STANDARD ARTICLE

Detection of the origin of atrial tachycardia by 3D electro-anatomical mapping and treatment by radiofrequency catheter ablation in horses

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Abstract

Background: Atrial tachycardia (AT) can be treated by medical or electrical cardioversion but the recurrence rate is high. Three-dimensional electro-anatomical mapping, recently described in horses, might be used to map AT to identify a focal source or reentry mechanism and to guide treatment by radiofrequency ablation.

Objectives: To describe the feasibility of 3D electro-anatomical mapping and radiofrequency catheter ablation to characterize and treat sustained AT in horses.

Animals: Nine horses with sustained AT.

Methods: Records from horses with sustained AT referred for radiofrequency ablation at Ghent University were reviewed.

Results: The AT was drug resistant in 4 out of 9 horses. In 8 out of 9 horses, AT originated from a localized macro-reentrant circuit (n = 5) or a focal source (n = 3) located at the transition between the right atrium and the caudal vena cava. In these 8 horses, local radiofrequency catheter ablation resulted in the termination of AT. At follow-up, 6 out of 8 horses remained free of recurrence.

Conclusions and Clinical Importance: Differentiation between focal and macro-reentrant AT in horses is possible using 3D electro-anatomical mapping. In this study, the source of right atrial AT in horses was safely treated by radiofrequency catheter ablation.

KEYWORDS
arrhythmia, atrial flutter, electrophysiology, focal atrial tachycardia, supraventricular tachyarrhythmia

1 | INTRODUCTION

Atrial tachycardia (AT), a subtype of supraventricular tachycardia, is occasionally found in horses. In general, AT refers to any rapid atrial rhythm with identifiable P′ waves on the surface electrocardiogram

(ECG).[1] The underlying mechanisms are still poorly understood.[2-4] Differentiation between a macro-reentrant circuit (eg, atrial flutter) and a focal source is based upon characteristics of the surface ECG but remains challenging.[5-7] In human medicine, invasive electrophysiological studies, such as endocardial mapping, are often required to identify the underlying AT mechanism.[5,8]

The technique of 3D electro-anatomical mapping (EAM) combines the recording of electrical activity from multielectrode, intracardiac catheters with a location tracking system that automatically determines the 3D position of the catheter in the heart. This 3D tracking of the catheter is based upon impedance sensing or on a magnetic sensor in the catheter in combination with an external magnetic field generator. By comparing the timing of multiple intracardiac depolarizations with a reference electrogram, the activation pattern underlying the AT (macro-reentrant circuit or focus) can be identified.[9] 3D mapping strategies are poorly developed in horses, mostly because the large thorax hampered the fluoroscopic positioning of catheters. However, recently 3D EAM of the right atrium[10] and entire heart[11] have been validated in horses to describe the electrical activation pattern during sinus rhythm.

In human medicine, 3D EAM is used to guide radiofrequency catheter ablation (RFCA) of drug-resistant arrhythmias. More specifically, catheter ablation markedly reduces the recurrence rate of AT compared to pharmacological treatment.[12] In the present paper, we describe the first-in-horse experience with 3D EAM and catheter ablation of sustained AT. Until now, sustained AT in horses has been treated with medication (quinidine sulfate) or transvenous electrical cardioversion albeit with a high likelihood of recurrence.[2,13]

2 | METHODS

Medical records of 9 horses with sustained AT that were examined with 3D EAM for treatment by RFCA at Ghent University were reviewed. Case 6 underwent 3 ablations (referred to as cases 6, 6′, and 6″). Signalment, history, base-apex, and 12-lead ECG, and standard echocardiographic data were recorded.[14-16] Follow-up was done by a telephone discussion with the owners or veterinarians. This included asking if the horse had returned to work after treatment and if the rhythm was regular on the last full clinical exam by the veterinarian.

3 | MAPPING AND ABLATION PROCEDURE

The 3D EAM of the right atrium (RA) and venae cavae was performed under general anesthesia, as described using the Rhythmia mapping system (Boston Scientific, Machelen, Belgium).[17] In brief, a decapolar steerable catheter (Dynamic XT, Boston Scientific, Machelen, Belgium) was inserted through the jugular vein and placed in the coronary sinus in the standing horse under echocardiographic guidance. The electrograms from this catheter served as timing reference for the atrial activation during the EAM. Before induction of anesthesia, sodium penicillin was administered intravenously (20 000 IU/kg, Penicillin 5.000.000IE, KELA pharma,

Hoogstraten, Belgium). After induction of anesthesia, during positioning on the table, the grounding patch of the RF ablation generator was placed under the left shoulder after shaving and degreasing the skin with alcohol. In the first 3 cases, the procedure was performed in dorsal recumbency and the magnetic field generator was fixated with tension straps at the left side of the thorax. From case 4 onward, mapping was performed with the horse in left lateral recumbency as it allowed easier fixation of the magnetic field generator upon the right thorax. The grounding patch of the RF ablation generator was placed under the left triceps muscle. From case 6′ on (because of left triceps myositis seen in cases 5 and 6) we opted for 2 in-parallel grounding patches on the right dorsal thorax with the horse positioned in right lateral recumbency with the magnetic field generator placed in a 15-cm thick wooden casing underneath the horse. Because of problems with tracking in cases 7 and 8 (compatible with magnetic interference from the metal from the surgery table), from case 9 onwards we used a 40-cm high wooden construction between the magnetic field generator and the surgery table (Figure S1, Supporting Information).

