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Transvenous Electrical Cardioversion of Equine Atrial Fibrillation: Technical Considerations

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Conventional treatment of equine atrial fibrillation (AF) involves administration of quinidine salts. Most uncomplicated cases respond to treatment, but pharmacologic cardioversion involves a range of adverse effects, and some horses are unable to tolerate medication. A study was undertaken to develop transvenous electrical cardioversion (TVEC) as an alternative treatment. Safety issues and catheter placement techniques with catheter-integrated cardioversion electrodes were investigated, and responses to shock application were evaluated. After the premortem catheterization of elective-euthanasia horses, no tissue abnormalities were detected at postmortem examination. To evaluate the response to the application of shocks and appropriate electrode positions, an electrical cardioversion of research horses in chronic AF was then attempted. After catheterization of the right atrium (RA) and pulmonary artery through the right jugular vein, horses were placed under general anesthesia. Biphasic, truncated exponential shock waves were delivered at incremental energies until cardioversion was achieved or until a maximum energy of 300 J was reached. Five treatment events were applied to 3 horses, with cardioversion achieved in one of the treatment events. No adverse effects of cardioversion attempts or general anesthesia were observed. The procedure was then applied to 8 client-owned horses, with cardioversion achieved in 7. No adverse responses to appropriately delivered shocks were observed. No antiarrhythmic medications were administered to any horse at any stage. Catheter design and placement technique evolved throughout the study, with combined ultrasonography and pressure guidance proving most effective in achieving appropriate electrode placement. Results suggest TVEC, as applied in the present study, is a safe, effective, and realistic therapeutic option for equine AF.

Key words: Cardiac disease; Electrophysiology; Heart; Horse.

Management of atrial fibrillation (AF) in horses has traditionally involved the administration, PO and, more recently, IV, of a quinidine salt.[1–4] The treatment is effective in approximately 80% of horses but involves a range of dose-related and idiosyncratic toxic responses varying from mild and benign to fatal.[1–4] Additional therapeutic modalities are required to avoid these adverse effects and to provide options for those horses that fail to respond to, or are intolerant of, quinidine salts.

Electrical cardioversion involves the application of electrical shock (with a defibrillator) with the goal of depolarizing all or part of the atrial myocardium. Electrical cardioversion of AF is becoming routine in human medicine, because the efficacy of this modality is often higher than that of pharmacologic methods for the restoration of sinus rhythm.[5] In humans, lower energy requirements and higher efficacy have been reported with internal electrical cardioversion with catheter-mounted electrodes (transvenous electrical cardioversion [TVEC]) than with external techniques with thoracic paddles,[5–7] and TVEC has been proven safe and effective.[8] Electrode positions are selected to encompass as much atrial tissue as possible between the electrodes to maximize the probability of blocking and thus terminating fibrillatory wavefronts. Right atrium (RA) (cathode) to coronary sinus or left pulmonary artery (PA) (anode) electrodes result in a highly effective, low-energy method of internal cardioversion in humans.[6,9–12] Large electrode dimensions allow access to a large volume of atrial myocardium and additionally decrease delivered current density. High current densities may be associated with myocardial injury.

We have previously reported successful TVEC in the horse,[13] though that report did not detail the evolution of catheter design and the technique for electrode positioning. The present report describes the issues addressed in refining the design of cardioversion catheters and evolving a safe and repeatable procedure for electrode placement. The investigation had 2 objectives: (1) to determine the safety of cardiac catheterization and intracardiac shock application with cardioversion catheters, and (2) to develop a repeatable, effective technique for TVEC in the horse. To reach these objectives, the investigation was separated into 3 studies, the 1st 2 running concurrently. In the 1st study, the acute safety of cardiac catheterization with cardioversion catheters was evaluated both clinically and at postmortem examination. In the 2nd study, the safety of shock application was evaluated in research horses. The procedure was applied to clinical cases in the 3rd study. Technique was critically evaluated and refined throughout. This paper documents the issues that arose and the manner in which they were handled and presents overall results of treatment. Details of the response to shock application by the final catheter design and placement technique are given in this report, and clinical and subsequent performance outcomes are presented in a separate clinical paper. Two horses are included in both reports.

Materials and Methods

The administration of antiarrhythmic medications at any stage of this investigation was specifically avoided so that effects of the procedure could be unambiguously assessed. The protocol used in this investigation was approved by the Animal Care Committee at the University of Guelph.

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Table 1. Outline of study design.

