ECG of the Month

A 6-year-old 1.86-kg (4.1-lb) spayed female Chihuahua mix was evaluated because of vomiting of 2 days’ duration. When the owner arrived home on the day of the evaluation, the dog was hesitant to ambulate out of its indoor crate. The owner subsequently carried the dog outdoors where it stumbled, vomited, and collapsed. The dog had no history of medical problems and no sudden diet changes. The dog was not receiving any medications, except heartworm preventative, and had no known exposure to toxic agents or human medications; its vaccination status was current.

At the evaluation, the dog was weak and had signs of depression. Physical examination revealed an irregular cardiac rhythm with a rate of 80 beats/min. The dog's breathing was shallow, and its respiratory rate was 56 breaths/min; its oral mucous membranes were light pink, and capillary refill time was 2.5 seconds. Femoral pulse quality was fair; the pulse was synchronous with the heartbeat. The dog was hypothermic (rectal temperature, 36.6°C [97.9°F]). Intravenous administration of an isotonic crystalloid solution and heat support (warm water bottles and a forced warm air blanket) were provided during diagnostic testing. Diagnostic procedures included a CBC, serum biochemical and electrolyte analyses, assessment of serum canine pancreatic lipase activity, and abdominal radiography.

The CBC revealed leukocytosis (19.9 X 10^3 WBCs/L; reference range, 6 X 10^3 to 17 X 10^3 WBCs/L) with granulocytosis (16.9 X 10^3 granulocytes/L; reference range, 3.5 X 10^3 to 12 X 10^3 granulocytes/L) and monocytosis (1.6 X 10^3 monocytes/L; reference range, 0.3 X 10^3 to 1.5 X 10^3 monocytes/L). Hematocrit was high (61.5%; reference range, 37.0% to 55.0%), as was the RBC count (9.4 X 10^6 RBCs/µL; reference range, 5.5 X 10^6 to 8.5 X 10^6 RBCs/µL). Serum biochemical analyses revealed azotemia (BUN, > 130 mg/dL; reference range, 7 to 27 mg/dL); creatinine, 6.5 mg/dL (reference range, 0.3 to 1.8 mg/dL); and hyperphosphatemia (> 16.1 mg/dL; reference range, 2.5 to 6.8 mg/dL). Other biochemical abnormalities included hyponatremia (129.0 mmol/L; reference range, 144 to 160 mmol/L), hypochloremia (78.0 mmol/L; reference range, 109 to 122 mmol/L), and hyperkalemia (9.1 mmol/L; reference range, 3.5 to 5.8 mmol/L). The sodium-to-potassium concentration ratio was 14.2:1. The canine pancreatic lipase test indicated an abnormal activity level. Abdominal radiography revealed a moderate amount of gastric gas. On the basis of history, physical examination, and available laboratory data, hypoadrenergocorticism or acute renal failure (or both) was highly suspected. Electrocardiography was also performed.

**ECG Interpretation**

A lead II single-trace ECG revealed that the dog's instantaneous spontaneous heart rate ranged from 38 to 75 beats/min (Figure 1). Because of the irregularity of the R-R intervals, the number of R waves was counted over a 60-second period, resulting in a mean heart rate of 55 beats/min. The duration of the QRS complexes was 0.06 to 0.08 seconds (upper limit, 0.05 seconds). The P-wave amplitude was 0.2 mV, and P-wave width ranged from 0.02 to 0.03 seconds. The PR intervals ranged from 0.08 to 0.1 seconds (most PR intervals were approx 0.08 seconds). The R-wave amplitudes consistently were 1.3 mV. The ST segment was depressed from baseline and measured 0.3 mV (values > 0.2 mV are considered abnormal). The QT interval was 240 milliseconds (range, 130 to 250 milliseconds). The QTc (ie, QT interval corrected for heart rate) was calculated by use of the Bazett formula1 (QT interval/RR interval)^0.5 and the Fridericia formula2 (QT interval/RR interval)^0.33, and values were 192 and 207 milliseconds, respectively. Ta waves (amplitude range, −0.1 to −0.2 mV) were evident immediately after each P wave. The ECG diagnosis was sinus bradycardia.