The mapping catheter (Intellamap Orion, Boston Scientific, Machelen, Belgium) was inserted through the jugular vein and a 3D EAM was made of the RA as described.[17] The location and mechanism of the AT were determined by analysis of the activation pattern. Macro-reentry was defined as activation recorded over the entire AT cycle length circling around an anatomic or functional line of block (large or localized) usually characterized by a passage of slow conduction consistent with an "isthmus" which was visually identified on the map. The direction of the reentry, clockwise or counterclockwise, was described from an outside view. Focal AT was defined as atrial activity originating from a discrete site activating the surrounding tissue centrifugally (not necessarily recorded over the entire AT cycle length).[12,18]

After mapping, a 7.5 F irrigated, deflectable ablation catheter (Intellanav OI, Boston Scientific, Machelen, Belgium) was inserted into the RA. Depending on the mechanism, the target for ablation was either the isthmus or source. Radiofrequency energy was delivered in power- or temperature-controlled mode (Stockert 70 generator, Biosense Webster, Machelen, Belgium) for 60 s with a target power of 30 to 40 W and an irrigation rate of 30 mL/min. The procedure was continued until the AT was terminated. In some horses, an extrastimulus pacing protocol was used to try to reintroduce the AT in order to confirm a successful ablation. This was not done by default because the pacing protocol could potentially induce AF. If required, the horse was converted to SR by transvenous electrical cardioversion (TVEC).[19]

After conversion to SR, all catheters were removed and the horse was allowed to recover. No anti-inflammatory drugs were administered.

4 | RESULTS

4.1 | Clinical characteristics and medical history of the 9 horses

Nine horses (2 mares, 6 geldings, and 1 stallion; 8 warmbloods and 1 trotter) underwent mapping of sustained AT between March 2018 and February 2020.

TABLE 1 General information, electrocardiographic (ECG) and echocardiographic findings of 9 horses which were presented for ablation of atrial tachycardia

Case	1	2	3	4	5	6	6′	6″	7	8	9
Sex	Stallion	Gelding	Mare	Gelding	Gelding	Gelding	Gelding	Gelding	Gelding	Mare	Gelding
Age (years)	4	8	7	9	3	10	11	11	12	3	12
Bodyweight (kg)	520	585	670	560	517	560	550	560	675	489	515
Height at withers (cm)	167	167	175	167	165	170	170	170	172	162	175
Iso-electric 12-lead ECG	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	No	Yes
Atrial rate (dpm)											
Base-apex ECG (standing)	217	160	213	200	200	165	129	135	219	201	162
CS electrogram (anesthesia)	146	169	192	207	176	166	132	125	194	160	134
Variation in atrial rate (%)	49	5	11	3	14	1	2	8	13	26	21
Echocardiography											
R-LAAd4C (cm^2) (36-75)[47]	70.7	74.9	68.1	74.4	56.7	62.7	68.3	70.3	82.2$^+$	72.3	71.7
R-LAAs4C (cm^2) (62-116)[47]	92.8	98.3	101.6	99.7	71.4	81.6	81.3	81.3	95.5	94.0	99.5
R-LA/AoSAX (1.05-1.29)[48]		1.24	1.31$^+$	1.29	1.17	1.19	1.20	1.14	1.35$^+$	1.18	1.26
Color flow doppler[16]											
Mitral valve regurgitation	Trivial		Mild	Mild		Mild	Mild	Mild			Trivial
Aortic valve regurgitation					Trivial						Mild
Pulmonary valve regurgitation										Trivial	Trivial
Tricuspid valve regurgitation										Trivial	Mild

Note: Variation in rate is the difference between the atrial rate when admitted to the hospital and the atrial rate during anesthesia. Echocardiographic measurements were made in sinus rhythm, 5 days after the ablation procedure.

Abbreviations: dpm, depolarizations per minute; iso-electric, no deflections are visible between subsequent P waves on the surface ECG; R-LAAd4C, end-diastolic left atrial area from a right parasternal 4-chamber view; R-LAAs4C, end-systolic left atrial area from a right parasternal 4-chamber view; R-LA/AoSAX, the ratio of the left atrium and aortic diameter measured from a right parasternal short-axis view; 6′, 6″ characteristics of horse 6 during the second and third ablation procedure respectively; values between brackets, reference values; $^+$, above reference values.

Most of the horses had previous treatment for AT or atrial fibrillation (AF) with medication or TVEC. Case 1 had been treated in our clinic for AT by transvenous electrical cardioversion (TVEC) but had AF 1 day later. The horse underwent a second TVEC. After 72 h of sinus rhythm, AF recurred, which was treated with quinidine sulfate to restore sinus rhythm. AT recurred after 3 months. Case 2 was referred because treatment with quinidine sulfate failed to restore SR. Cases 3 and 4 had been treated at our department for sustained AT with TVEC but both had recurrence after 3 and 30 days, respectively. Case 5 was referred because quinidine sulfate treatment had changed AF to sustained AT but failed to restore SR. Cases 6 to 8 were referred to our clinic for AT and were treated with ablation. Case 9 had been treated in our clinic for AT by transvenous electrical cardioversion (TVEC). Four years after the first treatment AF recurred which was treated by TVEC. One year after the last treatment, the horse had recurrence of AT and presented occasional signs of staggering and weakness, which seemed to be associated with stress. The horse was referred to our clinic.

