucose concentrations ≤ 400 mg/dL and > 400 mg/dL to explore potential correction factor differences between low and high glucose concentrations.\(^\text{10,20}\) Analysis using only sodium-glucose pairs measured on the NOVA was also performed to test for error due to blood glucose measurements obtained from multiple analyzers. Hospitalization events for which the first NOVA value in the series was < 239 mg/dL were removed from this specific analysis.
Results

A total of 76 separate hospitalization episodes from 67 different dogs were included in the study. Seven dogs were included in the study twice, and 1 was included 3 times. The median age of the dogs at the time of hospitalization was 10 years (range, 4 to 14 years). Of the included dogs, 37% (25/67) were female spayed, 4% (3/67) were female intact, 54% (36/67) were male castrated, and 4% (3/67) were male intact. A total of 33 different breeds were included, with the most common being mixed breed (12% [8/67]), Chihuahua (10% [7/67]), Maltese (9% [6/67]), miniature Pinscher (6% [4/67]), Dachshund (6% [4/67]), Corgi (6% [4/67]), and Pomeranian (4% [3/67]). All other breeds were represented by 2 or fewer subjects. The final diagnosis for each hospitalization episode was HHS in 8% (6/76) of cases, DKA in 62% (47/76) of cases, DK in 28% (21/76) of cases, and hyperglycemic diabetic in 3% (2/76) of cases. Almost all patients (93% [71/76]) had at least 1 identified concurrent disease process, and many patients (63% [48/76]) had multiple concurrent diseases. The most commonly reported concurrent diseases were pancreatitis (acute or chronic; 49% [37/76]), cardiac disease (either a heart murmur or myxomatous mitral valve disease stage B1-B2; 30% [23/76]), confirmed or suspected hyperadrenocorticism (29% [22/76]), bacterial infection (including urinary tract infection in 8 patients, pyelonephritis in 5 patients, aspiration pneumonia in 4 patients, abscession in 2 patients, and septic peritonitis in 2 patients; total of 22% [17/76]), gastrointestinal disease (20% [15/76]), and renal disease (acute injury or chronic disease; 21% [16/76]).

Over the study period, all dogs received fluid therapy, with 9% (7/76) receiving multiple fluid types. Most patients (97% [74/76]) received balanced isotonic crystalloids (lactated Ringer solution or Plasma-Lyte), while 4% (3/76) received 0.9% NaCl, 8% (6/76) received 0.45% NaCl, and 1 patient received packed RBCs. Additional therapy included electrolyte supplementation in 84% (64/76) of patients, with 23% (15/64) of those receiving multiple electrolyte supplements. Electrolyte supplements included potassium chloride (95% [61/64]), potassium phosphate (22% [14/64]), and magnesium sulfate (8% [5/64]). Almost all dogs (97% [74/76]) were administered regular insulin, using either an IV continuous rate infusion protocol (66% [49/74]) or an intermittent IM protocol (34% [25/74]). One patient remained on long-acting insulin (Humulin N), and 1 patient did not receive any insulin in-hospital until after their blood glucose concentration was ≤ 201 mg/dL.

A total of 244 sodium-glucose pairs were obtained from all 76 episodes (Figure 1). Of those, 209 of the glucose values were measured on the NOVA, 4 were measured on the clinical pathology analyzer, 1 on the after-hours chemistry analyzer, and 30 on the handheld glucometer. The NOVA-only subset included 202 sodium-glucose pairs, representing 69 episodes from 60 dogs. There was a median of 3 (range, 2 to 9) data points/episode for all data and a median of 2 (range, 2 to 7) data points/episode in the NOVA-only subset. Of the 8 dogs included in the study multiple times, collectively they contributed 11.8% (9/76) of episodes and 20.5% (50/244) of the total data points, with no more than 9 (9/244 [3.7%]) data points collected from a single dog. The median time period of data collection was 23.5 hours (range, 6 to 97.5 hours) for all data and 21.5 hours (range, 4.5 to 97.5 hours) for the NOVA-only subset. The median time from initial to second data point measurement was 11.5 hours (range, 1 to 41 hours). Packed cell volume values were available for 28 of 30 of the handheld glucometer samples. The median PCV for these samples was 44% (range, 23% to 62%).