The dog was monitored via telemetry and treated IV with 1.0 mL of 10% calcium gluconate solution (0.54 mL/kg [0.25 mL/lb]) and 1 U of regular insulin (0.54 U/kg), followed by IV administration of 2.0 mL of 50% dextrose solution (1.1 mL/kg [0.5 mL/lb]). Treatment was continued with a continuous rate infusion of 5% dextrose in 0.9% NaCl solution starting at 8 mL/h until referral and single IV injections of dolasetron mesylate (53.8 mg/kg [24.5 mg/lb]), ampicillin sodium (20 mg/kg [9.1 mg/lb]), famotidine (0.5 mg/kg [0.23 mg/lb]), and enrofloxacin (8 mg/kg [3.6 mg/lb]).

A lead II ECG trace was obtained 90 minutes after the aforementioned treatment and revealed a mean heart rate of 120 beats/min (Figure 2). The duration of

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Figure 1.—Lead II ECG recording obtained from a 6-year-old spayed female Chihuahua mix that was evaluated because of vomiting of 2 days’ duration and sudden collapse. At this time, the dog’s serum potassium concentration was 9.1 mmol/L (reference range, 3.5 to 5.8 mmol/L). The ECG diagnosis is sinus bradycardia. Paper speed = 50 mm/s; 1 cm = 1 mV.

Figure 2.—Lead II ECG recording obtained from the dog in Figure 1 one hour after treatment for hyperkalemia. Notice the normal sinus rhythm, which accompanied a decrease in serum potassium concentration from 9.1 to 5.5 mmol/L. Paper speed = 50 mm/s; 1 cm = 1 mV.
the QRS complexes was 0.04 to 0.06 seconds. The PR intervals (each 0.1 seconds) were constant. The P-wave amplitude was 0.3 mV, and P-wave width ranged from 0.01 to 0.02 seconds. The R-wave amplitudes ranged from 0.7 to 0.9 mV. The QT interval was 180 milliseconds; by use of the Bazett and Fridericia formulas, the calculated QTc was 253 and 226 milliseconds, respectively. The ECG diagnosis was normal sinus rhythm.

Reevaluation of clinicopathologic variables via a portable clinical analyzer 2 hours after the initial evaluation revealed low normal glucose concentration (63 mg/dL; reference range, 60 to 115 mg/dL), less severe hyperkalemia (5.5 mmol/L [decreased from 9.1 mmol/L]; reference range, 3.4 to 4.9 mmol/L), elevated BUN concentration (>140 mg/dL; reference range, 10 to 26 mg/dL), hypopon- tremia (115 mmol/L; reference range, 142 to 150 mmol/ L), hypochloremia (84 mmol/L; reference range, 106 to 127 mmol/L), and venous acidemia (blood pH, 7.11; reference range, 7.43 to 7.46). The dog was administered IV injections of 50% dextrose solution (2.0 mL [1.1 mL/kg]), sodium bicarbonate (2.0 mL [1.1 mEq/kg]), and dexamethasone sodium phosphate (0.5 mg/kg [0.14 mg/ lb]). Because of the need for continued diagnostic testing and aggressive care, the dog was referred to the Veterinary Medical Teaching Hospital at Texas AM University.

Hypoadrenocorticism was ruled out on the basis of ACTH stimulation test results, and a diagnosis of acute renal failure (cause undetermined) was made. After 3 days, the dog was discharged from the hospital. Two weeks later, the owner reported that the dog was doing well.