Details about the horses and electrocardiographic and echocardiographic findings are summarized in Table 1. On auscultation, an irregular rhythm was noted in all cases although periods with a regular rhythm were also identified. A left-sided systolic murmur was noted in case 1 (grade 1/6) and case 7 (grade 2/6). The atrial rate was averaged over 10 P′-P′ intervals on the base-apex surface ECG. The P′ waves had a bifid positive morphology in cases 1, 3, and 4, and a trifid positive morphology in all other cases (Figure 1). In cases 1, 2, 4, 5, 6, and 9 an iso-electric line between the different P′ waves was identified on all leads of the 12-lead ECG, suggestive for focal AT.[1]

4.2 | Mapping and ablation of sustained AT: Case description

In 8 out of 9 cases the AT originated in the caudal right atrium. Catheter ablation of the isthmus or source resulted in SR in all 8 cases (100%). Details of mapping and ablation data and follow-up are given in Table 2. In the first 4 cases it was not possible to identify bipolar low voltage (<0.3 mV, mapping system default value) areas because of excessive noise on the catheter electrograms (technical error).

- Case 1: The activation map of the RA was compatible with a focal source at the transition of the caudomedial right atrium to the caudal vena cava with a cycle length of 410 ms (Figure 2). Because the catheter could not be irrigated (technical error) we opted for temperature-controlled ablation targeting 60 W with a temperature limit at 60°C (for 40 s). During the 5th application AT
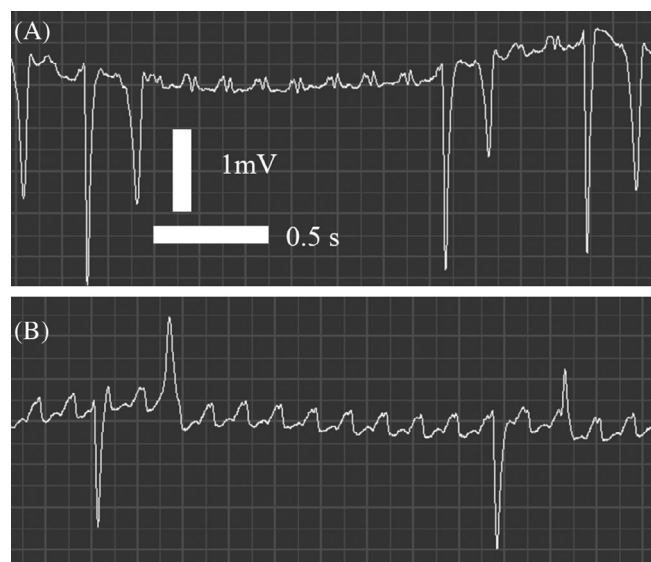
FIGURE 1 Base-apex electrocardiogram (ECG) at rest before the procedure, with the negative electrode on the withers and the positive electrode on the left thorax at the height of the elbow. Panel A (ECG of case 3) shows the bifid positive P' wave as seen in the 3/9 cases. Panel B (ECG of case 5) shows the typical trifid positive P' wave morphology on the base-apex lead as seen in 6/9 cases. Paper speed is 50 mm/s

terminated with ensuing sinus rhythm. After termination 4 additional RF energy applications were given at 60 W. No AT could be induced by burst pacing (at a basic cycle length of 390 ms) followed by an extra stimulus at 300 ms. Recovery was uneventful and the horse remained free of AT/AF 42 months after the procedure.

- Case 2: In the standing horse, AT was induced by burst pacing with an extra stimulus (S1-S1 = 370 ms, S2 = 350 ms) on the decapolar CS catheter (Biosense Webster CS, Biosense Webster, Machelen, Belgium). Mapping under general anesthesia revealed a clockwise macro-reentrant circuit confined to the transition between the medial region of the caudal RA and caudal vena cava with a cycle length of 355 ms (Figure 3). The dorsoventral line of block (12 mm) with doubled potentials was located 69 mm caudal to the intervenous tubercle. The first power-controlled RF application (target 50 W, 20 s) at the isthmus of the macro-reentrant circuit resulted in sinus rhythm. The extrastimulus pacing protocol no longer induced AT. Three years later the horse remained free of AT/AF.
- Case 3: Sustained AT originated from the caudo-dorsal right atrium at the transition with the caudal vena cava and was thought to be a focal source. After six 60 s applications (power-controlled 30 W), the AT cycle length increased from 313 to 407 ms but AT did not terminate. A detailed remap revealed a counterclockwise, localized macro-reentry with the isthmus at the dorsolateral aspect of the

TABLE 2 Mapping and procedure duration, type, and location of the arrhythmia, ablation details, outcome, and time of follow-up and recurrence in 9 horses

Case	1	2	3	4	5	6	6°	6°°	7	8	9
Mapping duration (min)	43	25	53	42	33	47	34	27	62	52	40
Procedure duration (min)	225	225	260	250	210	195	165	220	150	230	315
Focal (F) or reentry (R) AT	F	R	F + R		R	R	R	R	R	F	R
Length of reentry circuit (mm)		33	140		66	81	40	43	128		76
Direction of reentry circuit		CW	CCW		CW	CCW	CW	CW	CW		CW
Location	M	M	DM	LA	D	M	D	M	D	M	M
Distance to IVT (mm)	65	70	65		63	73	73	78	78	62	68
Ablation											
Total duration (s)	366	30	380	280	42	240	104	360	79	575	552
Number of applications	6	1	6	8	1	4	2	6	2	11	9
Power (W)	60	50	30	35	35	35	35	45	30	35	35
Max temperature (°C)	60	48		28	24	22	27	27	48	28	31
Irrigated	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SR restoration	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time of follow-up (months)	42	30	7	13	17	8	1	12	11	6	12
Recurrence	No	No	Yes	Yes	No	Yes	Yes	No	No	Yes	No

