Methods for Recording Electrograms of the Sinoatrial Node During Cardiac Surgery in Man

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SUMMARY Recent reports have shown that it is possible to record extracellular electrograms from the rabbit and dog sinoatrial (SA) node. We applied similar techniques to record SA nodal activity in 23 patients who underwent cardiac surgery for various forms of heart disease. Both a bipolar technique, using pairs of electrodes at various interelectrode distances, and a unipolar technique, using an exploring and an indifferent electrode, were used. To record SA nodal electrograms, polarity was reversed from the conventional electrocardiographic recording; high amplification (100 µV/cm) and low-pass filters (0.15–30 Hz) were used.

SA nodal electrograms were recorded from eight of 12 patients using the bipolar method and from nine of 11 patients using the unipolar method. There were no significant differences in the success rate or quality of the recording between the two methods. However, the unipolar method allowed a more accurate localization of the SA node.

Human SA nodal electrograms resembled those of the dog and rabbit and showed two distinct slopes: a diastolic slope and an upstroke slope preceding the P wave of the ECG. SA conduction times were 32.4 ± 2.8 msec (mean ± SEM) at sinus (PP) cycle lengths of 587.6 ± 35.6 msec for the bipolar method, and 38.2 ± 3.2 msec at sinus (PP) cycle lengths of 712.2 ± 50.7 msec for the unipolar method.

These methods for recording of extracellular SA nodal electrograms in man may prove useful in 1) localization of the SA node during open heart surgery and 2) assessment of SA nodal function in health and disease.

SINCE THE DESCRIPTION of the sinoatrial (SA) node by Keith and Flack in 1907,1 many attempts have been made to prove that the SA node initiates the cardiac impulse in the mammalian heart. In 1910, Lewis et al. used epicardial leads to record the “primary negativity” near the SA node.2 They concluded that the site of the impulse initiation, or the primum movens, was near the SA node.2 Their findings were confirmed by Wybaw in the same year and by Eyster and Meek in 1914,3,4 Several subsequent studies using extracellular electrodes placed in proximity to the SA node reported recording of what was believed to be electrical activity of the SA node. These studies, carried out in both canines and humans, showed various deflections preceding the P wave of the ECG;5–10 however, they could not show that these deflections truly represented the electrical activity of the automatic cells of the SA node.

Recently, we described techniques that permit extracellular recording of electrograms characteristic of pacemaker activity in the rabbit and canine SA node.11,12 The results were validated by correlating the extracellular electrograms with the transmembrane action potentials of the automatic cells in the SA node.11,12 In this paper we describe the application of these extracellular recording techniques to the in vivo human heart. The electrograms recorded during cardiac surgery resemble very closely those previously described for rabbit and canine hearts. Therefore, we believe those electrograms represent electrical activity produced by the membrane currents of human SA nodal pacemaker cells.

Materials and Methods

We studied 23 patients, 13 males and 10 females, with various forms of congenital and acquired heart disease during cardiac surgery. The patients' ages ranged from 1 month to 57 years. The recording of SA nodal activity was attempted in these patients in order to provide the surgeon with a more precise indication of the location of the SA nodal pacemaker so that damage to it during operation might be avoided. Informed consent was obtained before surgery. Studies were performed before, during or after cardiopulmonary bypass at esophageal temperatures ranging from 20–37°C. Preoperative medications given within several hours before surgery and pertinent clinical data are listed in table 1.

Two recording techniques were used: a bipolar and a unipolar method. For the bipolar method, we designed an electrode probe containing three pairs of bipolar electrodes with interelectrode distances of 6, 7 and 8 mm (fig. 1). To record SA nodal electrograms, a row of three electrode terminals was placed over the anticipated location of the SA node close to the sulcus terminalis, and the other row of three electrode terminals on the epicardial surface of the right atrial wall (fig. 1).

