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Multipolar Endocardial Mapping of the Right Atrium During Cardiac Catheterization: Description of a New Technique

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Objectives. Using a new mapping system that allows the simultaneous acquisition of data from 25 right atrial bipolar electrodes during cardiac catheterization, we mapped normal sinus rhythm and atrial reentrant tachycardia in 24 sheep (20 to 49 kg) and 7 pigs (25 to 35 kg).

Background. Rapid, high resolution mapping during cardiac catheterization may shorten ablation procedures and permit ablation of otherwise refractory arrhythmias.

Methods. A flexible, elliptic, basket-shaped recording catheter has five spokes, each with 10 electrodes arranged as 5 bipolar pairs. Catheter shape, electrode spacing and introduction technique were modified in response to the results of experiments in the first 23 animals. In the most recent eight animals, retraction of a string attached to the distal tip distended the basket, providing safe tissue contact. Filtered (30 to 250 Hz) bipolar recordings from all 25 electrode pairs, as well as a surface electrocardiogram, were recorded and digitized at 1,000 Hz using custom software. An activation map was digitally constructed and superimposed on anteroposterior and lateral fluoroscopic catheter images. Bipolar recordings were made in normal sinus rhythm (31 animals), with adequate signals recorded from >95% of electrode pairs. Rapid burst pacing and intentional right atrial air embolus (30 to 50 ml) induced sustained atrial reentrant tachycardia in five animals, which was also adequately recorded.

Results. Catheter positioning and complete atrial mapping required <10 min after venous access in the most recent eight experiments. The catheter was left in position for up to 4 h. Postmortem evaluation revealed minor superficial abrasion of the venae cavae or right atrial endocardium in six animals and moderate abrasion in two. No other damage was observed.

Conclusions. This new system may ultimately assist in mapping simple or complex atrial arrhythmias during cardiac catheterization.

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Multiple-channel recording systems that allow simultaneous acquisition of signals from large numbers of electrodes have been essential in elucidating the mechanisms of atrial arrhythmias (1–8) and have guided surgical attempts to disrupt abnormal conduction circuits (9–12). With the use of thoracotomy, existing mapping systems have used a variety of techniques to apply multiple electrodes to both the epicardial (2,6–12) and endocardial (13) atrial surfaces.

Recently, transcatheter radiofrequency or direct current energy to treat multiple atrial arrhythmias has provided a definitive cure for many patients, without the need for thoracotomy (14–26). To date, transcatheter procedures have relied on mapping techniques using electrical recordings from a relatively small number of electrodes, on multiple catheters, arranged in a predominantly linear array, moved sequentially around the heart (14–31).

Despite excellent initial results for radiofrequency ablation of accessory atrioventricular (AV) pathways and ectopic atrial tachycardia foci in children and adults (24–27), these procedures remain time-consuming and technically difficult in many patients. In addition, consistent, successful radiofrequency ablation of atrial reentrant tachycardia has remained elusive (32), particularly in patients with congenital heart disease (33). Many refractory arrhythmias, especially atrial reentrant tachycardia after repair of congenital heart defects, involve highly variable anatomic and functional mechanisms. Methods that would allow rapid, high resolution mapping could shorten ablation procedures and permit ablation of otherwise refractory arrhythmias.

This report describes such a mapping system. It allows simultaneous acquisition of electrical data from up to 25 bipolar electrodes within the right atrium during cardiac catheterization. The system uses a new, flexible, basket-shaped recording catheter, with 5 spokes, each with 10 electrodes arranged as 5 bipolar pairs (Fig. 1). Tissue contact is provided by distending the basket using a thin string attached to the distal basket tip (Fig. 2). This system was tested in two animal species and was used to map both

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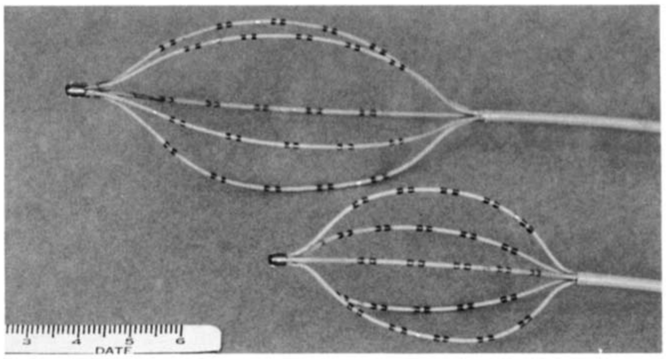