Note: The direction of the macro-reentrant circuit is described as seen from a left lateral view. As an anatomical marker, the distance to the intervenous tubercle (IVT) was measured on the electro-anatomical map as the shortest distance between the arrhythmia focus/circuit and the IVT. The ablation duration is the total duration of the application of radiofrequency energy, in 4 cases sinus rhythm (SR) was restored before the end of the application. All arrhythmia origins, focal sources as well as localized reentry, were situated at the caudal right atrium adjacent to the caudal vena cava, with exception for case 4. The maximal temperature of the catheter tip was not registered by the recording system in case 3. Case 3 initially showed a focal AT, but after successful ablation of the focal source of the AT a macro-reentrant AT mechanism was found with a different cycle length.

Abbreviations: AT, atrial tachycardia; (C)CW, (Counter)clockwise direction of the reentry wave; D, dorsocaudal RA; DM, dorsomedial caudal right atrium; IVT, intervenous tubercle; LA, suspected left atrial origin; M, caudomedial right atrium.
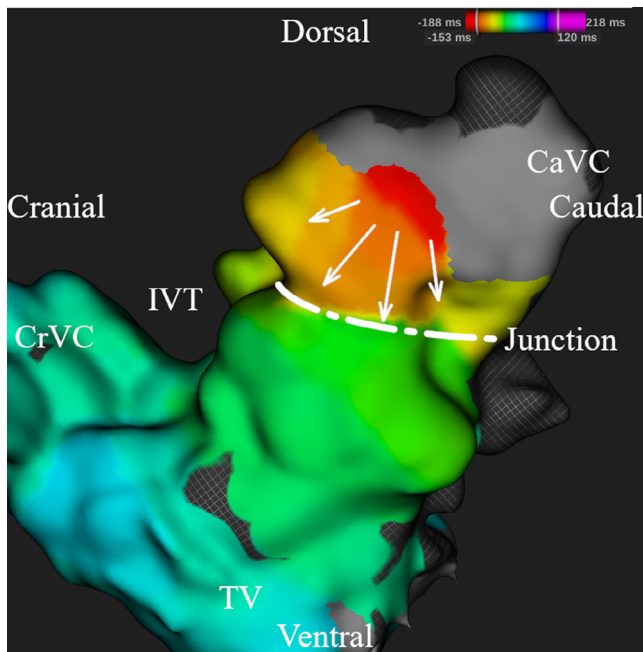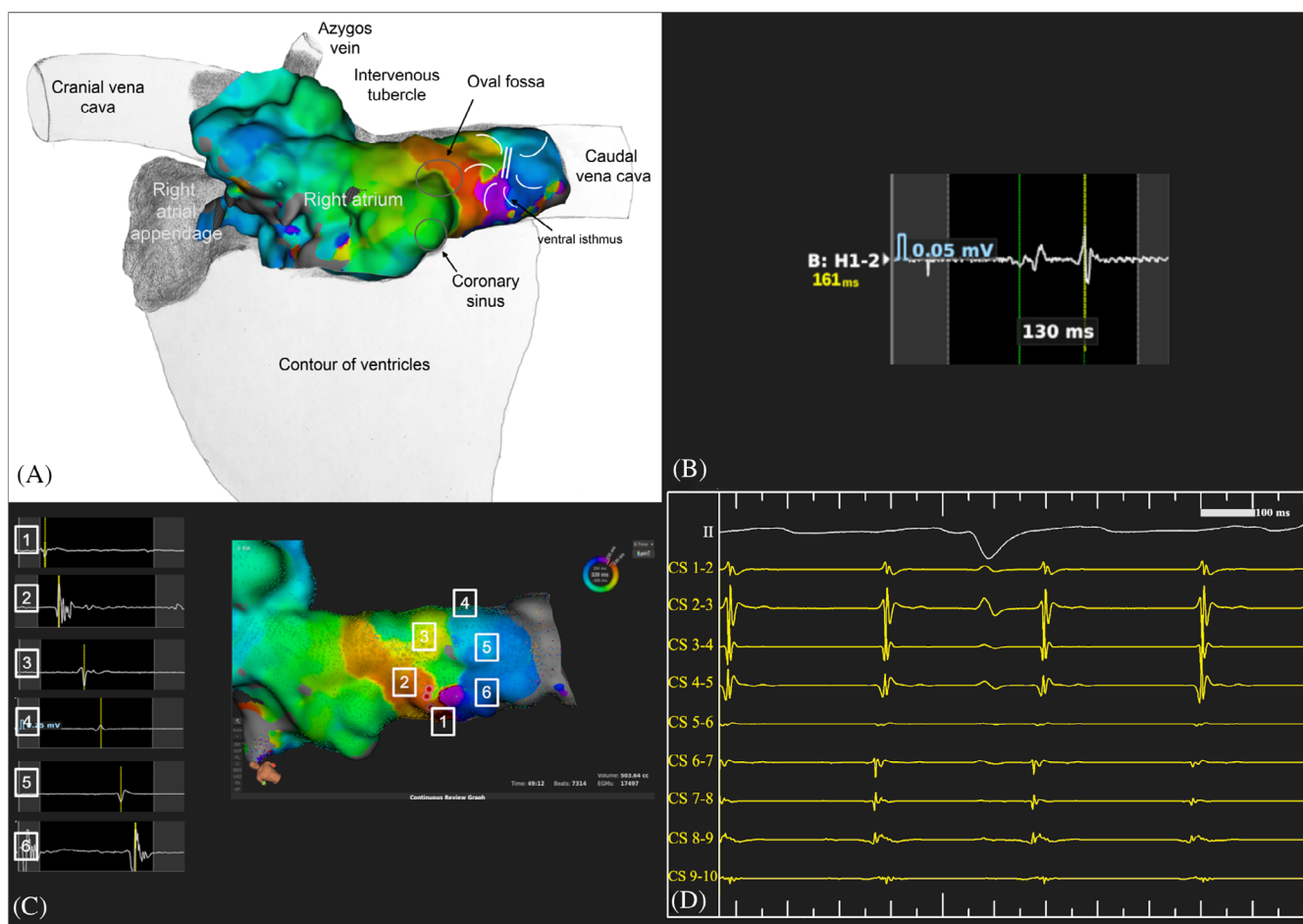
FIGURE 2 Activation map of the right atrium of case 1 showing focal AT with a cycle length of 385 ms. Left lateral view of the right atrium. The color varies following the rainbow spectrum from red (earliest activation) to purple (latest activation). The white arrows indicate the direction of activation, starting at the caudal vena cava (CaVC). The junction between the caudal RA and the caudal vena cava is also indicated. CrVC, cranial vena cava; IVT, intervenous tubercle; TV, tricuspid valve

