P Waves During Ectopic Atrial Rhythms in Man

A Study Utilizing Atrial Pacing with Fixed Electrodes

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SUMMARY
Threshold bipolar pacing was performed from one of 12 selected atrial sites with temporary implanted electrodes in 69 patients during open-heart surgery in order to study P wave polarity and morphology and the P-R interval during paced ectopic atrial rhythms. A negative P wave was recorded in lead I only with pacing the left atrium and only when pacing near the left pulmonary veins. A positive bifid P wave in V1 was recorded only with left atrial pacing and only when pacing was near the inferior pulmonary veins and coronary sinus. P wave polarity and morphology were otherwise of no use in localization of the origin of the impulse in these studies. The pacing stimulus to P wave interval was found to vary between 10 and 54 msec, making the duration of the P-R interval an unreliable indicator of the site of origin of the paced impulse. Although the relation of these paced rhythms to spontaneously occurring ectopic rhythms is unclear, the previously published criteria for localizing ectopic atrial rhythms are again demonstrated to be unreliable. P wave polarity and morphology and the P-R interval are of limited value in ascertaining the origin of ectopic atrial rhythms in man.

Over the years, the diagnoses of ectopic rhythms such as "A-V nodal" rhythm, coronary sinus rhythm, coronary nodal rhythm, left atrial rhythm, and right atrial rhythm have relied in large part on P wave polarity and morphology. Despite the fact that several previous reports have suggested that the polarity and morphology of the P wave and the P-R interval are poor indicators of site of origin of ectopic atrial impulse formation, these parameters continue to be utilized in the analysis of various arrhythmias. Most recently, the polarity and morphology of the P wave have been used to support the notion that the sinus node is the site of origin of the impulse in atrial re-entrant rhythms and in the Lown-Ganong-Levine and Wolff-Parkinson-White syndromes.

This study was designed to systematically analyze P wave polarity and morphology when the human heart was paced from selected ectopic atrial sites which might be expected to generate ectopic impulses or which have been suggested as the site of ectopic impulse formation. Importantly, this study utilizes fixed electrodes precisely implanted at these selected sites at the time of open heart surgery to record activity. In our hospital it is routine at open heart surgery to implant in the epicardium temporary teflon-coated stainless steel wire electrodes for postoperative diagnostic and therapeutic purposes. We have modified this routine procedure only in the specification of atrial sites for implantation.

This is the first known systematic study of ectopic P wave polarity and morphology in man using fixed electrodes. In addition to pacing the atria from sites not previously studied, this study overcomes previous criticism that earlier studies of ectopic P waves, which utilized the catheter electrode pacing technique, did not permit atrial pacing from precisely defined sites because of inability either to place the catheter precisely or to keep the catheter from changing its location due to catheter movement; and criticism that the studies which utilized intraoperative techniques were limited by the inability to record the precordial ECG leads.

Methods
Sixty-nine patients were studied on one occasion each. Their ages ranged from 20 to 75 years with a mean of 49 years. Nine patients were studied on the day of surgery, 40 patients on the first postoperative day, 12 patients on the second, six patients on the third, one patient on the sixth and one on the thirteenth postoperative day. The operative procedures performed are listed in Table 1.

In 65 patients, the right atrial appendage and the sinus intercavvarum (dorsal nontrabeculated portion of the right atrium) near the inferior vena cava were cannulated as part of the procedure for cardiopulmonary bypass. In the four...
patients who underwent closed mitral commissurotomy, the left atrial appendage was opened at its tip as part of the commissurotomy procedure. In no patient was any additional incision made in the atrium. There was no significant atrial enlargement, with the exception of a large left atrium in two of the patients who underwent a closed mitral valve commissurotomy. Forty-three patients were not receiving any cardiac medication, 16 patients were receiving digoxin alone, seven patients were receiving procainamide or quinidine sulfate, one patient was receiving both digoxin and quinidine sulfate, and two patients were receiving both digoxin and procainamide.

Using a technique previously described, at the end of the surgical procedure in each patient, a pair of teflon-coated stainless steel wires was implanted in the atrial epicardium at the preselected site (figs. 1, 2). The ends of wire electrodes were brought out through the anterior chest wall. Each electrode of the pair was implanted so that an approximate 5 mm interelectrode distance was obtained. The electrodes were placed at only one site per patient, but 12 different sites were selected (figs. 1, 2), six being on the right atrium and six on the left atrium.

