

Atrial Pacing Thresholds Measured in Anesthetized Patients with the Use of an Esophageal Stethoscope Modified for Pacing

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Transesophageal atrial pacing (TAP) with the use of standard, thermistor-equipped, esophageal stethoscopes, modified for pacing by incorporation of a 4-French, bipolar TAP probe (pacing esophageal stethoscope [PES]), was evaluated in 100 adult patients under general anesthesia. A commercially available TAP pulse generator supplied 10-ms pulses with current variable between 0 and 40 mA. Pacing distances (in centimeters) were measured from the infraaortic ridge to midway between PES electrodes (1.5-cm interelectrode distance). Pacing thresholds (milliamperes) were measured at the point of a maximum-amplitude P-wave (P_{MAX}) in the bipolar esophageal electrogram and points 1 cm proximal or 1, 2, or 3 cm distal to P_{MAX} . TAP (70-100 beats per min) was used for sinus bradycardia ≤ 60 beats per min (36 patients) or atrioventricular (AV) junctional rhythm (2 patients) and blood pressure changes with TAP documented. In male patients ($n = 49$), P_{MAX} was 32.7 ± 0.3 cm (mean \pm SE) and minimum pacing threshold 5.1 ± 0.4 mA (range, 1-13 mA) at 33.6 ± 0.3 cm (range, 30-37 cm). In female patients ($n = 51$), P_{MAX} was 30.4 ± 0.4 cm and minimum pacing threshold 4.4 ± 0.4 mA (range, 2-14 mA) at 31.1 ± 0.4 cm (range, 26-40 cm). TAP produced an average 13-16 mmHg increase in systolic, diastolic, or mean arterial pressure in patients with sinus bradycardia or AV junctional rhythm. There were no subjective patient complaints (epigastric discomfort, dysphagia) that could be attributed to TAP; objective evaluation (esophagoscopy) was not performed. It is concluded that TAP is widely applicable to anesthetized adults; low TAP thresholds can be obtained by first determining P_{MAX} and positioning the PES electrode 1 cm or less distal to P_{MAX} ; and TAP can be used to increase blood pressure in patients with sinus bradycardia or AV junctional rhythm. (Key words: Complications: arrhythmias. Heart, arrhythmias: atrioventricular junctional rhythm; sinus bradycardia. Pacing: atrial; transesophageal indirect atrial.)

TRANSESOPHAGEAL CARDIAC PACING was first attempted in dogs by Zoll in 1952¹ and successfully performed in humans by Shafiroff and Linder in 1957.² Although ventricular pacing and direct-current counter-shock have been accomplished from the esophagus,^{3,4} most success has been achieved with transesophageal atrial pacing (TAP),⁵⁻¹⁷ probably because of the closer prox-

imity of the posterior left atrium (≤ 1 cm) compared with the left ventricle (≥ 2 cm) to the esophageal mucosa as the esophagus descends in the posterior mediastinum.^{4,18,19} Esophageal electrocardiography or TAP has been used for arrhythmia diagnosis,⁵⁻⁷ induction and termination of supraventricular tachyarrhythmias,⁸⁻¹³ non-invasive electrophysiologic assessment of patients with the Wolff-Parkinson-White syndrome,^{14,19} evaluation of antiarrhythmic drug efficacy,^{9,15} and stress pacing.^{16,17} Anesthesiologists have also reported using TAP to treat bradycardia in adults^{20,21} and bradycardia or tachyarrhythmias in pediatric patients.²² Additionally, Chung *et al.* have evaluated TAP thresholds in anesthetized adults.²³ None of these anesthesia studies²⁰⁻²³ used readily available, standardized equipment.

The goals of this study were to evaluate positioning of TAP probes and pacing thresholds in adult surgical patients under general anesthesia. We used a commercially available TAP pulse generator and prototype TAP probe, which was used to modify an esophageal stethoscope for TAP. Additionally, we documented changes in blood pressure if TAP was used to treat sinus bradycardia or atrioventricular (AV) junctional rhythm.