For unipolar recording we used an electrode probe previously made to record His bundle electrograms during open heart surgery.13 This probe has three elec-

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trode terminals arranged triangularly 1 mm apart (fig. 2A). To record unipolar SA nodal electrograms, we paired one electrode terminal of the His bundle probe with a remote or indifferent electrode. The indifferent electrode, an atrumatic plastic clip containing electrode terminals (fig. 2B), was placed on the pericardium close to its superior vena caval and aortic reflection. The other two electrode terminals of the His bundle probe were paired to form a close bipolar electrode pair to record high right atrial electrograms from the vicinity of the SA node.

A frontal lead ECG showing the largest P wave, and the SA nodal and high right atrial electrograms were monitored and recorded simultaneously using Hewlett-Packard 8811A bioelectric amplifiers, a Hewlett-Packard 1308A oscilloscope and a multi-channel Honeywell 1858 CRT visiorder at a paper speed of 100 mm/sec. Filter settings were 0.15–300 Hz for the ECG, 50–300 Hz for the high right atrial electrograms, and 0.15–30 Hz for the SA nodal electrograms. The polarity of the recording of SA nodal electrograms was reversed from that used for conventional unipolar electrocardiographic recording in order to obtain upward deflections of the SA nodal potentials.11, 12 High amplification (about 100 μV/cm) was used to record SA nodal electrograms.

Sinus PP intervals and SA conduction times were measured and presented as average values for two to five consecutive beats. All measurements were made using a vernier measuring device having an accuracy of about 1 msec.

**Results**

We recorded SA nodal electrograms of adequate quality for the measurement of SA conduction time from 17 of the 23 patients, from eight patients with the distant bipolar and from nine with the unipolar method (table 1). Each recording was completed within less than 5 minutes after the placement of the
probe on the heart. The two recording methods did not result in differences in the diastolic and upstroke slopes.

Figure 3 shows an example of SA nodal electrograms recorded with the unipolar method during cardiopulmonary bypass, at an esophageal temperature of 31°C, from a 2-month-old infant operated on for double outlet right ventricle (patient 13, table 1).

As with the electrograms recorded from the rabbit and canine SA node,11,12 the human SA nodal electrograms show two deflections of low frequency and low amplitude preceding the high-frequency deflections resulting from atrial activity. Figure 4 represents an enlargement of those low-frequency and low-amplitude deflections. Two distinct slopes, previously termed the diastolic slope and the upstroke slope, can be seen.11,12 Because of the rapid sinus rate, the duration of the diastolic slope is much shorter than that recorded from dog and rabbit hearts. At the cycle lengths studied the diastolic slope ranged from 0.5–2 mV/sec and the upstroke slope from 4–15 mV/sec.

Those low-frequency and low-amplitude potentials were recorded only from a very small and strictly localized area on the epicardial surface close to the sulcus terminalis. Figure 5, from the same patient, shows electrograms obtained from different sites in the vicinity of the SA node. As the electrode probe was moved a small distance from the area where SA nodal electrograms were recorded (figs. 3, 4 and 5A), a diastolic slope still was recorded. This slope, however, no longer was followed by an upstroke slope; instead, a small downward (positive) deflection preceding the major atrial deflection was recorded (fig. 5B, bottom...
SA conduction time was measured from the point of departure of the upstroke slope from the trajectory of the diastolic slope (fig. 4) to the beginning of the P wave of the ECG in the bipolar records, or to the beginning of the high right atrial electrogram in the unipolar records. SA conduction times (mean ± SEM) measured from SA nodal electrograms recorded with the distant bipolar and the unipolar methods were 32.4 ± 2.8 msec at sinus (PP) cycle lengths of 587.6 ± 35.6 msec and 38.2 ± 3.2 msec at sinus (PP) cycle lengths of 712.2 ± 50.7 msec, respectively. When the data on SA conduction times and sinus (PP) cycle lengths of the two groups of patients were compared (nonpaired t test), no significant statistical difference was found. Individual values of sinus (PP) cycle lengths and SA conduction times are shown in table 1.