The right atrial sites were the following: in eight patients at the inferior vena cava-right atrial junction (site 1, fig. 1); in 21 patients along the sulcus terminalis, in 11 at a point approximately 6–8 cm from the sinus node (site 2, fig. 1) and in ten at a point approximately 3–4 cm from the sinus node (site 3, fig. 1); in 11 patients on the sinus intercavarum near the superior vena cava (site 4, fig. 1); in 12 patients on the lateral wall of the right atrium near the A-V (atrioventricular) sulcus, four being at the midlateral wall (site 5, fig. 2) and eight at the inferior lateral wall (site 6, fig. 1).

The left atrial sites were the following: in nine patients, the left atrial portion of Bachmann’s bundle (site 7, fig. 2); in four patients, the left atrial appendage (site 8, fig. 2); in one patient each at four different sites on the posterior left atrium (figs. 1, 2); site 9 between the left superior pulmonary vein and the left atrial appendage, site 10 between both inferior pulmonary veins and the coronary sinus, site 11 between the left inferior pulmonary vein and the coronary sinus, and site 12 lateral to the left inferior pulmonary vein.

**Figure 1**

*Selected atrial pacing sites. Ao = aorta; SVC = superior vena cava; PA = pulmonary artery; PV = pulmonary veins; LA = Left atrium; RA = right atrium; IVC = inferior vena cava; LV = left ventricle; RV = right ventricle; CS = coronary sinus.*
Figure 2

Another view of atrial pacing sites. RA = right atrium; SVC = superior vena cava; LA = left atrium; A = aorta; PA = pulmonary artery.

At the time of study, 68 patients were in a spontaneous sinus rhythm and one patient (No. 7-1) was in an A-V junctional rhythm. For each patient, a routine 12-lead electrocardiogram was recorded in the supine position first during a spontaneous rhythm. The same 12 leads were then recorded during a rhythm produced by bipolar threshold pacing via the atrial electrodes. Pacing rates were less than 10 beats per minute faster than the spontaneous rate, except in five patients in whom faster rates were used for therapeutic purposes. A Medtronic 1356 battery-powered pacemaker was used to deliver a pulse of 2 msec duration at a constant current. After a complete 12-lead ECG was recorded at threshold pacing at one polarity, in each patient the pacing poles were reversed and the procedure repeated. Electrocardiograms were recorded between a band pass of 0.1-500 Hz using either a Mingograf 61 (Elema-Schonander) strip chart recorder or an Electronics-for-Medicine DR-12 switched beam oscilloscopic recorder. All ECGs were recorded at paper speeds of 25-50-100 mm/sec. Those electrocardiograms recorded with the Electronics-for-Medicine recorder were also simultaneously recorded on a Honeywell 5600 tape recorder for later study.

The following electrocardiographic intervals were measured using a special vernier device which provided an accuracy of ±5 msec at the slowest paper recording speed.

During spontaneous rhythm: R-R interval, P-R interval (measured from the earliest inscription of the P wave in any of the standard or augmented leads to the earliest onset of the QRS complex in the same leads).

During paced atrial rhythms: Stimulus-to-stimulus interval, stimulus-to-P interval (measured from the stimulus artifact to the earliest onset of the P wave in any of the standard or augmented leads), stimulus-to-R interval (measured from the stimulus artifact to the earliest onset of the QRS complex in any of the standard or augmented leads), P-R interval (measured as above).

There was neither morbidity nor mortality associated with this study. On the contrary, we have again confirmed that temporary atrial bipolar electrodes are a safe and valuable diagnostic, therapeutic, and investigational tool when used in the postoperative period.36-41

Results

When the atria were paced from the selected epicardial sites shown in figures 1 and 2, the changes in P wave polarity and morphology were various, but the pattern was consistent for any given pacing site. Reversal of the pacing poles during threshold pacing made no difference in P wave polarity, morphology, or in the intervals measured.