Phase of Study	No. of Horses	Origin of Horses	Goal of Phase	Disposition of Horses	Catheter Type
1	4	Elective euthanasia	Technique and safety of catherterization	Euthanasia	Single-electrode ultrasound-guided catheter
2	3	Hospital owned	Technique and safety of shock application	Return to origin	Single-electrode ultrasound-guided catheter
3	3	Client owned	Clinical trial	Return to owner	Single-electrode ultrasound-guided catheter
	2	Client owned	Clinical trial	Return to owner	Single-electrode, balloon-tipped catheters with extended electrodes
	3	Client owned	Clinical trial	Return to owner	Single-electrode, open-lumen catheters with extended electrodes

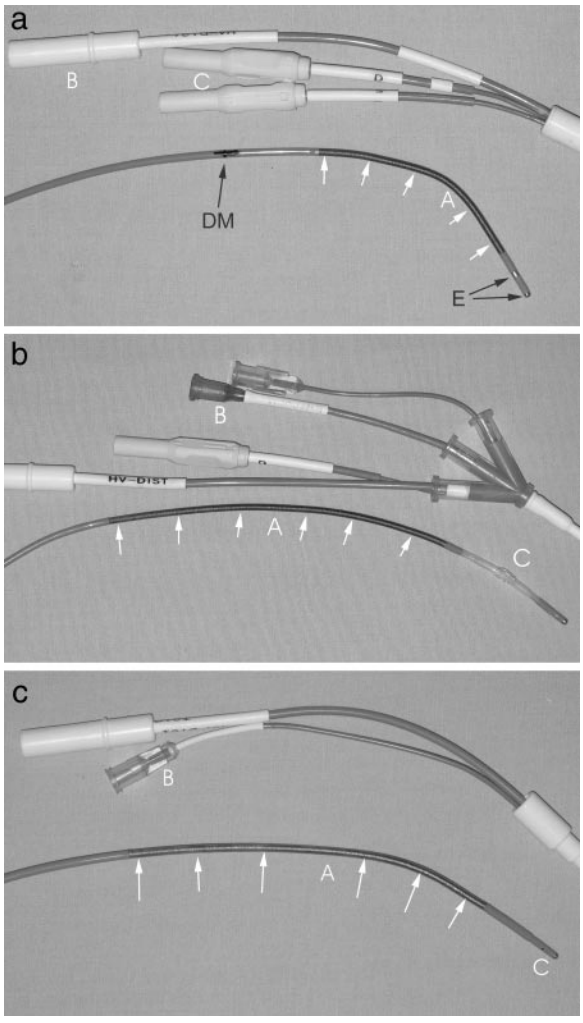

Fig 1. Photographs of cardioversion catheters used in the study. **(a)** Custom-designed modified rhythm catheter with a 6-cm electrode (A, white arrows). Defibrillator connection is labeled B, and sensing connections are labeled C. DM, depth marker; E, tip and ring sensing electrodes. **(b)** Custom-designed balloon-tipped catheter with an 8-cm electrode (A, white arrows). Ingress and egress (B) permits filling of balloon (C) with air or fluid. **(c)** Custom-designed open-lumen catheter with a 9.5-cm electrode (A, white arrows). Access port (B) connects through the lumen to a 1-mm hole in the catheter tip (C) to permit intracardiac pressure monitoring.

Study Design

The study design is summarized in Table 1. The investigation was divided into 3 separate studies, 1 nonsurvival and 2 survival. In each study, cardioversion catheters were placed, with catheter design and placement technique evolving on the basis of the experience gained with preceding cases.

Subjects

Three groups of horses were used, 2 experimental and 1 clinical. The 1st (nonsurvival) study used 4 experimental horses 2–27 years old and scheduled for euthanasia for reasons not associated with cardiovascular disease. Two had chronic, severe arthritis, and 2 had cervical vertebral malformation. In the 2nd (1st survival) study, 3 hospital-owned experimental horses with chronic AF were observed in a total of 5 treatment attempts. The 3rd study group consisted of 8 client-owned animals suffering from chronic AF (AF duration of greater than 7 days[14]), 3–9 years old, enrolled after full procedural disclosure to the client and demonstration of safe application of the procedure to experimental animals. A total of 9 treatment attempts were applied to this group of 8 horses.

Catheter Design

The initial cardioversion catheter was based on a catheter designed for human use; the only modifications were to lengthen the catheter to allow access to the equine PA and increase the distance between electrodes. Use of this single catheter carrying 3 separate cardioversion electrodes[a] was abandoned after the 1st treatment attempt because of difficulties in electrode placement. The interdependence of the electrodes made appropriate, safe positioning of all 3 electrodes extremely difficult, and possible complications associated with inappropriate shock delivery were thought to outweigh any potential benefits.

Subsequently, the basic design[b] was of 6.5-F, 160- to 175-cm catheters with a single 6.5-F coiled wire monofilament cardioversion electrode 6 cm in length (surface area, 4.069 cm^2) ending 1 cm from the tip of the catheter (Fig 1a). These catheters also carried 2 sensing electrodes distal to the coiled wire electrode that were not used in the study.