caudal RA with an area of block (5.4 cm^2), 50 mm caudal of the intervenous tubercle. After another 6 RFCA applications (35 W, 60 s) AT terminated, and sinus rhythm was maintained. At 7 months after the procedure, the horse experienced recurrence of AT.

- Case 4: After insertion of the decapolar coronary sinus catheter in the standing horse, the activation pattern from the coronary sinus catheter was from distal to proximal, which was opposite compared to cases 1 to 3, indicating a different left atrial activation. The procedure was continued. Mapping of the RA initially suggested a focal source from the dorsal interatrial septum with a cycle length of 289 ms. Ablation was attempted but AT could not be terminated. Failure to terminate the arrhythmia in combination with the different left atrial activation suggested a left atrial source with breakthrough via the interatrial septum. TVEC catheters were positioned as described.[20] A 150 J shock converted AT to SR. Recovery was uneventful, but the horse experienced AT recurrence after 13 months.

- Case 5: Mapping revealed a clockwise macro-reentrant circuit with a cycle length of 340 ms confined to the caudomedial RA near the transition to the caudal vena cava. A ventral and dorsal isthmus (Video S1) with a central low voltage area (7.5 cm^2), 22 mm caudal to the intervenous tubercle, were observed. To ensure stable contact, a 92-cm deflectable sheath (Zurpaz, Boston Scientific, Machelen, Belgium) was used to support the positioning of the ablation catheter. The first RFCA application at the isthmus (power-

controlled 35 W, 42 s) resulted in sinus rhythm after which the procedure was terminated. The horse remained free of AT/AF 17 months after the procedure.

- Case 6: Mapping of the AT with a cycle length of 361 ms revealed stable counterclockwise reentry localized in the caudodorsal RA with a narrow, fast conducting area dorsally and slow conducting area ventrally (Figure 3). A line of block (50 mm) was present 75 mm caudal to the intervenous tubercle. The reentry also involved a low voltage area of 23 cm^2, starting 41 mm caudal to the intervenous tubercle. During the 4th RF energy application (35 W, 60 s) at the dorsal isthmus sinus rhythm was restored. Because of recurrence of AT with a similar ECG morphology but slower atrial rate (AT cycle length of 447 ms) 8 months after the procedure, the patient was referred for repeat ablation (case 6′). Again, mapping was compatible with reentry at the transition from the right atrium to caudal vena cava, now in a clockwise direction and with a slow conducting area dorsally and ventrally. The dorsal slow conduction area, located at the previous ablation site, now showed double potentials, which had not been observed during the first ablation procedure. The ventral slow conducting area was targeted for irrigated RFCA since this area was narrower. Irrigated ablation restored SR during the second cycle of 60 s at 35 W. Because restoration of SR resulted in a slight change in cardiac position, an additional ablation point could not be added. One month after the second ablation procedure the horse experienced another recurrence of sustained AT (case 6″), with similar 12-lead ECG characteristics and an even longer cycle length (478 ms) compared to the previous procedures. RA mapping revealed clockwise reentry with double potentials and neighboring fractionated potentials indicating slow conduction at the dorsal area. Power-controlled ablation at the fractionated electrograms, now with higher power up to 45 W, resulted in SR after 4 s. To avoid catheter instability upon SR restoration, rapid atrial pacing at a cycle length of 480 ms was immediately started. To create a complete line of block, point-by-point ablation was performed from the area of double potentials (area of block because of prior ablation) caudally towards the nonconducting region of the caudal vena cava. An extrastimulus pacing protocol was performed to verify AT inducibility but resulted in AF. TVEC catheters were positioned and a single 150 J shock restored SR. After the last procedure, the horse remained free of AT 1 year after the last treatment.