Over the course of the study, the median blood glucose concentration decreased and the median blood sodium concentration increased (Figures 2 and 3). However, when episodes were examined individually, the blood sodium concentration increased in 67 of 76 (88%) episodes and decreased in 9 of 76 (12%) episodes. The median sodium decrease was small (~1.4 mEq/L), although the range was large (~0.2 to ~13.9 mEq/L). All patients in which the measured sodium concentration decreased exclusively received isotonic crystalloids for fluid therapy and had a similar time of data collection when compared to patients with increasing measured sodium (sodium decrease: median, 22.5 hours, range, 6.5 to 39.5 hours; sodium increase: median, 26 hours, range, 6 to 97.5 hours). Patients also had similar underlying disease processes, regardless of whether their sodium decreased (pancreatitis, 44% [4/9]; hyperadrenocorticism, 33% [3/9]; cardiac disease, 44% [4/9]; renal disease, 22% [2/9]; gastrointestinal disease, 22% [2/9]; infectious disease, 33% [3/9]) or...
increased (pancreatitis, 49% [33/67]; hyperadrenocorticism, 28% [19/67]; cardiac disease, 28% [19/67]; renal disease, 20% [14/67]; gastrointestinal disease, 19% [13/67]; infectious disease, 21% [14/67]) over the course of treatment.

Based on the linear mixed model, the overall sodium correction factor was 1.6 mEq/L (95% CI, 1.3 to 1.9 mEq/L) for each 100-mg/dL change in glucose for all data and 1.8 mEq/L (95% CI, 1.3 to 2.3 mEq/L) for the NOVA-only subset. Both correction factors were significantly different from 0 (P < .001). The 1.6-mEq/L correction factor was used to calculate the serial corrected sodium concentrations for each episode. Across all data points, the median difference between the corrected sodium and final measured sodium was 0.66 mEq/L (range, –11.36 to 19.36 mEq/L; n = 168). The median difference between the corrected sodium and final measured sodium at the first data point (∆-1, –0.574 mEq/L [IQR, –3.11 to 3.88 mEq/L]; n = 50) and second data point (∆-2, 0.76 mEq/L [IQR, –1.2 to 3.44 mEq/L]; n = 50) were not significantly different from one another (P = .056; Figure 4). Additional calculations for ∆-3 through ∆-8 were not compared due to a much smaller quantity of these measurements.
In the piecewise linear mixed model, the number of samples with a glucose concentration > 400 mg/dL was small (only 29% of samples from all data and 18% of samples from the NOVA-only subset). When glucose concentration was > 400 mg/dL for all data (glucose concentration 401 to 1,081 mg/dL; n = 71), the correction factor was 0.4 mEq/L (95% CI, –0.6 to 1.5 mEq/L). When the glucose concentration was > 400 mg/dL in the NOVA-only subset (glucose concentration, 400 to 500 mg/dL; n = 37), the correction factor was 2.9 mEq/L (95% CI, –3.0 to 8.7 mEq/L). For samples with a glucose concentration < 400 mg/dL, the correction factor was 1.4 mEq/L (95% CI, 0.8 to 2.0 mEq/L) for both all data (n = 173 samples) and the NOVA-only subset (n = 165 samples). The CI was significantly different from zero when the glucose concentration was ≤ 400 mg/dL for all data and the NOVA-only subset (P < .001 for both) but was not significantly different from zero when the glucose concentration was > 400 mg/dL (P = .415 and .321, respectively).

**Discussion**

The results of this study support the use of a sodium correction factor of 1.6 mEq/L (a 1.6-mEq/L decrease in sodium concentration for every 100-mg/dL increase in glucose concentration) for diabetic dogs undergoing treatment for hyperglycemia. This correction factor is also supported by multiple human studies and is routinely used in both human and veterinary clinical practice.\(^1\)\(^3\)\(^8\)\(^15\)

There are multiple factors that affect the blood concentration of sodium in hyperglycemic patients, and thus could impact the sodium correction factor. The primary determinants of sodium concentration in the normal patient are total body water, sodium, and potassium.\(^2\) Total body water is divided into intracellular fluid volume (ICFV) and extracellular fluid volume (ECFV), and the relative volume in each of these compartments (ICFV/ECFV) determines the amount of water available for osmotic exchange in response to changes in blood sodium and glucose concentration, thus impacting the sodium concentration and correction factor.\(^3\)\(^15\) In the hyperglycemic patient, sodium concentration is also influenced by the blood glucose concentration, water retention due to hyperosmolality, and water loss due to osmotic diuresis.\(^3\)\(^15\)

Despite the multitude of factors potentially impacting sodium correction, the 1.6-mEq/L factor was accurate when applied retrospectively to the study dataset. The median difference between calculated and measured sodium concentrations was clinically insignificant (all data, 0.66 mEq/L; Δ-1, -0.574 mEq/L; Δ-2, 0.76 mEq/L). Although the range of differences was large, most corrected sodium concentrations were within 10 mEq/L of the measured sodium and thus unlikely to alter the type of IV fluids selected for therapy. The large range of differences between corrected and measured sodium was likely due to the many different factors impacting sodium and water balance in each individual patient.