Materials and Methods

PATIENT SELECTION

With approval of our Institution and Human Research Review Committees, consenting adult (≥ 18 yr old) patients scheduled for nonemergent surgery under general endotracheal anesthesia were enrolled for study. Forty-nine men and 51 women were studied. Types of surgery included orthopedic, gynecologic, cardiac, thoracic, vascular, ophthalmic, and general surgical procedures. Pregnant patients and those with complete heart block, atrial fibrillation, esophageal disease, or abnormal esophageal anatomy were not enrolled in the study. The choice of anesthetic agents and hemodynamic monitoring techniques was left to the discretion of the attending anesthesiologist.

PACING ESOPHAGEAL STETHOSCOPE

An 18-French, thermistor-equipped esophageal stethoscope (Electromedics, Inc., Englewood, CO) was modified for TAP by insertion of a 4-French, bipolar, TAP elec-

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trode catheter (TAPCATH[™]; Arzco Medical Electronics, Inc., Vernon Hills, IL), as shown in figure 1. The TAPCATH[™] probe was approved for investigational use in humans by the Food and Drug Administration (Food and Drug Administration Investigational Device Exemption G900151).[§] The TAPCATH[™] is 105 cm long and equipped with two, 2.5-mm-wide, stainless steel electrodes spaced 1.5 cm apart. A 14-G angiocatheter was inserted into the proximal end of the stethoscope, and the TAPCATH[™], with wire stylet, was advanced to the level of the acoustic diaphragm of the stethoscope. A second 14-G angiocatheter was inserted into the most proximal diaphragmatic perforation of the esophageal stethoscope and used to "catch" the tip of the TAPCATH[™]. The TAPCATH[™] was advanced through the angiocatheter so that the electrodes were exposed at the level of the acoustic diaphragm, and the angiocatheter was removed. The distal end of the TAPCATH[™] was next tucked into the third diaphragmatic perforation, leaving the bipolar electrodes exposed at the surface of the stethoscope. Finally, the wire stylet was removed from the TAPCATH[™]. The esophageal stethoscope, so-modified for pacing (pacing esophageal stethoscope [PES]), was then ready for insertion.

DETERMINATION OF PACING THRESHOLDS

After anesthetic induction and tracheal intubation, the PES was inserted transorally into the esophagus and advanced to record a maximum-amplitude, bipolar P-wave (P_{MAX} , by visual inspection) in the esophageal electrocardiogram (ECG). The bipolar esophageal ECG was recorded by substituting the proximal and distal TAPCATH[™] electrode pins for the right arm and left leg electrode terminal inputs, respectively, and selecting the surface ECG lead II position, as shown in figure 2. The distance (in centimeters) from the infraalveolar ridge to a point midway between the bipolar TAPCATH[™] electrodes at P_{MAX} was recorded. P_{MAX} served as the reference point for later measurements of pacing distances (in centimeters) and thresholds (in milliamperes).

Pacing thresholds were determined with patients supine and an FDA-approved TAP pulse generator (model 7A; Arzco Medical Electronics, Inc., Vernon Hills, IL) powered by four 9-V batteries. Rectangular pulses lasting 10

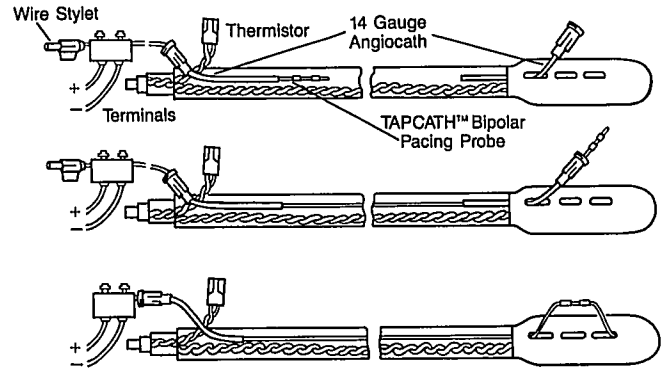


FIG. 1. Modification of a thermistor-equipped, esophageal stethoscope for transesophageal atrial pacing (TAP). *Top:* The TAPCATH[™] bipolar pacing probe is advanced into the proximal end of a 14-G angiocatheter. *Middle:* The TAPCATH[™] is advanced and "caught" at the level of the diaphragm by a second 14-G angiocatheter, which has been introduced into the first diaphragmatic, acoustic perforation. The TAPCATH[™] is then advanced through the second angiocatheter so that both electrodes are exposed. *Bottom:* The tip of the TAPCATH[™] is tucked into the third (proximal to distal) acoustic perforation under the diaphragm, and any slack is taken up by pulling back the pacing probe at the proximal end of the stethoscope. Both electrodes must be exposed between the first and third acoustic diaphragmatic perforations to record the esophageal electrocardiogram or to perform TAP.

ms were used for TAP, with current variable between 0 and 40 mA. The paced rate was set from 15 to 20% above the spontaneous rate and stimulation begun at 40 mA. Current was decreased until atrial capture was just lost and the current output value (in milliamperes) at loss of capture recorded as the threshold current for P_{MAX} .