Design modifications were made on the basis of experience gained in the treatment of clinical cases. The coiled wire filament electrode was increased to 8 cm in length (surface area, 5.426 cm^2), and a lumen was added to the catheter communicating with a small inflatable balloon positioned at the distal end of the lumen[c] (Fig 1b). The balloon was later eliminated, and the final catheter design[d] was a 7-F, 150-cm catheter with a single 9.5-cm (surface area, 6.898 cm^2) coiled wire monofilament cardioversion electrode. The catheter had a lumen throughout the length of the catheter opening through a 1-mm port 1 cm from the distal tip and with access provided by a Luer connector proximally (Fig 1c). One inactive sensing electrode was retained to improve catheter visualization by radiography.

All catheters were marked with indelible ink at 10-cm increments to facilitate catheter placement. A single circumferential line around the catheter was placed at 10 cm, 2 at 20 cm, 3 at 30 cm, and 4 at 40 cm. This pattern was then repeated along the length of the catheter. A longitudinal line was placed along the convex surface of the catheter to indicate the direction of curvature of the catheter tip.

Catheter Placement

Catheterization Site Preparation, All Horses. An IV catheter was placed in the left jugular vein in all but 2 horses, in which the catheter was placed in the left lateral thoracic vein because of the thrombosis of one of the jugular veins. The right jugular furrow (left in 1 horse) was clipped and then prepared, 1st with chlorhexidine soap until clean, followed by 70% isopropyl alcohol and then 0.5% cetrimide with 0.05% chlorhexidine in 70% isopropyl alcohol.

Two small areas of skin over the right jugular vein (left in 1 horse) approximately 15 and 25 cm from the thoracic inlet were anesthetized by 0.5 mL of 2.0% lidocaine at each site. A #15 surgical blade was used to create a 0.5-cm-long incision through the skin in those areas, and a 10-gauge IV catheter[e] was placed into the jugular vein through each incision. These catheters were used in preference to purpose-designed introducers with diaphragms for 2 reasons: (1) to minimize cost, and (2) to avoid damage to the coil electrodes by the introducer. Additionally, later cardioversion catheter designs were too large to fit through introducers with diaphragms. Catheters were immediately capped to minimize the entrance of air into the jugular vein.

All cardioversion catheters were placed in the standing horse. This served 2 purposes: (1) to facilitate correct catheter positioning, and (2) to minimize the duration of general anesthesia. Prior clinical and research experience has indicated that catheterization of the RA and PA can be difficult and time-consuming when attempted in the anesthetized horse, whereas cardiac catheters can be flowed into these sites with relative ease in the standing horse.

In each horse, a cardioversion catheter was placed through the proximal introducer and advanced until its cardioversion electrode was positioned in either the right or left PA, with the proximal end of the electrode 10–15 cm distal to the pulmonic valve. A 2nd cardioversion catheter was then placed so that its cardioversion electrode was positioned in the RA. The cardioversion catheter placement technique was modified in response to catheter design modifications as described in the following paragraphs.

Catheter Placement by Ultrasound Guidance Alone. This technique was applied in all experimental horses and in the initial 3 horses in the 3rd clinical study. Right-sided echocardiography was performed with a 2.5-MHz sector scan probe. Once the ultrasonographer visualized the right heart, the cap was removed from the proximal IV catheter while the vein was obstructed, and a cardioversion catheter was introduced into the right jugular vein through the IV catheter. The curvature of the cardioversion catheter was maintained so that the tip of the catheter pointed down. The cardioversion catheter was advanced 20 cm into the right jugular vein, and then the IV introducer catheter was removed from the vein along the shaft of the cardioversion catheter. The cardioversion catheter was then advanced in 10-cm increments until it was identified in the RA on ultrasonography. The ultrasonographer then guided further advancement of this catheter through the right atrioventricular (tricuspid) valve (RAVV), through the right ventricle (RV), and into the PA (Fig 2). Once the tip of the catheter was observed deep within the PA, the catheter was firmly secured to the skin immediately adjacent to the catheterization site with sutures. A 2nd cardioversion catheter was placed in a similar manner until the catheter tip was noted by echocardiography to be within the RA. This catheter was then secured as for the 1st catheter.

Catheter Placement with Balloon-Tipped Catheters with Extended Electrodes. This technique was applied to 2 horses in the clinical study. Two single-electrode 6-F balloon-tipped catheters with 8- and 9-cm coil electrodes were used. The balloons were added to facilitate the catheterization of the PA and had a single lumen for balloon inflation. Balloons were inflated with saline once the catheters were within the jugular vein, and a pressure transducer[f] was then attached to the 1st catheter to observe whether changes in intracardiac pressure could be detected through pressure fluctuations within the saline-filled balloon. Right-sided echocardiography was then performed. Balloon inflation pressure proved to be markedly higher than intravascular pressure, and pressure guidance was not possible; therefore, catheters were advanced under ultrasonographic guidance. The remaining catheters of this design were placed under ultrasonographic guidance, as described earlier, and the balloons were inflated to aid in ultrasound recognition of catheter tips and for flow direction.