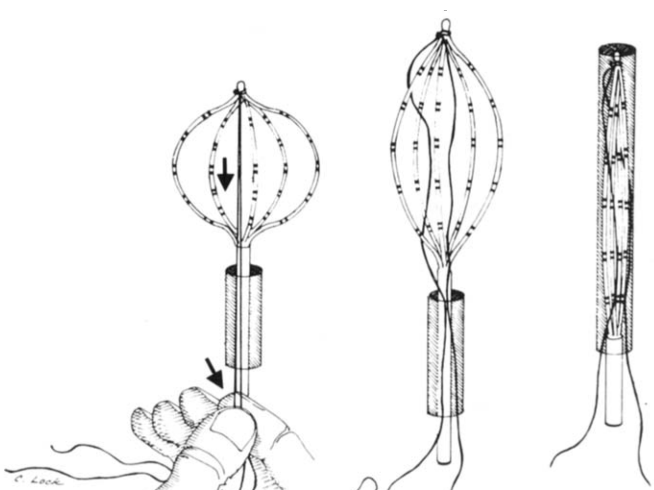
Figure 1. Distal ends of a 10-cm (upper) and a 7-cm (lower) basket recording catheter. Five bipolar pairs (1-mm spacing) and a platinum identifier can be seen along each "spoke."

normal sinus rhythm and induced atrial reentrant tachycardia.

Methods

Catheter development. Catheter design requirements for successful mapping of the atrial endocardium included 1) provision of a large number of sensing electrodes capable of sampling a large part of the atrial surface; 2) the capability of maintaining stable electrical contact with the endocardium throughout the cardiorespiratory cycle; 3) minimal interference with the mechanical function of the heart or with the electrical properties of the myocardium; 4) a small collapsed profile, introducible through a delivery sheath of practical size for use in humans; and 5) the capability of distending the atrium such that the shape of the catheter approximates the atrial shape, thus facilitating computer reconstruction of atrial maps.

Figure 2. A string attached to the distal basket tip allows the basket to be fully distended without forward pressure. **Right,** The basket and string are collapsed inside the delivery sheath. **Center and left,** The basket is partially (center) and fully (left) distended by means of the string mechanism.



To achieve adequate tissue contact, we initially explored multiple catheter designs with independently mobile components that could be advanced against the atrial surface. Ultimately, a flexible prototype catheter, designed to fulfill the criteria just listed, was developed by Webster Laboratories, Inc., using nitinol superelastic wire spokes in a basket design. This catheter proved to have sufficient flexibility to maintain good electrical contact without the need for independently mobile components and became the basis for subsequent work.

Cardiac catheterizations. Cardiac catheterizations using the basket prototype, with subsequent modifications, were performed in 31 animals: 24 sheep (20 to 49 kg) and 7 pigs (25 to 35 kg). The catheterization protocol was approved by the Animal Care and Use Committee at our institution. Catheterizations were performed using nonsterile technique in the fluoroscopy suite of the Children's Hospital animal research facility. Sedation was provided with intramuscular ketamine (10 mg/kg body weight) (sheep) and a combination of intravenous ketamine (10 mg/kg), xylazine (2 mg/kg) and diazepam (0.5 mg/kg) (pigs). Venous access was obtained via the femoral vessels (30 animals) or the internal jugular vein (1 animal) using a standard Seldinger technique or cutdown. All animals received heparin (150 U/kg, 6,000 U maximum). Electrical recordings were made in normal sinus rhythm (all animals) and in atrial reentrant tachycardia (five animals). Anteroposterior and lateral cut film radiographs of the catheter position were taken in 24 animals. After catheterization, the animals were killed, and the hearts were excised, examined for catheter-induced trauma and photographed.

Catheter and introduction technique modification. *Animals 1 and 2 (sheep).* The initial prototype catheter consisted of an elliptic basket with five spokes, each containing five single electrodes spaced over the length of the basket wire. This catheter was placed in the right atrium via an 11F long sheath in Animal 1 and provided reasonable electrical contact from the central three electrodes of each wire. Subsequent modifications included 1) replacement of the single electrodes with bipolar pairs (1-mm spacing), 2) identification of each component wire along the basket shaft with a small piece of platinum (visible by fluoroscopy), and 3) more central placement of the five electrode pairs along each spoke. A second catheter with a narrower elliptic shape was tested in Animal 2. The narrow design did not open adequately within the atrium and was abandoned.