To find the minimum pacing threshold (Th_{min}), pacing thresholds and distances were also recorded at points referenced to P_{MAX} , including 1 cm proximal ($P_{MAX} - 1$) and 1, 2, and 3 cm distal ($P_{MAX} + 1, 2, 3$). These points were selected based on previous studies that suggested that Th_{min} should be 1–2 cm distal to P_{MAX} ,^{8,10,14,24} as well as information supplied by the manufacturer (Arzco). A Th_{min} was always recorded at one or more of these points (P_{MAX} or referenced). If Th_{min} was observed at only one point, the range for Th_{min} was arbitrarily 1 cm; if at two adjacent points, the range for Th_{min} was 2 cm, and so forth. Because, in many patients, Th_{min} was observed at two or more points, the distance to Th_{min} was recorded as the average of the infraalveolar ridge-to-electrode distances to respective points of Th_{min} . Thus, if, for example, Th_{min} was 5 mA at 30 cm (P_{MAX}), 31 cm ($P_{MAX} + 1$), and 32 cm ($P_{MAX} + 2$), the range for Th_{min} would have been tabulated as 3 cm and distance to Th_{min} as 31 cm.

If patients were later turned from the supine position to the lateral decubitus or prone position, pacing thresholds were redetermined at the same point(s) at which Th_{min} had been obtained previously.

[§] The TAPCATH[™] electrode is similar to previously marketed esophageal catheters and a pill electrode (TAPSUL[™], Arzco) intended for transesophageal pacing of the left atrium and recording the esophageal ECG. Based on information supplied by Arzco (results of animal and human testing), neither TAP with currents ≤ 40 mA and pulse durations ≤ 10 ms nor transesophageal ECG cause evidence of esophageal burn injury (visible ulceration or necrosis) when use is limited to less than 4 h. Nevertheless, patients agreeing to participate in the study were informed of the possible risk of esophageal injury.

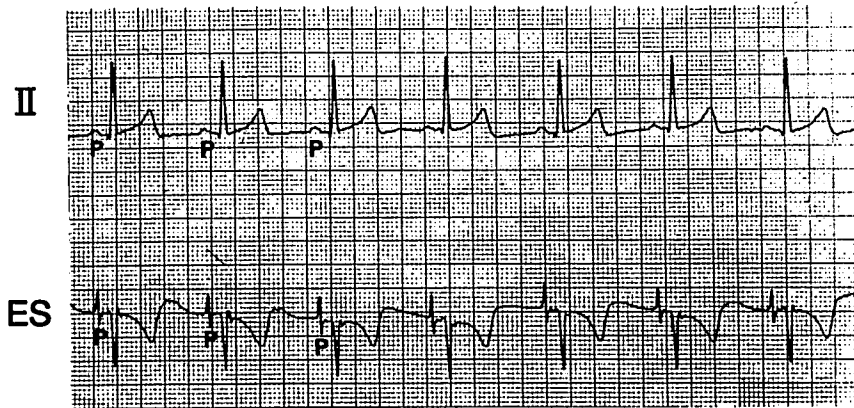


FIG. 2. Simultaneous recordings of surface ECG lead II (II) and bipolar esophageal ECG (ES) at the point of a maximum amplitude esophageal P-wave in one patient. Sinus rhythm (65 beats per min). P waves in II or ES are indicated by P for the first three complexes. Paper speed = 25 mm/s; 1 mV = 1 cm.