- Case 7: Mapping revealed a clockwise macro-reentrant AT with a cycle length of 309 ms located near the transition of the caudomedial RA to the caudal vena cava. A mediodorsal and medioventral low voltage area (12.2 and 2.8 cm^2, respectively) were found 42 and 76 mm caudal to the intervenous tubercle, with the isthmus of the reentry in between. Mapping took 62 minutes because the tracking of the mapping catheter was disrupted in different areas of the heart. During the first RFCA application (30 W, 40 s) AT terminated. At the time of conversion, a small change in cardiac position was noticed. As a result, during a second ablation cycle of 60 s at the same location, the ablation catheter tip appeared outside the electro-anatomical map, indicating that the 3D anatomical position had slightly changed. No further ablation

FIGURE 3 Details of the reentrant AT in cases 2 and 6. (A) Overlay of the 3D electro-anatomical map of the right atrium of case 2 on a schematic drawing of the right heart, seen from the left as if all other cardiac structures have been removed. The walls of atria and blood vessels are semi-transparent to show the dark shaded area which represents myocardial tissue from the right atrium and the myocardial sleeves in the cranial and caudal vena cava, and the azygos vein. The 3D electro-anatomical map of the right atrium and caudal vena cava is shown in its correct anatomical position. Curved white lines represent the clockwise reentry pathway which shows a narrow isthmus ventrally. The double white line shows a line of block. (B) Example of double potentials, recorded at the line of block in case 2. The yellow line indicates the automatically annotated time of activation. The green line indicates the reference point for the mapping system, in this case the tip electrode pair of the coronary sinus catheter. The time in between is 130 ms, the scale is 0.05 mV. (C) On the right, the 3D electro-anatomical map of case 6 shows a clockwise macro-reentry circuit with a narrow ventral isthmus. At each number along the entire circuit, the corresponding electrogram is displayed on the left. The complete cycle length of the tachycardia could be found on the macro-reentry pathway. (D) Surface ECG lead II (upper white trace) and electrograms from the coronary sinus (CS) catheter (yellow traces) of case 6 are shown with CS 1-2 as the most distal electrodes (deep in the CS). Electrode 10 was outside the coronary sinus. The earliest deflection on the coronary sinus catheter is on electrode pair CS 8-9, suggesting that the initial depolarization of the atrial tachycardia is originating from the right atrium

attempts were made and the horse recovered uneventfully with no recurrences at follow-up 11 months after the procedure.

- Case 8: Mapping revealed a focal source with a cycle length of 375 ms near the transition of the caudodorsal RA to the caudal vena cava (Video S2). However, no clear delineation could be made of the area of the first activation, partially because the tracking of the mapping catheter was again disrupted in different areas of the heart. Ablation with 35 W was performed at the assumed area of earliest activation. After 10 ablation cycles of 60 s, the AT cycle length remained unaltered. A remap was performed in 20 minutes. The remap revealed that during the first mapping, the catheter had not always been in contact with the endocardium at the site of

earliest activation. The second map revealed a clear focal source of the AT caudomedial of the initially suspected region. This focal source was targeted with the ablation catheter and SR could be restored after 19 s of ablation at 35 W. At 6 months after the ablation, the horse experienced recurrence of AT. The owners chose not to treat the horse again.

- Case 9: Mapping in case 9 showed a counterclockwise macro-reentrant AT mechanism with a cycle length of 447 ms confined to the caudomedial RA near the transition to the caudal vena cava. The reentry was located around a low voltage area (12.5 cm²), 57 mm caudal to the intervenous tubercle. A line of block (45 mm) was present 86 mm caudal to the intervenous tubercle. Irrigated

RFCA with 35 W at the dorsal isthmus could restore SR after 4 cycles of 60 s. Atrial pacing at the tachycardia cycle length was started after conversion to SR to avoid changes in atrial morphology. Seven additional locations were ablated in cycles of 60 s to ensure proper closure of the dorsal isthmus. As the horse developed an episode of AF during the extrastimulus pacing protocol, TVEC catheters were positioned and a single 150 J shock restored SR. The horse remained free of recurrence of AT and AF.

4.3 | Complications

Case 4: After recovery the horse showed a transient left facial nerve paralysis which resolved after 3 days of treatment with 5 g of thiamine orally once a day and local application of prednisolone ointment (Ekyflogyl, Audevard, Clichy, France) 4 times a day. Oral treatment with 10 mg/kg phenytoin (Diphantoine, KELA pharma, Hoogstraten, Belgium) twice a day was administered for 6 weeks.

Case 5: At the time of recovery, the horse had a myopathy of the left triceps muscle at the height of the grounding patch of the ablation generator. The horse was treated with prednisolone (1 mg/kg i.v., Solu-Delta-Cortef, Zoetis, Zaventem, Belgium) followed by flunixin administration (1.1 mg/kg p.o., Finadyne, Intervet International, Brussels, Belgium) on the second day. The triceps muscle was locally treated with a prednisolone ointment every 6 hours and with daily physiotherapy. The clinical signs resolved gradually with full return of muscle function 6 days after the procedure.