Pacing From Right Atrial Sites (fig. 3)

Site 1

In 8/8 studies, the P wave was negative in leads II, III, and aVF; positive or diphasic (+ −) in lead aVR, and positive in lead aVL. In 7/8, the P wave was positive in lead I (fig. 3) and in 1/8, flat. In 8/8 studies the P wave was negative in leads V₄₋₆, and in 4/8 the P wave was negative across the entire precordium (fig. 3).

Site 2

With atrial pacing there were minor changes in P wave polarity and morphology in the standard leads and very little change in the precordial leads when compared to that during spontaneous rhythm.
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Site 3

In all ten studies there was little difference in P wave polarity and morphology in the standard or precordial leads between the spontaneous and the paced rhythms.

Site 4

When atrial pacing from this site was compared to sinus rhythm, there were only minor changes in P wave polarity and morphology from the spontaneous rhythm in the standard and precordial leads.

Site 5

In all four patients in whom the right atrium was paced from this site, the P wave was positive in leads I, II, and aV1; negative in aVR; and positive, diphasic (+ -) or triphasic (- + -) in III and aVF. In all four patients, the P wave was positive in V5 and V6 and negative in V1-3.

Site 6

The P wave was positive in leads I and aVL in all eight patients studied in whom the atrium was paced from this site. In lead II, the P wave was positive in 5/8, flat in 1/8, triphasic (- + -) in 1/8, and negative in 1/8. In lead III the P wave was negative in 5/8, positive in 1/8, and flat or triphasic (- + -) in 2/8. In aVF, the P wave was positive in 1/8, flat in 2/8, triphasic (- + -) in 2/8, diphasic (- +) in 1/8, and negative in 2/8. In 8/8 patients, the P wave was negative in V1-3; in 4/8, negative in V4 (fig. 3), and in 1/8, negative across the entire precordium.

Pacing from Left Atrial Sites (fig. 3)

Site 7

In all nine patients in whom the atria were paced from this site, the P wave was positive in leads II, III, aVF, and in 7/9, positive in lead I (fig. 3). In 2/9 the P wave was flat in lead I. The P wave was negative in aVR, aVL, and V1-3 in 9/9 (fig. 3), negative in V3 in 5/9, and negative in V4 in 1/9.

Site 8

In 4/4 in whom the atria were paced from this site, the P wave was negative in lead I and aVL, positive in leads II, III and aVF, and biphasic (+ -) (2/4) or negative (2/4) in lead aVR. The P wave was variable in the precordial leads, in 2/4 being all positive, in 1/4 all biphasic (- +), and in 1/4 flat in V3-6, diphasic (- +) in V2, positive in V1 (fig. 3).

Site 9

No significant atrial enlargement was noted in this patient at the time of surgery. With atrial pacing, the P wave was negative in leads I and aVL; flat in aVR; positive in leads II, III and aVF; and positive in all the precordial leads. A positive bifid P wave was not noted in V1.

Site 10

Left atrial size in this patient was estimated as normal at the time of surgery. With atrial pacing the P wave was positive in lead I, positive in aVR and aVL, negative in II, III, and aVF, positive in V1-3 with a bifid positive P wave in V1, and negative in V4-6.

Site 11

Left atrial size in this patient was estimated as moderate at the time of surgery. With atrial pacing the P wave was negative in lead I, positive in aVR, flat in aVL, biphasic (- +) in II, III and aVF, positive with a bifid morphology in V1-3, and negative in V4-6.

Site 12

The left atrial enlargement in this patient was estimated to be marked on fluoroscopy and moderate at the time of surgery. With atrial pacing, the P wave was negative in lead I, flat in II and aVR, positive in III and aVF, diphasic (- +) in aVL, bifid positive in V1, and flat in V2-6.

Stimulus-to-P and P-R Intervals

An isoelectric interval between the stimulus artifact and the onset of the inscription of the P wave, i.e., a stimulus-to-P (S-P) interval, always was present regardless of the atrial site paced. The S-P interval ranged from 10-54 msec. Although it is readily apparent in all the figures which demonstrate P wave polarity and morphology during the paced ectopic atrial rhythms, the S-P interval is best demonstrated in site 1 (fig. 3) where it is 54 msec. P-R intervals of 0.12 sec or less were recorded in four of nine patients paced from site 1, 2 of 11 patients paced from site 2, one of ten patients paced from site 3, two of 11 patients paced from site 4, one of 10 patients paced from site 7, and one of four patients paced from site 8. All these sites are some distance from the A-V junction, although site 1 is close to the point where the coronary sinus enters the right atrium.