The corrected sodium concentration is only representative of the patient’s sodium/water balance at the time of blood collection. Because of this, in human medicine it is recommended to repeat sodium measurement and correction frequently to reduce the impact that treatments and comorbidities have on the accuracy of corrected sodium predictions.\(^3\)\(^4\) We attempted to account for this by comparing the difference between corrected and measured sodium at serial data points. While the Δ-2 IGR and median were closer to zero than Δ-1, this difference did not reach statistical significance (P = .056). The lack of significance may have been due to the prolonged time between data points (the median time from first to second sodium measurement was 11.5 hours), and more frequent measurements may be needed to detect significant increases in accuracy. Based on the Δ value trend toward significance, we still recommend serial sodium measurement and correction, although further research is needed to prove the clinical utility of this recommendation.

In a small subset (12% [9/76]) of hospitalization episodes, measured sodium concentration decreased over the course of the study, rather than increasing as expected. All of these patients exclusively received balanced isotonic crystalloids for fluid therapy. The time periods of data collection and comorbidities for this subset were similar to the overall population. While a clear explanation for the difference in this patient subset was not identified, we suspect that it was due to individual variation in treatments and comorbidities that the present study was underpowered to identify. In human patients with DKA, a decrease in sodium concentration during treatment is thought to be a sign of impending cerebral edema, and cerebral edema increases patient morbidity and mortality.\(^2\) Mortality and adverse effects (such as cerebral edema) were not investigated in the current study but provide an interesting avenue for future research.

Because this study was retrospective, the treatments that patients received were not standardized and created variability within our dataset. We attempted to account for this by only recording data until the blood glucose concentration was “normalized” (< 201 mg/dL), thereby minimizing the cumulative effects of treatment during a prolonged hospitalization on the calculated correction factor. While 201 mg/dL is not within the typical reference range for euglycemia, we chose this value because it is a subjectively acceptable blood glucose concentration for a hospitalized diabetic patient. Using 201 mg/dL as a “normalized” glucose concentration cutoff, rather than requiring a glucose within reference range, allowed the inclusion of more patients in the study, while still ensuring that all patients had a decrease in glucose over the study period. Additionally, further minor reductions in glucose into reference range would be unlikely to have significant effect on sodium concentration. Most episodes had data recorded for < 72 hours. However, because intervals between bloodwork timing were not standardized, it is possible that some patients’ blood glucose concentrations normalized prior to documentation with a blood glucose measurement. Despite the lack of standardization, most patients ultimately
received similar treatments, including balanced iso-
tonic crystalloids, potassium supplementation, and
regular insulin. The lack of a standardized treatment
protocol mimics clinical practice in that there is no
standardized treatment protocol for hyperglycemic
diabetic, DK, DKA, or HHS patients in veterinary
medicine. The fact that the 1.6-mEq/L correction
factor had a small CI despite the lack of a standard-
ized treatment protocol suggests that our study re-
results can be applied to a diverse population of dia-
abetic hyperglycemic dogs.

Patients included in this study had a variety of
current medical conditions that could have im-
paired sodium concentration and thereby the so-
dium correction factor. The percentage of patients
with concurrent diseases (93% [71/76]) was higher
than previously reported (up to 74%).23,24 However,

prior studies defined concurrent diseases as only
those for which confirmatory testing had been per-
formed, while the present study recorded all iden-
tified or clinically suspected problems regardless
of confirmatory testing.23,24 The broader definition
in this study and the patient population presenting
to our referral institution likely accounted for the
increased percentage of concurrent diseases. Previ-

ous studies have reported pancreatitis, urinary tract
infections, and hyperadrenocorticism as the most
common concurrent diseases in canine patients with
DKA.23–25 These comorbidities were also common in
the present study. It is also notable that renal (21% [16/76]) and cardiac (30% [23/76]) disease were
common in the present study's patient population,
as these disease processes have many mechanisms
through which they can affect sodium concentration,
glucose concentration, and total body water content.
The variety of concurrent diseases and their pos-
sible effects on the sodium correction factor added
a source of variability to the present study but also
resulted in a sample population that is representa-
tive of the general population of diabetic dogs undergo-
ing treatment for hyperglycemia.