The PES was left at a Thmin position for the duration of anesthesia but not used for pacing unless sinus bradycardia (≤ 60 beats per min) or AV junctional rhythm developed. If pacing was used to treat sinus bradycardia or AV junctional rhythm, blood pressure changes with pacing were noted. Measurements of systolic, diastolic, and mean arterial pressure (noninvasive or direct) during spontaneous rhythm and with TAP were also included. Because three patients were also monitored with thermolulution pulmonary artery catheters, cardiac output and pulmonary artery wedge pressure were recorded before and during TAP for these patients.

DATA ANALYSIS

Unless otherwise stated, data are shown as mean \pm standard error of the mean. Paired (two-tailed) and unpaired *t* tests were used for statistical comparisons, with $P \leq 0.05$ considered significant. Simple regression was used for linear correlations, including distance to P_{MAX} or Thmin with patient height, age, or body surface area (BSA).

Results

PATIENT DEMOGRAPHICS

The average age, height, weight, and BSA and median ASA physical status for patients of this study are provided in table 1. There was no difference in age or ASA physical status between male and female patients, but height, weight, and BSA were less in women ($P < 0.05$).

PACING THRESHOLDS

Pacing thresholds (in milliamperes), distances (in centimeters), and range for Thmin (in centimeters) are provided in table 2 for supine patients, and changes in Thmin in patients with position changes are shown in table 3.

Pacing thresholds were not less in female compared with male patients, but distances to Thmin, P_{MAX} , and points referenced to P_{MAX} were less in women compared with men (table 2). The range for Thmin (approximately 2 cm) was the same in both groups of patients (table 2). Thmin was located approximately 1 cm distal to P_{MAX} in both male and female patients (table 2); changing the patient from supine to the right, but not left, lateral decubitus or prone positions increased Thmin. Finally, although there was a statistically significant linear correlation between patient height and distance to Thmin or P_{MAX} in male but not female patients, respective R values were low in both patient groups: 0.378 and 0.363 (men) and 0.250 and 0.249 (women).

PACING FOR BRADYCARDIA

Twenty-one of 49 male (43%) and 17 of 51 female patients (33%) required TAP for sinus bradycardia (36 patients) or AV junctional rhythm (2 female patients). Blood pressure changes with TAP compared with spontaneous rhythm are shown in table 4 and indicate that an average 13–16-mmHg increase in systolic, diastolic, or mean arterial pressure can be expected with pacing. The effect of TAP rate changes on blood pressure was not tested. In three patients with sinus bradycardia and pulmonary artery catheters, hemodynamic changes with TAP

TABLE 1. Patient Demographics

| | Men | Women |
|-----------------------|-----------------|------------------|
| n | 49 | 51 |
| Age (yr) | 42 \pm 3 | 48 \pm 3 |
| Height (cm) | 180 \pm 1 | 163 \pm 1* |
| Weight (kg) | 83.3 \pm 1.9 | 67.0 \pm 2.1* |
| BSA (m ²) | 2.02 \pm 0.03 | 1.71 \pm 0.03* |
| ASA | 2 | 2 |

BSA = body surface area; ASA = median ASA physical status.
* $P \leq 0.05$.

TABLE 2. Pacing Thresholds, Distances, and Range for Th_{min} in Men and Women Patients

| | | Th _{min} | P _{max} | P _{max-1} | P _{max+1} | P _{max+2} | P _{max+3} | Range |
|-------------------|----------------|-------------------|------------------|--------------------|--------------------|--------------------|--------------------|-----------|
| Men (n = 49) | Threshold (mA) | 5.1 ± 0.4 | 7.8 ± 0.7 | 13.1 ± 1.3 | 6.6 ± 0.4 | 8.8 ± 0.8 | 13.0 ± 1.4 | — |
| | Distance (cm) | 33.6 ± 0.3 | 32.7 ± 0.3 | 31.7 ± 0.3 | 33.7 ± 0.3 | 34.7 ± 0.3 | 35.7 ± 0.3 | 1.7 ± 0.1 |
| Women (n = 51) | Threshold (mA) | 4.4 ± 0.4 | 7.1 ± 0.9 | 11.6 ± 1.5 | 5.7 ± 0.6 | 8.2 ± 0.9 | 13.7 ± 1.3 | — |
| | Distance (cm) | 31.1 ± 0.4* | 30.4 ± 0.4* | 29.4 ± 0.4* | 31.4 ± 0.4* | 32.2 ± 0.4* | 33.3 ± 0.4* | 1.7 ± 0.1 |

Values are mean ± SE.