Animals 3 to 11 (sheep). A 9F basket, modified as described for Animals 1 and 2, with a basket length of 10 cm, was tested in Animals 3 to 9. A similar 7-cm basket was deployed in Animals 10 and 11. An 11F long sheath introduced the catheter by way of the inferior or superior vena cava into the right atrial appendage (two animals) or along the tricuspid valve ring (six animals). Contact between the electrodes and the right atrial wall was achieved by advancing the catheter to forcibly distend the basket. Although excellent electrical signals were recorded using this technique, the tricuspid valve was injured in three animals, with two myocardial perforations. On postmortem inspection, there were significant ecchymoses of the myocardium in five animals.

Animals 12 to 19 (sheep) and 20 to 23 (pigs). To prevent tricuspid valve injury, the 11F long sheath was advanced into the tip of the right atrial appendage over a 35-gauge stiff guide wire.

The basket (10 cm in three animals, 7 cm in nine animals) followed the sheath to the appendage tip, and the sheath was withdrawn, allowing the basket to open. If the basket did not open fully, it was rotated and advanced slightly to improve tissue contact. This technique resulted in adequate tissue contact in all but two animals but required frequent repositioning. Although the basket tip perforated the atrial appendage in three animals, the tricuspid valve remained uninjured.

Animals 24 to 28 (sheep) and 29 to 31 (pigs). To improve tissue contact and avoid myocardial perforation or trauma, 6-lb (2.7 kg) fishing line was attached to the basket tip. A 10F long sheath followed the guide wire from the inferior vena cava into the superior vena cava. The 10-cm catheter, with the attached string, was positioned through the sheath into the superior vena cava. The sheath was withdrawn to the junction between the basket and the catheter shaft, and the basket was opened within the superior vena cava. This basket-sheath combination was then withdrawn as a unit until the basket fell into the right atrium. Once in the atrium, retraction of the string opened the basket fully, making tissue contact (Fig. 2). This procedure took <5 min in all animals. The basket was left in position for a variable period of time (10 to 250 min) to assess sustained electrical recording potential and myocardial injury.

Electrical recordings. Beginning with the bipolar catheter, signals from each of the 25 bipolar pairs were amplified and bandpass filtered (30 to 250 Hz ± 60 Hz notch) using an Electronics for Medicine VR-16 recording system (Honeywell). In initial experiments these signals and a surface electrocardiogram (ECG) were recorded on magnetic tape (Hewlett-Packard 3968A, bandwidth 0 to 625 Hz at 1-7/8 in./s [4.76 cm/s]). Beginning with Animal 12, the signals and ECG were digitized at 1,000 Hz using a Keithly-Metrabyte DAS-16f analog/digital board with 12-bit resolution and were recorded directly to disk on a Swan 386-20D personal computer using custom software. Owing to amplifier limitations, signals were recorded for 10 s sequentially from each catheter "spoke" (five bipolar electrodes each) and thus were not simultaneous.

The software allows simultaneous display of the surface ECG with the five recordings from the intracardiac electrodes on each spoke. Regions of the recordings can be expanded in the time scale to permit more accurate identification of activation onset time. Atrial activation times for each electrode pair were digitally calculated during interactive data display, using a fiducial point chosen from the surface ECG, usually the onset of the P wave for normal sinus rhythm and the peak of the "flutter" wave for atrial reentrant tachycardia. Onset of atrial activation was assigned by inspection as the first, most rapid deflection of the electrical signal to cross the baseline.

Induction of atrial reentrant tachycardia. Standard atrial programmed stimulation failed to induce atrial reentrant tachycardia (defined as abrupt onset of rapid, sustained, regular atrial activity with single "P wave" configuration on surface ECG and variable AV conduction) in eight animals (Animals 16 to 23) (four sheep, four pigs). However, after the fortuitous recognition that atrial reentry lasting >3 min was easily inducible after an inadvertent air embolus in one sheep, air emboli (1 to 3 ml/kg) were administered to all eight animals, and attempts to induce tachycardia with atrial stimulation were repeated.

Results

Electrical recordings. Electrical signals were recorded from all 31 animals. Results are summarized here from the most recent 20 animals, reflecting the experience with latter catheter techniques. The newly designed catheter yielded excellent electrograms in normal sinus rhythm from all 25 bipolar pairs in 17 (85%) of 20 animals. Two animals had inadequate signals recorded from one and two electrode pairs, respectively. In one additional animal, five signals were insufficiently recorded. Thus, the basket catheter mapping system provided adequate signals from >95% of electrode pairs.