Discussion

Technique

Unlike human atria or ventricles,14 samples of the SA node cannot be obtained during open heart surgery for electrophysiologic studies on the human SA node. For that reason, the in vivo heart would be most suitable for such electrophysiologic studies.

We thought that we could record SA nodal activity from patients during cardiac surgery because our earlier studies on dog and rabbit hearts showed the feasibility of recording SA nodal electrograms through electrodes placed on the epicardium in close proximity to the SA node15, 16 and also because of the proximity of the human SA node to the epicardial surface.18 Studies on dogs had shown that it was possible to record SA nodal electrograms using either a bipolar method or unipolar method with an indifferent electrode placed on the superior vena cava.19 To avoid trauma to the superior vena cava, the indifferent ter-

Figure 4. An enlargement of sinoatrial (SA) nodal electrograms from the first complex in figure 3. SA conduction time (SACT) is measured from the point of departure of the upstroke slope (B) from the trajectory of the diastolic slope (A) to the beginning of the P wave or the high right atrial electrogram.
minal was placed on the pericardium in close proximity to the superior vena cava and aorta.

Proper filter settings and high amplification are important in recording SA nodal electrograms. Our previous studies showed that undistorted SA nodal electrograms could be recorded through either direct-coupled or condenser-coupled amplifiers with a time constant of about 0.1 second; those two types of amplification did not result in significant differences in the recorded SA nodal electrograms.\textsuperscript{11, 12} In this study, we have used condenser-coupled amplifiers.

Although we could record SA nodal electrograms of adequate quality to measure SA conduction time using the bipolar method, we found that the unipolar method was technically superior because the smaller probe allowed a more precise localization of the pacemaking area of the SA node.

Like the previously reported rabbit and canine SA nodal electrograms,\textsuperscript{11, 12} human SA nodal electrograms showed low-amplitude and low-frequency negative deflections, followed by a rapid negative atrial deflection. The pre-auricular deflection reported by Hecht\textsuperscript{8} and the electrical activity in the region of the SA node reported by Warembourg et al.\textsuperscript{5} consisted of a low-amplitude and low-frequency positive or diphasic deflection, followed by a rapid positive atrial deflection; therefore, those deflections probably did not represent the human SA nodal electrical activity. Equally unlikely is the S wave recorded in the human heart\textsuperscript{6} by Battro and Bidoggia, which consisted of a rapid negative deflection preceding a rapid positive atrial deflection. The high-frequency oscillations preceding the rapid negative atrial deflection recorded in the canine heart by van der Kooi et al.\textsuperscript{7} and Théry et al.\textsuperscript{10} also are inconsistent with our data. Ramalau recorded in the canine heart low-frequency, low-amplitude negative deflections followed by high-frequency negative deflections preceding the major atrial deflection; however, he failed to recognize that the low-frequency components represented the SA nodal electrical activity.\textsuperscript{8} The origin of those rapid deflections and the positive or diphasic low-frequency deflections is speculative; atrial fibers around the SA node ("perinodal fibers") may give rise to such deflections.

Clinical Uses and Limitations

The recording of human SA nodal electrograms has many potential uses. It should prove to be an effective means of preventing damage to the SA node during cardiac surgery. In children with certain forms of complex congenital malformations of the heart, such as transposition of the great arteries, accepted procedures for surgical repair require incisions and placement of sutures close to the SA node. These procedures may damage the SA node and, as a result, the patients may develop a variety of cardiac arrhythmias related to SA nodal dysfunction.\textsuperscript{16, 17} There is some variability in the location of the SA node,\textsuperscript{15} and estimation of its location may be difficult. Electrophysiologic delineation of the exact anatomic position of the His bundle during cardiac surgery has been useful in preventing damage to the atrioventricular conduction system.\textsuperscript{18} A similarly effective and reliable means to identify the precise location of the SA node can be expected to have similar beneficial effects on the outcome of surgery.