* P < 0.05 versus men.

are listed in table 5. All three patients showed improvement in cardiac output. Finally, the ASA physical status of patients who underwent TAP for bradycardia or AV junctional rhythm (ASA physical status 2) was not different from that of patients without these rhythm disturbances.

Discussion

The transesophageal atrial pacing thresholds we observed were similar to those obtained by Chung *et al.* (4.6–9.3 mA).²³ Chung *et al.* used a bipolar, transvenous pacing lead with an interelectrode distance of 2.9 cm (compared with our 1.5 cm), and their distance to site of minimum pacing threshold (36 ± 2 cm [standard deviation], 11 patients) was somewhat greater than the average distances (men, 34 cm; women, 31 cm) in our patients. These discrepancies might be explained by differences in interelectrode distance, proximal reference point for measurements, distinction as to sex of patients, and numbers of patients between the two studies. Finally, TAP thresholds in our study and that of Chung *et al.* are considerably less than TAP stimulation parameters for thresholds previously reported for adult patients. Backofen *et al.* (37 patients) used pulse widths of 20 ms and currents of 25 mA (interelectrode distance not specified),²⁰ and Buchanan *et al.* (11 patients) found TAP current thresholds of 18 mA for a pulse width of 10 ms.²¹

At least in theory, minimizing TAP thresholds should reduce the risk of esophageal damage with protracted use of TAP. We did not perform endoscopy to evaluate our patients for evidence of esophageal injury, and there were no subjective patient complaints (*e.g.*, epigastric discomfort or dysphagia). Continuous TAP has been performed for as long as 60 h without evidence of esophageal injury,²⁵

and two recent reviews did not mention thermal, electrical, or other injury to the esophagus as a direct consequence of TAP.^{18,19} Nevertheless, until more complete data are available, if extended durations (>3–4 h) of pacing are anticipated, one should consider alternative routes for pacing, including transvenous pacing.

Factors that have been evaluated for minimizing pacing thresholds include stimulus duration, stimulation site, and interelectrode distance.¹⁸ These are considered below.

STIMULUS DURATION

Gallagher *et al.* found that pulse widths between 5 and 10 ms minimized current requirements.⁸ This range was confirmed for anesthetized patients in the subsequent study by Chung *et al.*²³ Benson remarked that pulse widths exceeding 10 ms should have little effect on reducing TAP thresholds in most patients.¹⁸ Exceptions might be those patients in whom TAP thresholds exceed 14 mA for a pulse width of 10 ms.²⁶ In that case, pulse widths of 15 or 20 ms could reduce TAP thresholds substantially.²⁶

STIMULATION SITE

Several studies have suggested that the site of minimum TAP thresholds could be located by finding the site of the maximum-deflection P-wave in the esophageal ECG.^{8,10,14,24} This might be a unipolar or bipolar esophageal ECG, because P-wave amplitudes correlate well with

TABLE 3. Pacing Thresholds at Th_{min} after Position Changes in Men or Women Patients

| Position | n | Pacing Thresholds (mA) | |
|----------|---|------------------------|--------------|
| | | Supine | New Position |
| RLD | 4 | 6.3 ± 1.4 | 9.0 ± 2.0 |
| LLD | 2 | 5.0 ± 2.0 | 5.0 ± 2.0 |
| Prone | 1 | 5.0 | 33.0 |

RLD = right lateral decubitus; LLD = left lateral decubitus.

TABLE 4. Effects of TAP on Blood Pressure in Patients with Sinus Bradycardia or AV Junctional Rhythm

| | Men (n = 21) | | | |
|------------|----------------|---------|---------|---------|
| | SBP | DBP | MBP | Rate |
| Before TAP | 102 ± 5 | 56 ± 3 | 74 ± 4 | 53 ± 1 |
| After TAP | 118 ± 5* | 69 ± 4* | 88 ± 4* | 85 ± 2* |
| | Women (n = 19) | | | |
| | SBP | DBP | MBP | Rate |
| Before TAP | 100 ± 4 | 58 ± 3 | 73 ± 3 | 57 ± 2 |
| After TAP | 115 ± 4* | 71 ± 3* | 88 ± 3* | 80 ± 1* |

SBP, DBP, MBP = systolic, diastolic, and mean arterial pressures (mmHg), respectively. Rate = heart rate (beats per min).