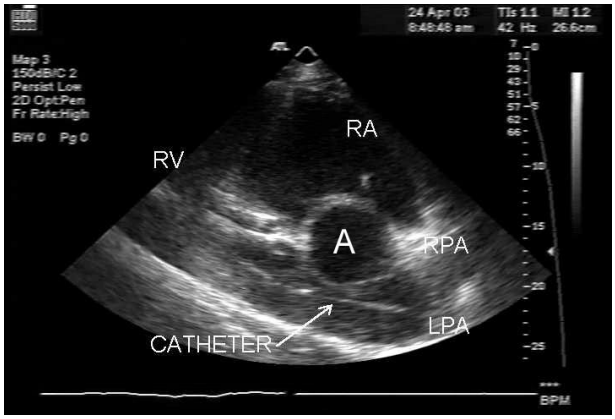

Fig 2. Ultrasonographic image of catheter within the pulmonary artery (PA). Right parasternal long-axis view of right ventricular outflow tract. The PA catheter can be identified as a linear echogenic object within the lumen of the PA. The catheter tip in this image is positioned at the bifurcation of the PA. A, aorta; RA, right atrium; RV, right ventricle; LPA, left pulmonary artery; RPA, right pulmonary artery.

Catheter Placement with Open-Lumen Catheters and Pressure Guidance. This technique was applied to 4 horses in the clinical study. Several 7-F open-lumen catheters with 9.5-cm coil electrodes were used. The lumen of each catheter was filled with saline before use. Cardioversion catheters were placed into the jugular vein, after which a pressure transducer was attached, and pressure contours were monitored. Catheters were advanced until a pressure contour consistent with that of the RV was noted, and they were then advanced until the pressure contour changed to be consistent with that of the PA. Catheters were then advanced a further 15 cm into the PA to ensure the entire electrode was within the artery. Ultrasonography was performed simultaneously and was used to attempt direction of the PA electrode into the left PA. RA catheters were positioned by advancing a cardioversion catheter into the RV and then withdrawing the catheter until the ventricular pressure contour was lost. This placed the proximal end of the electrode at the junction of the cranial vena cava and RA.

Catheterization Studies

Nonsurvival Study. Catheters were placed and maintained in position, in the awake horse, for 2 hours. During this time, horses were monitored closely for any change in clinical status. In addition, continuous ECG was performed. After this period, catheters were removed. Horses were then monitored clinically until euthanasia, which was performed from 1 to 24 hours postcatheter removal.

Complete postmortem examinations were performed. The heart was opened from the RA to the apex of the RV along the ventricular septum. The RAVV, the endocardium, the pulmonic valve, and the proximal PA were inspected for gross changes. Portions of the RV and pulmonic valve were placed in formalin and submitted for histopathologic examination in 3 horses.

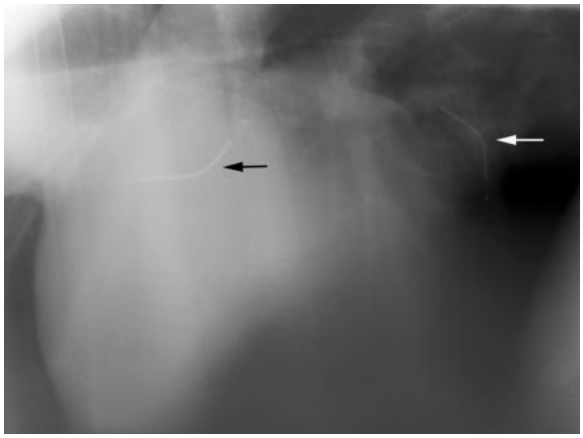

Fig 3. Radiographic image of effective electrode positioning. Left lateral thoracic radiograph centered at heart base. Two catheters with 6-cm coil electrodes are present. One electrode is placed within the right atrium (RA) (black arrow), just beyond the junction with the cranial vena cava, and the 2nd electrode (white arrow) is deep within the pulmonary artery (PA).

Survival Studies. There were 2 survival studies, the 1st performed with experimental animals and the 2nd performed with clinical cases. In all horses, after catheter placement, general anesthesia was induced. Horses were sedated with xylazine[g] (0.5–1.2 mg/kg) before induction. Induction was achieved with combinations of IV ketamine,[h] diazepam,[i] and glyceryl guaiacolate,[j] and horses were placed in left lateral recumbency on a padded surface, except for 1 horse, which was placed in right lateral recumbency. An orotracheal tube[k] (24 mm in diameter) was placed, and isoflurane[l] (1.5–3%) inhalant anesthesia in 100% O_2 delivered by a circle breathing system was then initiated. Mechanical ventilation was provided throughout the anesthetic period, initially at a tidal volume of 10–15 mL/kg and a frequency of 6 breaths/min. Ventilation was adjusted as necessary to achieve a $Paco_2$ of 35–45 mm Hg. IV lactated Ringer solution[m] was administered throughout the procedure. Dobutamine[n] was administered IV to maintain arterial blood pressure but was withdrawn a minimum of 5 minutes before the administration of electrical shocks. Arterial blood gas analysis was also performed before shock delivery.