Discussion

Several points are clear from this study.

1.) A positive P wave in standard lead I was produced with either right or left atrial pacing. However, a negative P wave in lead I was produced only with pacing the left atrium, and only when the pacing site was near the left pulmonary veins. These data support previous studies in the canine heart2, 23 and man9, 15, 27 which demonstrated a negative P wave in lead I during left atrial activation. They also support in part the several observations3-5, 8, 16-18 in man.
which were thought empirically to represent left atrial rhythms.

2.) A negative P wave in leads II, III and aVF could be produced from pacing either the right or left atrium, but the site of origin of atrial activation was always from an inferior site in either atrium. This supports the previous such demonstrations from more limited studies in the experimental animal and in man.³⁰

3.) The negative P wave in the precordial leads:

\[\text{Site 1} \quad \text{Site 5} \quad \text{Site 6} \]

\[\text{Site 7} \quad \text{Site 8} \quad \text{Site 9} \]

\[\text{Site 10} \quad \text{Site 11} \quad \text{Site 12} \]
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Negative P waves in the left precordial leads were produced when pacing from either left or right atrial sites, but only from inferior sites in each atrium. Negative P waves in leads V_{1,3} were recorded when pacing from both left superior and right inferior atrial sites.

4) A bifid positive P wave in lead V_1 was produced only when pacing the posterior inferior left atrium near the coronary sinus. This may be a variant of the “dome and dart” P wave described by Mirowski.20

Analysis of the Criteria for Localization of Ectopic Atrial Rhythms

A) Left Atrial Rhythms

In the light of the present and previous studies,9 8, 16-18, 20, 23, 26 examination of the criteria for left atrial rhythm one by one is in order.

1) Negative P wave in lead I: Several previous studies have demonstrated that activation of the left atrium need not produce a negative P wave in lead I.9, 11, 15, 21, 27, 42 However, as distilled from this present study, and from previous studies in man9, 16, 27 and in the canine heart,9, 23 a negative P wave in lead I has been demonstrated only when pacing the left atrium, and as we have shown in this study, only when pacing from a site near the left pulmonary veins. However, while a negative P wave in lead I may suggest an ectopic left atrial rhythm, there are other causes of a negative P wave in this lead, namely, dextrocardia,43-46 marked hypertrophy, or dilatation of the right atrium,47 A-V junctional rhythm,46, 48 and probably the most common cause, reversal of proper placement of the arm leads of the ECG recording cable.

2) Negative P waves in lead V_e: Previous studies9, 15 have demonstrated that the P wave need not be negative in V_e when the left atrium is paced. However, the present study clearly demonstrates that the P wave in fact may be negative in V_e when right atrial as well as left atrial sites are paced. There is one previously reported case in which the right atrium was paced using a transvenous electrode catheter and a negative P wave was recorded in V_e.24

3) Negative P waves in V_{4,6} or in all precordial leads: This study clearly demonstrated for the first time in man that negative P waves could be produced in V_{4,6} or in all the precordial leads when pacing from the right atrium.

4) Dome and dart P wave in lead V_1: Our study did demonstrate a positive bifid P wave in V_1 when the posterior-inferior left atrium near the coronary sinus was paced. There are previous reports of an apparent dome and dart P wave produced when the atria were paced from the right inferior pulmonary veno-atrial junction and from the central posteroinferior left atrium9 and from the left superior pulmonary vein.15 However it is clear from this and these previous studies9, 15 that a bifid positive P wave need not be present in V_1 during activation of the left atrium.

In summary, based on the present study and previous studies, it is clear that most of the proposed criteria for left atrial rhythms are unreliable.

B) Right Atrial Rhythms

In the light of present and previous studies,3, 14, 19, 23 examination of the criteria for right atrial ectopic rhythm is in order.