Greenwood et al.\textsuperscript{19} reported a 14% incidence of SA nodal dysfunction after the Mustard operation and a lower incidence after repair of other types of congenital heart disease.\textsuperscript{19} In 75% of their cases, SA nodal dysfunction was recognized in the immediate postoperative period. Of our 23 patients, 16 had various forms of congenital heart disease. SA nodal electrograms were recorded intraoperatively in 12 of the 16 patients; none of those 12 patients developed SA nodal dysfunction in the immediate postoperative period and in the 1–8-month follow-up period. We therefore might conclude that the use of these records as an aid to the surgical procedure were beneficial. However, we cannot reach a definite conclusion because of the small sample size and lack of a randomized study.

Consistent with results of previously reported studies\textsuperscript{19, 20} and our studies on dogs,\textsuperscript{21} we found marked shifts in the site of the dominant pacemaker. Areas of the SA node that are not functioning as active pacemaker cells can be recognized by the presence of a diastolic slope only (fig. 5B) rather than by both a diastolic and an upstroke slope.\textsuperscript{11, 12} Thus, to avoid damage to the SA node, it may be necessary to identify not only the pacemaking area from which both the diastolic and upstroke slopes are recorded, but also the areas where latent pacemaker cells are located and from which only a diastolic slope is recorded.

Recording of the SA nodal electrograms may aid in the differentiation of normal from abnormal SA nodal function and identification of certain atrial arrhythmias with possible SA nodal involvement, e.g., sinus arrest, SA block and SA nodal reentrant phenomena. The prevailing indirect methods for evaluation of SA nodal function, i.e., the measurement of sinus recovery time and the indirect measurement of SA conduction time, apparently have great limitations.\textsuperscript{31, 22} By direct measurement of SA conduction time and assessment of SA nodal responses to single and multiple premature stimuli and to various drugs, a better way of differentiating normal from abnormal SA nodes may be possible.

Our data on SA conduction time clearly differ from the previously reported values obtained indirectly using a single premature atrial stimulus.\textsuperscript{23, 24} In adults, Strauss et al.\textsuperscript{23} reported SA conduction times measured using a single premature atrial stimulus of 68–156 msec.\textsuperscript{23} Kugler et al.\textsuperscript{24} reported in children SA conduction times ranging from 85–193 msec.\textsuperscript{24} The discrepancy between our data and those data may partly be explained by the fact that the assumptions made when SA conduction time is estimated indirectly are not true at all times. It has been shown in the rabbit heart that single atrial premature stimulus affects the intrinsic sinus cycle length and that the antegrade and retrograde SA conduction times may not be
equal.22, 25, 26 The difference in the values for SA conduction time may also be explained by the fact that we studied patients during cardiac surgery; most of them have rapid heart rates, presumably due to decreased vagal tone and/or increased sympathetic tone.

The feasibility of accurately measuring SA conduction time may be affected significantly by rapid heart rates. With rapid sinus rates (over 140 beats/min) both the diastolic and upstroke slopes may not be recognized because they may coincide with the preceding T wave of the surface ECG. In our study we processed data for patients in whom the T and P waves were clearly separated in time.

Another possible limitation to the use of these techniques to measure SA conduction time is the difficulty in the determination of the point of departure of the upstroke slope from the trajectory of the diastolic slope. Since both slopes are of low frequency and low amplitude, we estimated that errors in measurement of about 5 msec are likely to be made.

The use of the P wave of the ECG vs the high right atrial electrogram represents another potential source of error. In our unipolar records, the P wave always starts later than the high right atrial electrogram by a 2–5-msec interval:

Conclusion

Our study shows that in humans SA nodal pacemaker cells and latent pacemaker cells may be localized anatomically using extracellular recording techniques during cardiac surgery. These techniques allow recording of specific deflections representing electrical activity of the pacemaker and latent pacemaker cells in various localized areas of the SA node; therefore, they should provide a means of preventing damage to the SA node during cardiac surgery. Direct measurement of SA conduction time from SA nodal electrograms may prove useful in assessment of SA nodal function and probably will be superior to the current methods that use premature atrial stimulation.

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