Some patients included in the study were ane-
imic, and this could have impacted glucose measure-
ments taken on the handheld glucose analyzer. The
handheld glucose analyzer used in this study over-
estimates glucose concentration in hemodiluted
samples and underestimates it in hemoco-ncen-
trated samples.22 In the study population, the median pa-
tient PCV was 44% (range, 23% to 62%) when glucose
measurement was obtained via handheld analyzer.
Lane et al22 developed an algorithm to correct the
effect of PCV on handheld glucose analyzer results.
Based on this algorithm, the PCV could have resulted
in a glucose error of −44.5 mg/dL in the most anemic
patient and +17.9 mg/dL in the most hemoconcen-
trated patient. However, this algorithm is less accu-
rate at higher glucose concentrations.22 Because very
few samples (12% [30/244]) were obtained from the
handheld glucometer and even the most abnormal
samples would have had a minimal effect on glucose
concentration based on the published algorithm, we
suspect that anemia ultimately had little effect on
the calculated sodium correction factor.

The piecewise linear mixed model was made
to determine whether a different correction factor
should be applied to severely hyperglycemic (glu-
cose concentration > 400 mg/dL) samples, as sug-
gested by a research study20 of healthy humans with
induced hyperglycemia. When glucose concentration
was ≤ 400 mg/dL, the correction factor (1.4 mEq/L
for all data and the NOVA-only subset) was similar
to that from the entire dataset (1.6 mEq/L). The
1.4-mEq/L correction factor was significantly differ-
ent from zero but had a wider CI than the correction
factor generated from the total dataset. When glu-
cose concentration was > 400 mg/dL, neither correc-
tion factor (from all data or the NOVA-only subset)
was significantly different from zero. The small sam-
ple size included in the > 400-mg/dL subgroup likely
contributed to this lack of significance, since only 71
of 244 of all data samples and 37 of 202 of the NOVA-
only samples had a blood glucose concentration >
400 mg/dL. The use of different glucose analyzers in
the > 400-mg/dL subgroup could also have contrib-
uted. Due to the lack of statistical significance, wide
CIs, and small sample size, no conclusions could be
drawn from the > 400-mg/dL data subset. Whether
there is a different sodium correction factor for the
extreme hyperglycemic range or not, the overall so-
dium correction factor of 1.6 mEq/L for each 100-
mg/dL increase in glucose calculated over the whole

The NOVA-only subset was further evaluated
to determine whether variability between glucose
analysis machines added a source of error to the cal-
culated correction factor. When comparing the cor-
rection factor generated from all data (1.6 mEq/L;
95% CI, 1.3 to 1.9) with the NOVA-only subset (1.8
mEq/L; 95% CI, 1.4 to 2.3), both correction factors
were significantly different from zero. However, the
CI for all data was narrower, making the 1.6-mEq/L
correction factor better for clinical use. While the
use of multiple analyzers to measure blood glucose
concentration did introduce a source of variability in
the study, non-NOVA glucose measurements only
represented 14% of the total samples analyzed, and
including these allowed for evaluation of more hos-

tpitalization episodes, more dogs, and more sodium/
glucose pairs. Most importantly, inclusion of the
non-NOVA samples facilitated evaluation of a wider
range of glucose concentrations that would be more
likely to cause dilutional hyponatremia. This broader
sample population represented a more realistic sce-
nario for patients presenting in diabetic crises with

The retrospective nature of this study introduced
multiple potential sources of error. Patient treatments
were not standardized, and patients with a variety of
comorbidities were included in the study. The timing
of blood collection was also not standardized, and ini-
tial normalization of glucose values may have fallen
between measurements and been missed, thus in-
creasing the time that factors other than the sodium/
The glucose relationship had to impact the sodium concentration. Variability between chemistry analyzers, time from blood draw to bloodwork analysis (which could not be verified), and other bloodwork abnormalities such as anemia may also have created error.

Future avenues of research should include a prospective study with standardized blood sampling times and a single chemistry analyzer. It should also include a larger patient population, particularly including patients with blood glucose concentration > 400 mg/dL, so that the possibility of a nonlinear sodium/glucose relationship can be further investigated. A larger patient population may also allow for analysis of the correction factor in different patient subgroups, such as those with renal or cardiac disease. Finally, this study should be repeated in other species.

In summary, we determined that a sodium correction factor of 1.6 mEq/L was optimal for dogs undergoing treatment for hyperglycemic diabetes, DK, DKA, or HHS. This is the same correction factor often recommended for clinical use in human medicine.11,18 As in human medicine, serial calculations of the corrected sodium over the course of treatment should be considered, as this may improve clinical assessment of sodium changes in response to therapy and minimize shifts in osmolality.

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