Discussion

Hyperkalemia is a serious electrolyte disorder that may result in life-threatening cardiac arrhythmias.2,3 Hyperkalemia is most commonly associated with hypoadrenocorticism, acute renal failure, urethral obstruction, pseudohypoadrenocorticism, and excessive intake of supplemental potassium.2 Decreased excretion of potassium is the most likely cause of hyperkalemia because hyperkalemia rarely develops if renal function is normal.4

Potassium is the most abundant cation in the body (95% to 98% is located intracellularly), whereas sodium is the most abundant cation in the extracellular fluid compartment.4 The concentration ratio of intracellular potassium to extracellular potassium determines the resting membrane potential of a cardiac myocyte.4 The Na+–K+–ATPase pump maintains this balance by transporting 3 sodium ions out of a cell in exchange for influx of 2 potassium ions. The resting membrane potential (phase 4 of an action potential) of a cardiac myocyte is approximately –90 mV.6,7 A myocyte remains in this phase until it is electrically stimulated by an adjacent cardiac myocyte or spontaneous depolarization occurs (via pacemaker cells). This stimulation causes a rapid influx of sodium ions, which increases the cell’s transmembrane potential to –60 mV and creates an action potential responsible for calcium ion influx and myocyte contraction.2 There are 5 phases (0 through 4) of an action potential. The initial rapid depolarization and overshoot (phase 0) are results of the opening of voltage-gated sodium channels,5 which increases the transmembrane potential temporarily to approximately +35 mV.2 Repolarization then occurs during 3 phases: phase 1, closure of sodium channels and rapid transient outward current of potassium ions; phase 2 (plateau phase), closure of potassium channels (decreasing potassium permeability) and slow prolonged opening of voltage-gated calcium channels (allowing calcium to enter the cell); and phase 3, reopening of potassium channels (allowing potassium to exit the cell) and closure of calcium channels (ending calcium influx).2,7,8 These events return the cell to the resting potential of –90 mV.

Changes in the extracellular potassium ion concentration affect cardiac myocytes’ resting membrane potential2 and may have a profound effect on their electrophysiologic function.6,7 Hyperkalemia decreases the concentration gradient of potassium across the cell membrane, initially resulting in a less negative resting membrane potential (–80 mV).2 This causes an increased cell membrane excitability because of the decreased difference between the resting and threshold potentials.2,7,8 If the resting membrane potential decreases to less than the threshold potential, depolarization occurs. This opens some voltage-gated sodium channels, but not as many as would be expected as with a normal resting membrane potential. Because the resting membrane potential is less negative than normal, some of the fast sodium channels remain in an inactivated (closed) state, thereby causing a lesser response to excitation of the cell membrane and a lower rate of rise of phase 0 of the action potential (Vmax).2 After a short period, these open sodium channels become inactivated and refractory, increasing the threshold for generation of an action potential.2 As extracellular potassium content continues to increase, depression of myocyte action occurs2 because the proportion of available sodium channels decreases as the resting membrane potential progressively becomes less negative. This leads to a decrease in the inward sodium current and a concurrent decrease in Vmax; as a result, myocardium impulse conduction through the myocardi um slows and membrane depolarization becomes prolonged. This can be manifested on an ECG trace as progressive prolongation of P waves, PR intervals, and QRS complexes.2 Hyperkalemia affects phase 3 of the action potential. During phase 3, the calcium channels close, whereas the potassium channels continue to conduct potassium ions out of the cell.2 Hyperkalemia inactivates the sodium-potassium channels that allow potassium ion efflux during the resting phase, causing cells to reach threshold potential more slowly. This decreased potassium ion efflux delays the cardiac muscle’s recovery and prolongs the cardiac action potential’s duration.2

Electrocardiographic findings associated with hyperkalemia include peaked narrow T waves, prolonged QRS complexes and PR intervals, bradycardia, ST segment depression, and prolongation of the QT interval.1,2 The tented T waves are more commonly seen in traces from leads V3 and V4 than from frontal plane leads.2 As serum potassium concentration increases, atrial standstill can develop and progress to a sinoventricular rhythm followed by ventricular fibrillation and cardiac standstill.2 Results of a clinical study7 in dogs and cats indicated that other cardiac arrhythmias (eg, sinus tachycardia, ventricu lar premature contractions, and atrioventricular dissociation) may be associated with hyperkalemia; thus, it
can be assumed that multiple factors affect cardiac electrophysiologic processes, such as hypocalcemia, venous acidemia, hypotonatremia, and hypermagnessemia.