In 18 (90%) of 20 animals, at least one basket spoke protruded through the tricuspid valve annulus, resulting in a pure ventricular signal from one or more bipolar pairs. One spoke protruded through the valve in 8 (40%) of 20 animals, and two spokes protruded through the valve in 10 (50%) of 20. The remaining spokes recorded either pure atrial or atrial and ventricular electrical activity. An example of high quality electrograms recorded from the basket catheter in normal sinus rhythm is shown in Figure 3. When the basket was expanded using the string mechanism, the electrical recordings were made with a total procedure time of <10 min after venous access. All animals remained in stable condition throughout the procedure.

Induction and recording of atrial reentrant tachycardia. After air embolus, sustained atrial reentrant tachycardia was easily inducible in three of four sheep (cycle lengths 135 to 173 ms) and two of four pigs (cycle length 172 to 260 ms), although one pig required additional administration of intravenous epinephrine. The remaining sheep developed atrial reentrant tachycardia that deteriorated into atrial fibrillation before electrical recordings. Two pigs did not have inducible atrial arrhythmias, and one died after a large (3 ml/kg) air embolus. The electrical signals recorded in atrial tachycardia were qualitatively similar to those observed during normal sinus rhythm (Fig. 4).

Atrial activation maps. Representative atrial activation maps superimposed on X-ray catheter images taken just

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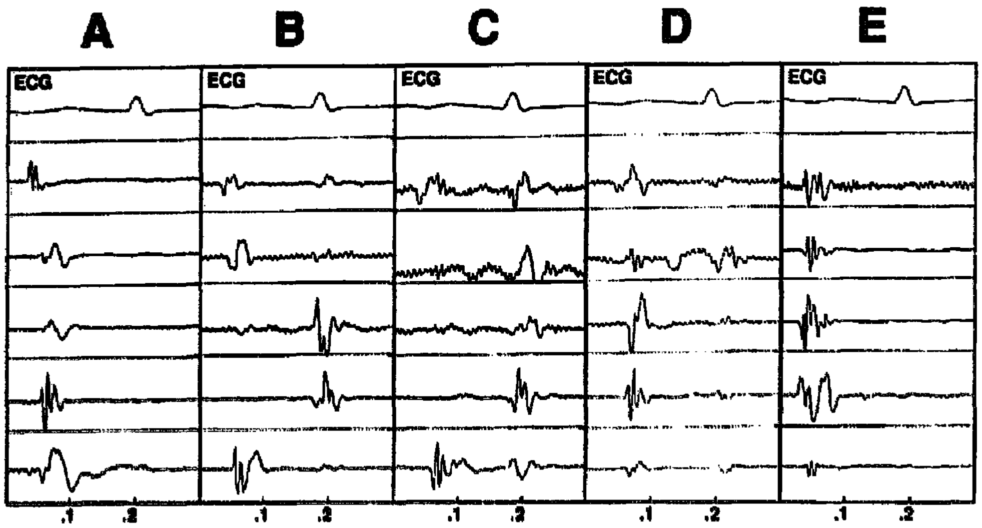

Figure 3. Electrograms during normal sinus rhythm from each basket "spoke" (A to E), as well as a surface electrocardiogram (ECG). Spokes B and C show significant ventricular activity, indicating that these wires have partially protruded through the tricuspid valve.

after electrical recordings are shown during normal sinus rhythm (Fig. 5) and atrial reentrant tachycardia (Fig. 6).

Myocardial injury. Myocardial injury resulting from the early experiments was summarized briefly in the Methods section. Eight procedures were subsequently performed using the modified basket and string design, which eliminated catheter tip pressure as the means for providing tissue contact. In five sheep (25 to 50 kg), the basket was left in position for 10, 15, 25, 30 and 250 min, respectively. Postmortem examination revealed trivial to small superficial abrasions of the inferior and superior venae cavae, the superior vena cava–right atrial junction or base of the right atrial appendage in all animals and of the right atrial surface of the tricuspid valve in four of five animals. The tricuspid valve apparatus was undamaged in all cases.