After the induction of general anesthesia, lateral thoracic radiography was used to confirm appropriate electrode placement. For PA catheters, this involved confirming that the silhouette of the cardioversion electrode did not overlay the cardiac shadow and that RA catheters lay within the RA and cranial vena cava (Fig 3). Catheters were repositioned as necessary with the aid of ultrasonography.

ECG electrodes were attached in a standard base-apex (11 horses) or inverted base-apex (3 horses) configuration, and a biphasic electrical defibrillator[o] was used to monitor the body surface ECG. The inverted configuration was used in 3 horses in an attempt to lessen synchronization of the defibrillator with T waves but was unsuccessful in this regard. The cardioversion catheters were then connected to the defibrillator with custom connectors,[p] with the RA electrode as the cathode and the PA electrode as the anode. The defibrillator delivers a biphasic truncated exponential shock wave. To avoid shock-induced ventricular arrhythmias, shocks were delivered synchronously with the R wave. Stepwise increases in shock energy were used in all horses, but to minimize the total delivered energy, the steps were not evenly spaced. Step size thus increased as delivered energy increased. The initial energy for the 1st 5 treatment events was 2 J. However, to further minimize total delivered energy and because of a lack of response to low energy in initial treatment events, the selection of initial energy between 30 and 50 J was chosen for the remainder of the study. Stepwise energy increases (70, 100, 125, 150, 175, 200, 250, and 300 J) were then applied until cardioversion was achieved or a maximum shock energy of 300 J had been applied.

After anesthetic recovery, heart rate, clinical status, and ECG were monitored in the following order: (1) hourly for 6 hours, (2) every 4 hours for 24 hours, and then (3) twice daily for 7 days. Echocardiography was performed on postprocedural days 2 and 7. Postprocedural heparinized blood samples at 4, 8, 12, 16, 20, 24, 36, and 48 hours were compared with preprocedural samples for cardiac troponin I concentrations. Troponin I assays were performed at the Laboratory Reference Centre, Hamilton, Ontario, Canada. In the absence of currently available normal values for troponin I in the horse, the minimum detection value of the assay of 0.3 μg/mL was adopted as the threshold for normality in the present study on the basis of the results obtained in the assay of 8 clinically normal Standardbred horses (2 sedentary and 6 in full race training). This threshold was supported by determining troponin I concentrations in 2 confirmed diseased horses, one with congenital heart disease and failure and the other with an aortic ring rupture in which concentrations ranged from 0.6 to 1.8 μg/mL. Serum biochemical profiles were performed 48 hours after cardioversion. Clinical cases were discharged from the hospital after 7 days.

Results

Nonsurvival Studies

No ECG abnormalities were noted in 3 horses during catheterization or during catheter maintenance. An occasional premature ventricular complex was observed during catheterization in 1 horse. Once the catheter was advanced into the PA, no further ectopic activity was noted. Heart and respiratory rates remained within normal limits. No abnormalities in demeanor or clinical examination findings were noted after catheter removal.

Two presumed fibrin deposits (2.5 × 1 cm and 0.5 × 1 cm) along the endocardium of the RV outflow tract were noted in the 1st horse on gross pathology. These separated from the endocardium when the specimen was placed in formalin, and no histopathologic changes were detected. No other changes were noted in the heart or PA in that horse. No gross abnormalities were detected in the heart or PA in the other 3 horses, nor were any microscopic changes observed in the 2 horses for which histopathology was performed.

Catheter Placement

Ultrasound Guidance Alone. The 1st cardioversion catheter to be placed was easily visible by ultrasound, providing minimal air was present in the right heart, but the cardioversion electrode could not be differentiated from the rest of the catheter ultrasonographically. Catheters were visualized by ultrasound within the RA at a distance of 60–70 cm from the proximal insertion point and within the PA at a distance of 100–120 cm from the insertion point. Passing through the RV, the PA catheter followed a ventral path along the floor of the right heart at the junction between the interventricular septum and right ventricular free wall. Visualization of the tip of the catheter at the pulmonic valve allowed the distance required to place the electrode well into the PA to be estimated. Coiling of a catheter within the RV was noted in 1 horse. This was corrected by withdrawing the catheter into the RA and then advancing it smoothly into the PA.