Assessment of the initial ECG trace obtained from the dog of this report revealed bradycardia, a prolonged QRS segment, the presence of Ta waves, and a depressed ST segment. All of these abnormalities resolved or improved (some QRS segments were still mildly prolonged) following treatment to address hyperkalemia. The P-wave amplitude also increased from 0.2 to 0.3 mV. The Ta waves represent atrial repolarization. Abnormal deviations have been detected in people with atrial infarction and periartirdis and during exercise. A Ta wave normally extends from the P wave into and through the QRS complex; such waves are typically not seen via surface ECG because of their low amplitude and their superimposition on the much higher amplitude QRS complex. The large observed amplitude of Ta waves was possibly attributable to accelerated potassium ion efflux from atrial myocytes during hyperkalemia. The potassium ion current, Ikr, located on the myocyte cell membrane, is largely responsible for potassium ion efflux during phases 2 and 3 of the cardiac action potential. These currents are sensitive to extracellular potassium concentrations; as extracellular potassium concentration increases, potassium conductance through these currents increases so that more potassium leaves the myocyte.

The dog’s QT interval (from the onset of depolarization to the end of repolarization) changed markedly once it was corrected for heart rate. The QT interval lengthens in conjunction with bradycardia and shortens in conjunction with tachycardia. Calculation of QTc is typically done by use of the Bazett or Fridericia formulas. The Fridericia formula is an improved modification of the Bazett equation because the cube root correction factor provides more accurate results. However, application of either formula overcorrects when heart rates are high and undercorrects when heart rates are low. In people, the QTc is a prognostic marker of ventricular tachyarrhythmias and death. In particular, increases in QTc can result in torsades de points (a rapid, polymorphic ventricular tachycardia). Torsades de points occurs in people with genetic mutations in genes that control expression of sodium or potassium channels (ie, long QT syndrome) and as a complication of use of drugs that prolong the QT interval via blockade of potassium channels. Increasing cellular calcium concentration can then lead to depolarization of the myocytes (early after depolarization) and result in an extracardiac heart beat. This early heart beat may result in depolarization of neighboring myocytes, thereby triggering torsades de points, which can degenerate to ventricular fibrillation and, ultimately, sudden death.

Hyperkalemia can shorten the QT interval, and for the dog of this report, application of the Bazett and Fridericia formulas revealed that the QTc was shortened prior to treatment. The QTc lengthened considerably from 191 to 255 milliseconds after treatment. The PR intervals before and after treatment were considered normal, but the interval did increase from 0.08 seconds (before treatment) to 0.1 seconds (after treatment). It is known that early stages of hyperkalemia may cause shortening of the PR interval in humans. Shortened PR intervals are evident in people with preexcitation syndromes (eg, Wolff-Parkinson-White syndrome and circus movement tachycardia). It was speculated that the dog of this report may have a preexisting condition or that the short PR interval detected before treatment was indicative of preexcitation secondary to hyperkalemia.

The treatment for hyperkalemia involves 3 steps: antagonize the effects of hyperkalemia at the cellular level (membrane stabilization), decrease serum potassium concentration by promoting the influx of potassium intracellularly, and remove potassium from the body. Calcium antagonizes the effects of hyperkalemia at the cellular level. Regular insulin and dextrose promote transcellular entry of potassium into cells. Sodium bicarbonate moves potassium to the intracellular space in exchange for hydrogen ions; the hydrogen ions leave cells and titrate the bicarbonate in the extracellular fluid. Intravenous administration of fluids causes plasma volume expansion (which dilutes the potassium) and increases the glomerular filtration rate (which increases renal excretion of potassium). In the dog of this report, posttreatment clinicopathologic analyses revealed a decrease in serum potassium concentration (from 9.1 to 5.5 mmol/L) and a resultant improvement in the ECG abnormalities.

An intriguing aspect of this case was that despite the dog’s high serum potassium concentration, some of the expected ECG changes were not observed. However, there was a substantial observed change in the ECG findings after treatment. Overall, this case highlights the fact that the link between serum potassium concentration and ECG changes may not be precise. Thus, clinicians should be aware that ECG findings may not always be a reliable indicator of severe hyperkalemia.

References