1) Positive P wave in lead I. Although right atrial pacing in the present study resulted in a positive P wave in lead I in 51/52 patients studied, left atrial pacing resulted in a positive P wave in lead I in 8/17 patients studied. Positive P waves in lead I also were produced during left atrial pacing utilizing the catheter technique in 6/12 patients studied by Harris and coworkers.8

2) Negative P waves in the right precordial leads. The present study demonstrated for the first time in man that negative P waves in these leads resulted when the left atrial side of Bachmann’s bundle was paced. Thus, the proposed criteria for right atrial ectopic rhythms are unreliable.

C) A-V Junctional Rhythms

Analysis of the P wave in A-V junctional rhythms in which the P wave follows the QRS complex is instructive.6, 8, 22, 26, 30, 48, 49 As emphasized by El-Sherif6 and Gonzales-Videla,8 the criteria for ectopic left atrial

Figure 3

Twelve lead ECG recorded during threshold bipolar atrial pacing from Sites 1, 5, 6, 7, 8, 9, 10, 11, and 12. Each site is mounted so that in the left column proceeding from the top are leads I, II, III, aV_{1}, aV_{2}, and aV_{3} and in the right column proceeding from the top are leads V_{1,6}. The ECG recorded when site 1 was paced also serves to illustrate how misleading the P-R interval can be. In this example, the P-R interval was 85 msec (0.085 sec), but the S-P interval was 54 msec, resulting in an interval from the stimulus artifact to the onset of the QRS complex of 139 msec. Using standard ECG analysis, some would interpret this ECG as demonstrating an “upper nodal” rhythm.44, 45 Unless one assumes that an isoelectric delay before the onset of the P wave does not occur with initiation of atrial activation by spontaneous (rather than electronic) pacemakers, the beginning of the P wave provides at best only an imprecise index of the time at which the spontaneous impulse is initiated in the atrium.
rhythm and for A-V junctional rhythms with retrograde activation of the atria are in conflict, since in the latter instance, initial atrial activation is from a point in the A-V junction. Thus, analysis of spontaneous A-V junctional rhythms provides additional evidence that most of the proposed criteria for localization of ectopic atrial rhythms are inadequate. In fact, it suggests that rhythms thought by some to represent left atrial rhythms may be initiated in the A-V junction.

The P-R Interval

If there is no reason to suspect a change in A-V transmission time, it is usually assumed in clinical electrocardiography that differences in the P-R interval reflect changes in the site of origin of the atrial impulse or, less frequently, changes in conduction time in the atrial muscle. Our findings demonstrate that differences in the P-R interval do not always provide an accurate indication of the time lapse between the initiation of the impulse in the atrium and the arrival of the impulse at the ventricles. As previously shown in the experimental animal and during open-heart surgery in man, there may be an isoelectric interval between the time of activation of the atrium and the first clear evidence of a P wave on the body surface leads. The S-P interval in man was previously reported to range from 10-25 msec but has been documented as long as 59 msec. In the present study, the S-P interval ranged from 10–54 msec. It is clear that the initial inscription of the P wave does not necessarily indicate either the anatomic site or the time of impulse initiation (fig. 3).

Spontaneous Ectopic Atrial Rhythms

The relationship of paced rhythms to spontaneous ectopic atrial rhythms remains unclear. For instance, the sequence of atrial activation which results when the atria are activated by a spontaneous ectopic pacemaker well may be different from that which results from bipolar epicardial pacing from the same ectopic site. Also the sites of origin of spontaneous pacemakers are unknown. However, six of the 12 pacing sites were selected because of their proximity to the internodal and interatrial pathways (fig. 4) because it was reasonable to suspect that these pathways might demonstrate automaticity under pathologic conditions.

As we learn about ectopic atrial rhythms, perhaps the ECG patterns which they produce will become clearer and more meaningful. However at this juncture, P wave polarity and morphology appears to have limited usefulness as guides to the site of origin of ectopic impulse formation. After careful analysis of these paced rhythms, no new criteria relating to P wave polarity and morphology have been derived for

Figure 4

Sites 7 and 9 are near the left atrial portion of the normal interatrial pathway. Site 4 is near the middle internodal pathway. Sites 3, 2, and 1 are near the posterior internodal pathway.
localization of ectopic atrial impulse formation. Only a confirmed respect for the complexity of P wave analysis can be offered.

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