The 2nd catheter was more difficult to observe in the RA

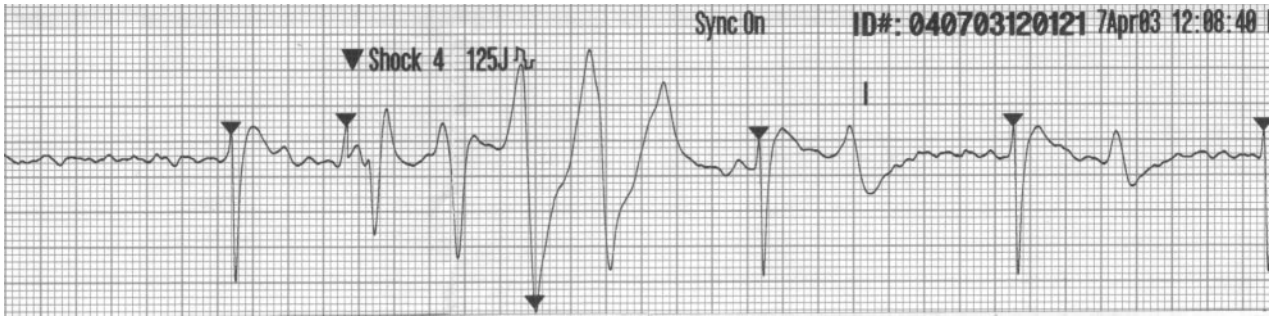

Fig 4. ECG image after the delivery of a 125-J shock in horse 6 (study 3). Base-apex ECG recorded during the application of a 125-J shock in horse 6 (study 3). Note the presence of ''f'' waves and the absence of P waves, indicating atrial fibrillation (AF) at the beginning and end of the recording. Shock delivery synchronous with the T wave (shock 4) resulted in a polymorphic ventricular ectopy of short duration before the return to normal ventricular complexes (paper speed = 25 mm/s).

because of the shadowing from the 1st catheter and the presence of air bubbles. This catheter was more easily visualized in short-axis views as a 2nd echodensity at the RAVV. It was advanced until observed within the RV and then withdrawn into the RA. A tendency for the catheter to move into the caudal vena cava was observed in 3 horses, and coiling of the catheter in the RA was noted in 2. Catheters were repositioned by withdrawing them into the jugular vein and then advancing them smoothly into the RA. Catheter placement required 30–90 minutes until confirmation of appropriate electrode placement by ultrasonography could be obtained.

Balloon-Tipped Catheters with Extended Electrodes. The addition of an inflatable balloon to the catheter made the catheter tip easier to see by ultrasound. However, the balloon gave the catheter increased flexibility and mobility, which caused it to flow directly from the RA across the RV to the PA without following the contours of the RV. This combination resulted in a catheter that lacked stability and tended to move excessively. In 1 horse, PVCs were observed. These were not associated with shock application and resolved immediately when the PA catheter was removed. The pressure required to inflate the balloon was approximately 300 mm Hg, completely damping intracardiac pressure waveforms and eliminating any possibility of pressure monitoring by the balloon to guide electrode placement. Catheter placement took approximately 45 minutes in each horse.

Catheters with a Lumen and Extended Electrodes. The use of an open-lumen catheter allowed direct pressure monitoring. Differences in pressure recordings allowed rapid identification of catheter tip location, and catheter placement was confirmed by means of pressure contours in all horses, except in one of them, in which the pressure recordings were lost once the catheter was within the PA. Simultaneous ultrasonongraphy confirmed appropriate placement and was necessary for selective positioning of electrodes within the left PA. An interval of approximately 20 minutes was required to place the catheters.

Confirmation of Catheter Positioning by Radiography. Thoracic radiography was used to confirm electrode position after induction of general anesthesia. Radiographic evaluation led to the modification of catheter placement in 10 of 13 treatment attempts. The RA catheter was noted to be within the caudal vena cava in 2 horses and was repositioned. The PA catheter was repositioned in 9 horses, most often to position the electrode deeper in the vessel. The PA catheter was folded within the PA in 2 horses. Because of the limited curvature of the PA catheters, slight variations in technique and possibly individual variations in anatomy, catheters passed caudoventrally, horizontally, or occasionally caudodorsally in the pulmonary arterial tree. The precise direction appeared not to influence outcome. However, when judged to be appropriately positioned (after repositioning if deemed necessary), the silhouette of the cardioversion electrode did not overlay the cardiac shadow on lateral thoracic radiography.

Survival Studies

Electrical Shock Application. R-wave recognition by the defibrillator was achieved in all horses, but additional interpretation by the defibrillator of T waves as R waves was noted. Delivering the shock on the T wave could be avoided in most instances by pressing the shock button after observation of a T wave, allowing the shock to be delivered synchronously with the next R wave. Delivery of shock on the T wave had no effect in 1 experimental horse at 70 J but resulted in 2 seconds of polymorphic ventricular ectopic activity at 125 J (Fig 4). All further shocks in this horse were delivered synchronously with the R wave. No abnormal rhythm was noted on application of electrical shock when applied synchronously with the R wave in any horse.