Case 6: This horse had a left triceps myopathy at the height of the grounding patch after recovery. Clinical signs resolved after 5 days of treatment with local prednisolone ointment 4 times a day, daily physiotherapy, and phenylbutazone (2.2 mg/kg p.o., Butagran Equi, Dopharma, Raamsdonksveer, the Netherlands).

5 | DISCUSSION

Atrial tachycardia is characterized by a rapid atrial activation that originates from a rapidly firing focus (focal AT) or a macro-reentry circuit (macro-reentry AT). In each situation, a depolarization wave moves over the atrial myocardium resulting in a clear, monomorphic P′ wave on the surface ECG.[21] Atrial fibrillation, on the other hand, consists of a large number of chaotically moving depolarization waves, resulting in F waves on the surface ECG.[22] An important finding in this study was that AT can change into AF. As such, in a horse with AF, it remains unknown whether or not the arrhythmia started with AT. This might, at least in part, contribute to the observed recurrence rates of AF and could lead to new treatment perspectives for AF in future.

RFCA is the recommended treatment for humans with either focal and macro-reentry AT since this addresses the underlying cause of the arrhythmia thereby reducing the rate of recurrence.[12] In horses, no specific recommendations regarding AT treatment exist but the arrhythmia is treated similar to AF since RFCA was not available.[13] Current treatment

options for AT in horses include biphasic TVEC,[2] administration of quinidine sulfate,[7,13] overdrive pacing, and administration of amiodarone.[3,4] Flecainide has been used for the cardioversion of AT but is potentially lethal and its issue is not advised in humans.[16,23] In humans, electrical cardioversion is mainly used when the patient is hemodynamically too unstable to perform an ablation procedure. Hemodynamic instability at rest because of AT, as observed in case 9 is unusual in horses because the AV node usually blocks most impulses from the atria, resulting in a normal heart rate but irregular rhythm.[24]

The presence of iso-electric lines on the surface ECG suggests focal AT in humans and small animals, while saw-toothed P′ waves are rather associated with macro-reentrant AT or typical flutter.[9,25] However, there is considerable overlap between ECG characteristics of focal and reentry AT as an iso-electric line can result from conduction slowing. An invasive electrophysiological study is needed for proper diagnosis.[1] 12-lead ECG recording did not allow identification of the underlying mechanism in any of our cases 2. However, the 12-lead ECG was useful to predict the anatomical site of origin of atrial ectopy.[25,26] In human patients, focal AT often has variations in atrial rate while this is less the case in macro-reentrant AT.[27] If the irregularity exceeds 15% of the cycle length, a focal arrhythmia is likely to be present. In our horses, the variation in atrial rate because of anesthesia exceeded 15% in cases with focal atrial tachycardia while cases with macro-reentrant AT remained below 15% variation. Theoretically, an exercise test could help to differentiate between focal AT and reentrant AT. In contrast to a macro-reentrant AT, the heart rate of a focal AT might be overridden during an exercise test. However, because of the high atrial rates, an exercise test would probably have been inconclusive in our horses.[2]

Macro reentrant circuits (flutter) in humans and dogs typically cover the entire atrium and have a length of 44 ± 7 mm.[28] The length of the reentrant circuits in the current cases is comparable to the length of macro reentrant circuits in humans, but because of the large atrium this circuit only covered a small area and could therefore be considered as a local macro-re-entrant circuit. In the current study 8 out of 9 ATs were located in the RA, all at the transition from caudal RA to caudal vena cava, which contrasts with AT in humans and small animals. The crista terminalis, tricuspid, and mitral valve annulus, and pulmonary veins are the most predominant predilection sites for focal AT in humans.[29] The cavotricuspid isthmus circuit in the RA and the peri-mitral or roof-dependent circuit in the LA are responsible for more than 90% of reentries in humans.[27] Atrial arrhythmias originating from the ostium of the coronary sinus are described in humans, but are considered rare.[30] In dogs, focal AT is more likely to occur in the RA, with a predilection for the crista terminalis and triangle of Koch,[31] and reentry has been described at the RA mid septum and free wall but is considered rare.[32] In humans, ectopic beats originating from the inferior (caudal) vena cava have been described, but are considered rare.[33] The superior (cranial) vena cava and ostia of the pulmonary veins are a more likely origin for atrial ectopy because of the arrhythmogenic properties of the irregularly delineated myocardial sleeves in these locations in humans.[34] The inferior vena caval myocardial sleeves are sharply delineated in human patients but,

irregularly delineated electrical active tissues present in the caudal vena cava and pulmonary veins of horses.[11,35,36] The presence of myocardial sleeves in the equine caudal vena cava has been confirmed.[37] Because the medial wall of the caudal vena cava is closely located to the LA, it remains possible that "far field" LA electrical signals are picked up by the mapping system. Retrograde LA mapping via the aorta has been performed in horses[17] and would have allowed better differentiation between a caudal right atrial and left atrial origin by detecting the earliest depolarization. In human medicine, the transseptal puncture technique has been developed to overcome these limitations of the retrograde approach, but this technique has not been described in horses. Therefore mapping and ablation were not continued in case 4. In case 4, the site of earliest activation at the dorsal septum remained stable after ablation. The dorsal intercaval area is also a left-to-right atrial breakthrough site in humans,[38] indicating that this was most likely the breakthrough site from the left to the right atrium. The current system did not include contact force or local impedance measurement for ensuring contact with the myocardial wall which was an important limitation and which might have resulted in false low voltage areas because of inadequate contact. Therefore, low voltage areas were not used in the current study for determining the most optimal ablation target.