In three pigs (25 to 30 kg), the basket was left in position for 20, 60 and 125 min, respectively. After 20 min, one animal had findings similar to those observed in the five sheep. After 60 min one animal had a moderate superficial abrasion at the superior vena cava–right atrial junction. Slightly more extensive findings were observed after 125 min and included a moderate intramural hemorrhage at the superior vena cava–right atrial junction. Once again, the tricuspid valve apparatus was undamaged in all cases.

Sustained electrical recording potential. Repeat electrical recordings in normal sinus rhythm were made in three animals after the catheter was in position for 60, 125 and 250 min, respectively. The electrical signals obtained were qualitatively unchanged from those obtained previously.

Discussion

Previous workers have used loops to pace the atrium (34) or described designs to map inside of the heart (35). However, this report describes the design and successful practical testing of a new, catheter-based mapping system that allows the simultaneous acquisition of electrical signals from

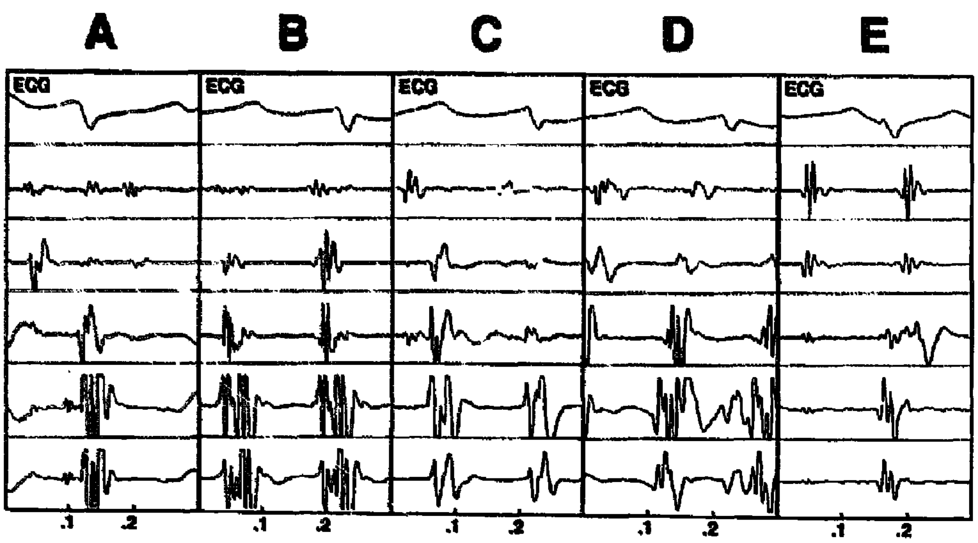

Figure 4. Electrograms during atrial reentrant tachycardia from each basket "spoke" (A to E). ECG = surface electrocardiogram.

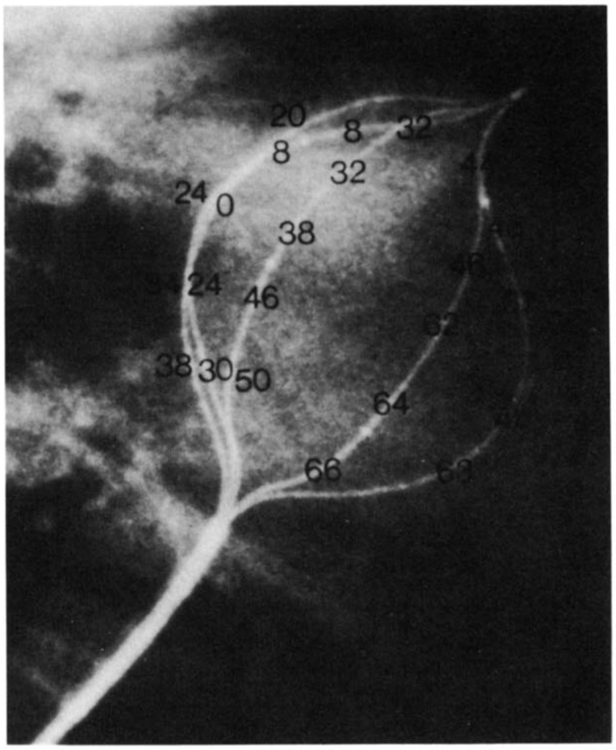

Figure 5. Lateral radiograph of the mapping catheter deployed in the right atrium of a lamb during normal sinus rhythm. Activation times from each electrode pair are labeled. Earliest activation is at the superior vena cava–right atrial junction.