Extensor thrust of the forelimbs, particularly of the upper limb, was noted with every shock application. The extent of this limb movement did not increase with increasing energy delivery and was as evident at 2 J as at 300 J. There was no detectible impact on depth of anesthesia or change in heart rate, and the only consequence of the movement was a tendency for the horse to displace the supporting cushions beneath the lower end of the forelimbs. The range of movement was very limited. Incremental increases in shock energy were used in all horses, and shocks were not repeated at the same energy. If cardioversion was not achieved after the 300-J shock, then the horse was recovered from anesthesia, except for 2 horses in which the PA electrode was advanced deeper into the left PA, and an

additional single shock at 300 J was delivered. Cardioversion was achieved in 7 of 8 horses (7 of 9 treatment attempts).

Induction of anesthesia was smooth in all instances, and horses were maintained on inhalant anesthesia without supplemental IV agents. Anesthetic recovery was without complications in all treatments. One horse developed signs of postanesthetic myopathy within 4 hours of recovery. This was successfully managed with IV fluid therapy and flunixin meglumine[q] administration. This animal had a recurrent history of exertional myopathy.

Resting cardiac troponin I concentrations were below 0.3 μg/mL in all horses except for one of them, in which resting concentrations of 0.5 μg/mL were detected. No increases in cardiac troponin I were noted in any horses after cardioversion attempts, and with the exception of the horse with myopathy, there were no changes in the CBC or serum biochemistry.

Discussion

Initial catheter selection was based on a readily available configuration used in human subjects and designed for placement by fluoroscopic guidance. Cardioversion catheters are routinely placed in humans by this technique.[7,14] The body size, lack of suitable equipment, and position of the forelimbs when standing preclude the use of this method in the horse.

Ultrasonography was the means by which electrode placement was guided in studies 1 and 2 and in the 1st 5 horses in study 3. Our experience is that, in the horse, as long as catheters are advanced smoothly and without interruption once the RAVV has been crossed, they can be flowed into the PA with ease in anatomically normal animals without further guidance. Positioning by ultrasonography alone, however, is inconsistent. The tip of the catheter was easily visible in the RA as the 1st (PA) catheter was placed, but the 2nd (RA) catheter was difficult to distinguish from the 1st, complicating accurate placement of RA catheters. Also, whereas catheters could be observed within the RA, RV, and PA, it was difficult to locate the tip of the PA catheter and confirm precise electrode placement, because electrodes could not be differentiated from the body of the catheter by ultrasonography. Radiography was therefore necessary to confirm placement. Difficulty in catheter visualization resulted in excessive time spent trying to accurately place electrodes by this technique.

The balloon-tipped catheters were more readily visible on ultrasonography. These catheters, however, could not be placed by pressure guidance; it was not anticipated that such high pressures would be needed to inflate the balloon. The catheters were also less rigid than earlier designs. Increased flexibility and a tendency for the catheter to flow directly into the PA rather than follow the contours of the RV led to decreased catheter stability and a tendency for positioned electrodes to shift, compromising the safety and consistency of the technique. PVCs in one of the horses were thought to be associated with the movement of the catheter within the ventricle. Ventricular ectopic activity has been reported as a possible complication of cardiac catheterization.[15–18] Limited benefits from these catheters were noted during catheter placement; therefore, further modifications were made.

The open-lumen catheter functioned well. This catheter was initially not available because of difficulties in manufacturing an open-lumen cardioversion catheter that could deliver and withstand high energies, but these issues were resolved with the design of balloon-tipped catheters. With open-lumen catheters, pressure recordings could be used to guide catheter placement, and the significance of variable catheter visualization by ultrasonography was therefore diminished. The conformation of RV and PA pressure recordings is known, and Swan-Ganz catheterization of the equine heart is an established technique.[19,20] Damping of pressure waveforms (limited frequency response) was noted with the present catheters, but waveforms were nonetheless more than adequate to indicate the location of the catheter tip. These catheters were placed with ease in all but 1 horse, in which 1 catheter folded within the PA.

Once the horse was anesthetized, radiography was used to confirm accurate electrode positioning. None of the techniques completely eliminated the need to reposition electrodes. However, the frequency of repositioning was less for the pressure-guided technique, as was the time required to make changes when repositioning was felt to be necessary. With PA catheters, repositioning involved advancing catheters to a deeper location only, because withdrawal had an unpredictable effect on electrode location. Although not experienced in this study and unlikely to be encountered, a PA catheter that advances cranioventrally might best be repositioned so that it does not overlay the ventricles to avoid including ventricular myocardium in the path of the depolarizing current.