Conversion to SR during the ablation procedure was achieved in 10/11 procedures, which is in line with ablations of focal/macro-reentrant AT in human medicine (75%-100%).[12] In the current study, 2 of the 8 ablated horses had recurrence although the recurrence rate is difficult to compare with human medicine. In humans, the recurrence rate varies depending on the underlying mechanism of the AT. Typical atrial flutter and focal AT usually have a recurrence rate of <10% of ablation,[12] with the second treatment after relapse being curative in most cases.[39] On the other hand, nontypical atrial flutter can have a recurrence rate varying from 12% up to 84% if paroxysmal AF was detected during the period of AT.[39-41] The recurrence rate of the current cases was comparable to that of a previous small study in which AT was treated with TVEC (2/7, 28%).[2] The current numbers should be interpreted with caution because of the number of patients is too small to draw strong conclusions and the application of this technology in horses is still in its infancy. This is illustrated by the different adaptations made throughout the study period. It should also be noted that 2 cases (1 and 3) had undergone a successful TVEC procedure before a relapsed into AT within a short period while they now remained in SR for a long period (42 and 7 months). The 2 remaps of the recurrences of case 6 suggested reconnection of the previous ablation site because of insufficient ablation. Reconnection is also frequently observed in humans but is not necessarily accompanied by recurrence of the arrhythmia.[42,43] Lesion quality markers, such as ablation index, have been introduced in human medicine to deliver qualitative ablation lesions and prevent reconnection.[43] Unfortunately contact force-sensing catheters which are necessary for scoring the ablation lesions were not used in our horses. In addition, since no features were available in both the mapping and ablation catheter to verify atrial wall contact, it was unknown if the 3D electro-anatomical map was complete and whether or not the ablation catheter actually

delivered the energy to the myocardium. This was especially applicable in cases 6 and 8 because of it was difficult to visualize the region of interest because of the interference problems with the electromagnetic field. This was demonstrated in case 8, where a missing part of the 3D electro-anatomical map led to a failure of the first ablation attempts. Both cases 6 and 8 showed AT recurrence, indicating that the ablation lesion was not adequate, probably because of the tracking issues which were later resolved. Little is known about the optimal (safe) ablation settings in horses. In the current case series, different ablation settings were applied, making comparisons difficult. Delivery of ablation energy is a delicate balance between applying too little (lesion not deep enough) and too much power (perforating the atrial wall). In the first 2 cases, ablation was performed with relatively high power settings (60 and 50 W). After offline analysis of the maps of the first 2 cases we noticed that the ablation targets were very close to the caudal vena cava, which is a thin walled region. To reduce the potential risk of wall perforation, ablation settings were lowered to 35 W in the following horses, comparable to coronary sinus ablation in humans.[40] Because of the high recurrence rate in the cases which were ablated at lower power settings, the last cases (8, 9, and 6″) were again ablated with a higher setting of 45 W, which is more commonly used for ablation of the atria in humans and dogs.[32,40] Because of the small number of horses, no recommendations can be made for the power settings in horses. Further in vitro and in vivo studies are necessary to determine the most optimal ablation settings for horses. In most of our cases, the ablation was ended once the rhythm converted to SR, with exception of cases 1 and 6″ (2 cases without recurrence of AT). Postablation conduction over the isthmus in cases with macro-reentrant AT was not tested and AT inducibility was only verified in a few cases. In addition, a point-by-point complete line of block was not created in most cases with macro-reentrant AT[44] as ablation was usually ended as soon as sinus rhythm restored. Therefore, the arrhythmogenic substrate was probably not sufficiently neutralized, allowing AT and AF to recur. In future, these issues should be addressed.

In the current study, 2 out of 8 cases had signs of triceps myopathy after recovery. Both horses had a single grounding patch of the RF generator located at the triceps muscle. Similar complications have not been reported in human medicine. Usual complications of ablation include vascular complications, hematoma, perforation, and, rarely, skin burns, but not myopathy.[45,46] Complications were no longer encountered after adjusting the positioning of the horse and changing the location and increasing the area of the grounding patch. Recently, mapping of the right atrium was performed in the standing horse using impedance tracking to determine catheter position. Impedance tracking uses small, high-frequency electrical currents between the surface electrodes and catheters for localization of the catheters.[10]

6 | CONCLUSION

Three-dimensional EAM of the right atrium under general anesthesia is feasible in horses to differentiate focal from macro-reentrant AT,

and to guide the RFCA without the use of fluoroscopy. The caudal vena cava appears to be an anatomical predilection site for AT in horses. Ablation of both focal and macro-reentrant AT is feasible in horses. Ongoing technical improvements, use of catheter contact-force technology and gain of experience will further improve outcome in the future.

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CONFLICT OF INTEREST DECLARATION

Authors declare no conflict of interest.

OFF-LABEL ANTIMICROBIAL DECLARATION

Authors declare no off-label use of antimicrobials.

INSTITUTIONAL ANIMAL CARE AND USE COMMITTEE (IACUC) OR OTHER APPROVAL DECLARATION

Authors declare no IACUC or other approval was needed.

HUMAN ETHICS APPROVAL DECLARATION

Authors declare human ethics approval was not needed for this study.

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