25 bipolar electrodes positioned on the right atrial endocardial surface during cardiac catheterization. The system fulfills the design requirements outlined previously in the Methods section. The 9F flexible basket recording catheter can be advanced inside a 10F sheath, making use feasible in adults and in children weighing >8 kg. Modification of the catheter design with a simple string attached to the tip eliminated the need for catheter tip pressure to provide tissue contact. The catheter provided a large number of electrodes evenly spaced over the atrial surface and maintained good electrical contact throughout the cardiorespiratory cycle. In up to 4 h of testing in two animal species, the catheter did not seem to interfere with either the mechanical function of the atrium or tricuspid valve or with the electrical properties of the myocardium, and it induced minimal cardiac injury.

We used this system to safely and rapidly create three-dimensional atrial activation maps during normal sinus rhythm in animals. The unexpected method of inducing sustained atrial reentrant tachycardia (using atrial stimulation after an air embolus) allowed further recordings of atrial reentrant tachycardia. The catheter has the added potential to provide rapid, nearly real-time, atrial activation maps that are easily superimposable on biplane fluoroscopic images familiar to interventional electrophysiologists. As such, this new system may ultimately improve understanding of complex atrial reentrant tachyarrhythmias and is likely to assist in the ablation of complicated arrhythmias that require sophisticated intracardiac mapping techniques.

Conclusions. We have shown that a new catheter-based atrial mapping system meets reasonable criteria for rapid mapping of both sinus rhythm and complex atrial arrhythmias. When properly deployed, it can be safely used for >4 h with minimal cardiac trauma. Use of this system for mapping in selected patients with complex atrial arrhythmias appears warranted at this time.

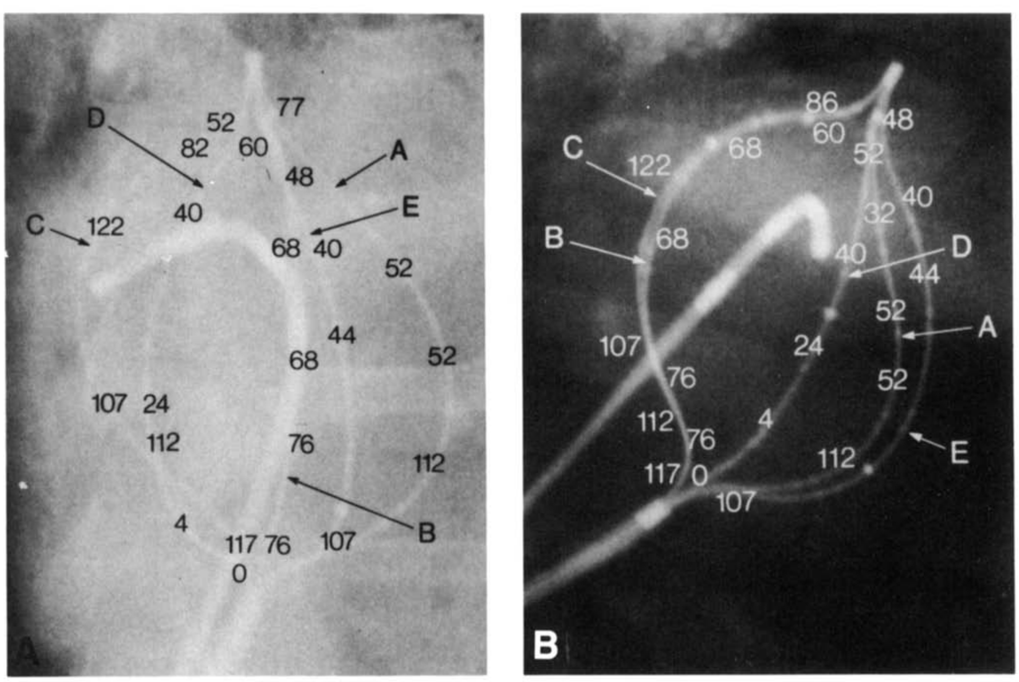

Figure 6. Anteroposterior (A) and lateral (B) radiographs of the catheter mapping reentrant atrial tachycardia (cycle length 155 ms). Earliest activation is at the inferior vena cava–right atrial border, with the latest activation occurring at the low-lateral right atrial border. Each wire (A to E) is identified by platinum markers (distal marker [A] near 48 ms at the catheter tip; proximal marker [E] near 112 ms at the catheter base) variably positioned along the spoke.

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