Ventricular ectopic activity after the application of shocks synchronously with the T wave in one of the horses clearly demonstrated the need for careful synchronization of shocks. Presumably, in that horse, the shock button was pressed prematurely. The T wave is considered the susceptible period for ventricular fibrillation in shock application.[21,22] Recognition of T waves as R waves by the defibrillator reflects the large dimension and high-frequency content of the equine T wave and appears to represent an unavoidable potential complication of synchronized shock delivery in this species. Modification to the equipment to prevent the defibrillator from detecting the T wave is unlikely. Repositioning of the ECG electrodes to date has not eliminated this issue. Careful visualization of the T wave before the application of shocks is of critical importance if the risks of shock delivery are to be minimized.

The deep PA to RA electrode positions used in this study, together with increasing the length of the cardioversion electrodes, maximized the volume of atrial myocardium exposed to the electrical current while minimizing current density and the technical difficulty of catheter placement. Efforts were also made during catheter placement to selectively position the PA catheter deep within the left in preference to the right PA. This was performed in a further attempt to maximize the volume of exposed atrial myocardial tissue and is a configuration with known low-energy requirements for cardioversion in other species.[6,9,12] These strategies can all be expected to increase the probability that atrial electrical activity will be successfully interrupted and

arrhythmia terminated. Studies to assess the relative importance of a left versus right PA position for the anode, specifically the probability of successful cardioversion with use of minimal energy, are ongoing.

The most dramatic risks of electrical cardioversion in humans are embolic events and cardiac arrhythmias.[21] Embolism reflects preexisting atrial thrombosis, a complication of AF in humans that has not been reported in the horse. Myocardial damage is also possible and is minimized with low current densities.[21] High energies have been safely delivered in experimental and clinical AF, with energies as high as 720 J applied externally.[23] Acute pulmonary edema has been reported after electrical cardioversion of AF in humans.[24] This complication is considered rare. Preexisting hypertension and valvular heart disease were present in most reported cases.[24] Conduction disturbances are considered uncommon.[21] No abnormalities were detected in the horses in this study aside from intermittent premature atrial complexes in 3 horses, which resolved within 3–6 hours postcardioversion.

Conclusions

In this investigation, we demonstrated that the placement and maintenance of cardioversion catheters in the horse for up to 2 hours is safe. The use of 2 single-electrode, open-lumen catheters combined with pressure guidance and ultrasonography for electrode positioning represents the most efficient configuration on the basis of studies to date. Pressure guidance with ultrasonographic guidance is preferable to ultrasonographic guidance alone, but radiography is desirable to confirm appropriate electrode placement. Positioning of electrodes remains the most critical and demanding aspect of the procedure. The application of cardioversion shock energy to horses is safe, and TVEC of equine AF is a safe procedure, providing shock is not delivered during the T wave. Improvement in electrode design, reduction in minimum effective energy, and determination of the most effective electrode positions require further investigation. However, positioning of catheters so that one electrode (the cathode) is in the RA at the junction of the cranial vena cava with the RA and that the other (the anode) is deep within the PA (preferably the left PA) is a relatively uncomplicated, effective, and repeatable procedure.

Footnotes

[a] Modified impact catheters, Rhythm Technologies Inc, Huntington Beach, CA
[b] Modified rhythm catheters, Rhythm Technologies Inc, Huntington Beach, CA
[c] Custom balloon catheter, Rhythm Technologies Inc, Huntington Beach, CA
[d] Custom open-lumen catheter, Rhythm Technologies Inc, Huntington Beach, CA
[e] Angiocath, Becton Dickinson and Company, Franklin Lakes, NJ
[f] Criticare, Criticare Systems Inc, Waukesha, WI
[g] Rompun, Bayer Inc, Toronto, Ontario, Canada
[h] Ketalean, Bimeda-MTC Animal Health Inc, Cambridge, Ontario, Canada
[i] Diazepam, Sabex, Inc, Boucherville, Quebec, Canada
[j] Guaifenesin powder, Rhodia Canada, Mississauga, Ontario, Canada
[k] Aire-cuf, Bivona Medical Technologies, Gary, IN
[l] Isoflurane, Bimeda-MTC Animal Health Inc, Cambridge, Ontario, Canada
[m] Lactated Ringer Injection USP, Baxter Corporation, Toronto, Ontario, Canada
[n] Dobutrex, Abbott Laboratories Ltd, Saint-Laurent, Quebec, Canada
[o] Lifepak 12 3D, Medtronic Physio-Control, Redmond, WA
[p] Custom connector cable, Rhythm Technologies Inc, Huntington Beach, CA
[q] Flunazine, Bimeda-MTC Animal Health Inc, Cambridge, Ontario, Canada

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