* P < 0.05 versus before.

TABLE 5. Cardiac Output and Pulmonary Artery Wedge Pressure before and after TAP in Three Men Patients with Sinus Bradycardia

| Patient | Before TAP | | After TAP | |
|----------------|---------------|--------------|---------------|--------------|
| | CO | PWP | CO | PWP |
| 1 | 4.8 | 13 | 7.3 | 17 |
| 2 | 3.6 | 8 | 4.5 | 9 |
| 3 | 3.5 | 12 | 4.9 | 10 |
| Mean \pm SEM | 4.0 \pm 0.4 | 11 \pm 1.5 | 5.6 \pm 0.9 | 12 \pm 2.5 |

the two techniques.²⁶ In available studies of anesthetized patients, Backofen *et al.* did not examine the relation between maximum P-wave amplitude and minimum pacing threshold.²⁰ Buchanan *et al.* also did not examine it, although they inserted their cardioesophagoscope to a depth determined by the greatest P-wave deflection.²¹ Chung *et al.* used surface landmarks to initially position the TAP electrode, which was then withdrawn by 1-cm increments until a minimum pacing threshold was obtained.²³ None of the foregoing studies in anesthetized patients provide a reproducible and convenient way to locate the site of minimum TAP thresholds. Our study, in agreement with findings in nonanesthetized patients, suggests that minimum pacing thresholds can be obtained 1 cm or less distal to P_{MAX}.

INTERELECTRODE DISTANCE

An esophageal pacing probe with sliding electrodes (1–8-cm spacing) was used by Gallagher *et al.* to evaluate the effect of interelectrode distance on TAP thresholds.⁸ In seven patients, the threshold current for 10-ms pulse widths was slightly lower for interelectrode spacing of 3 cm. Benson *et al.* concluded that, for interelectrode spacing of 1.5–2.8 cm, interelectrode distance was not a critical factor for minimizing pacing thresholds.²⁶ Nishimura *et al.* found that TAP thresholds were lowest for interelectrode spacing of 2.4 cm.²⁴ Neither we nor others who have reported TAP thresholds for anesthetized patients have determined the effect of interelectrode distance on minimizing TAP thresholds.^{21–23} Nevertheless, our results and those of Chung *et al.*²³ suggest that TAP thresholds for a stimulus duration of 10 ms are lowest and nearly the same for interelectrode distances between 1.3 and 2.9 cm. Much higher (approximately threefold) TAP thresholds can be expected with 10-cm interelectrode spacing.²¹

We found that TAP thresholds increased when patients were turned from the supine to prone or right (not left) lateral decubitus positions. To our knowledge, the effect of position changes on TAP thresholds has not been examined previously. More detailed knowledge of this might be of interest to anesthesiologists who contemplate using TAP for intraoperative management of bradycardia and

supraventricular tachyarrhythmias amenable to pacing therapy.^{8–13} The distance between the left atrium and esophagus is said to be less than 1 cm in supine adults.^{27,28} Based on inspection of anatomic drawings depicting relations between the posterior wall of the heart and esophagus,^{19,29} we surmise that this distance would increase least in the left lateral decubitus compared with other, non-supine positions.

There was a surprising high overall incidence of sinus bradycardia or AV junctional rhythm in our patients; comparable data are not available.³⁰ TAP produced substantial hemodynamic improvement in our patients, with increases in blood pressure similar to those previously reported with TAP for bradycardia in anesthetized patients having cardiovascular surgery.^{20,21} Additional studies are required to compare TAP with existing methods for treating bradycardia, including drugs and noninvasive transcatheter ventricular pacing.³¹ We believe that TAP might be preferable to the latter for treating hemodynamically deleterious bradycardia in patients with intact atrioventricular conduction and not in atrial fibrillation, because TAP preserves atrial transport function. Preserved atrial contraction should be most critical in patients with impaired ventricular relaxation.^{32–34}

In conclusion, TAP appears widely applicable in anesthetized, adult surgical patients. It can be established easily with acceptably low pacing thresholds if pacing electrodes are positioned 1 cm or less distal to the maximum-amplitude P-wave in the esophageal ECG. Finally, TAP can be expected to improve hemodynamics in patients with sinus bradycardia or AV junctional rhythm.

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