Cryosurgical Ablation of Accessory Atrioventricular Connections

A Method for Correction of the Pre-excitation Syndrome

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SUMMARY Cryothermia, a new technique for definitive treatment of the pre-excitation syndrome, is described in two patients. The first patient presented with a normal P-R interval with a delta wave and reciprocating tachycardia. Preoperative electrophysiologic study suggested a free-wall atrioventricular connection on the left posterior atrioventricular (A-V) groove. At surgery, epicardial mapping confirmed the site of pre-excitation on the posterior left ventricular (LV) wall. An electrogram arising from the accessory pathway (AP) was recorded at the site of earliest ventricular activation. Interventricular delay combined with an apparently long accessory pathway to the ventricle caused the P-R interval to appear normal.

Local pressure abolished pre-excitation. The site of early ventricular activation was cooled to −60°C with a specially designed cryoprobe. All evidence of pre-excitation and arrhythmias disappeared.

The second patient presented with a refractory reciprocating tachycardia and was found to have an AP in the septum capable of only retrograde conduction. Retrograde conduction was abolished by applying a temperature of 0°C to the annulus at this site during tachycardia. Conduction over the AP and reciprocating tachycardia returned with rewarming. Ablation of the AP was obtained by applying a temperature of −60°C for 90 seconds on two occasions to the same area. The His bundle was not injured.

SURGICAL INTERRUPTION of the accessory pathway underlying the pre-excitation syndrome is now an accepted mode of therapy for patients with life-threatening or disabling symptoms.1−3 In this report we describe a new mode of ablating pre-excitation utilizing local cryothermia. The method was applied successfully in two unique patients: one with an epicardial accessory pathway associated with a variant form of pre-excitation (normal P-R interval, delta wave, and reciprocating tachycardia) and one with a septal accessory pathway, adjacent to the His bundle, capable of only retrograde conduction. This technique permits induction of a reversible block at 0°C before an irreversible lesion at −60°C is created.

Methods

Clinical Studies

According to methods previously described,1−4, 6 pacing and measurement of refractory periods were performed from the right atrium, right ventricle, atrial or coronary sinus, and right ventricle. Heparin, 100 units/kg, was administered after introduction of all catheters. Sequences of retrograde atrial activation were recorded during induced or spontaneous reciprocating tachycardia (RT) and during ventricular pacing.6 The ventriculo-atrial (V-A) conduction intervals were measured from a constant reference (onset of ventricular activation) to the local bipolar electrogram recorded at any given atrial site. Exploration of right atrial and septal activation during these sequences was accomplished by a special 7F mapping electrode catheter developed in our laboratory. This consisted of a luminal catheter* with two electrodes mounted 2 mm apart at the tip, through which a blunt trocar could be introduced. The trocar was curved at the tip, similar to a Brockenbrough needle, permitting control of the position of the exploring electrodes within the right atrium.6−8 When any doubt existed as to the position of this catheter, contrast was injected through the catheter under fluoroscopic control.

Intracavitary electrograms were obtained by filtering out frequencies below 50 Hz and above 1 kHz. Simultaneous recordings of these electrograms and surface electrocardiographic leads were recorded on magnetic tape at a speed of 3 3/4 inches/sec. Refractory periods were determined using a stimulator† utilizing photoelectric isolation. Stimuli were delivered at pulses of 2 msec duration and twice diastolic threshold. A sensing circuit of the same stimulator allowed introduction of programmed premature beats into the right ventricle during reciprocating tachycardia.6−7 All stimulated events could be monitored on an oscilloscope triggered by a stimulator. Graphic records were also obtained on-line by a Mingograf 800 eight channel ink jet recorder at a paper speed of 200 mm/sec. A 10 msec time code was generated with the data during all recording.

Intraoperative Studies

Epicardial and intracardiac mapping was performed utilizing methods previously described.1−4 Briefly, unipolar and bipolar electrograms were recorded from 60 to 100 epicardial and intracavitary sites using a hand-held mapping probe with two electrodes separated by 1 mm. Standard surface electrocardiographic leads with a reference epicardial lead and the data from the probe were channeled by field

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†Designed by Michael Feezor, Ph.D., and built by Philip Talbert.
The Cryoprobe

The instrument† and methodology employed in this work are identical to that described in an accompanying article by our laboratory for use in ablating the His bundle. The bipolar recordings from the reference and data electrodes were used to trigger a special digital timer which allowed on-line display of activation times on a beat-to-beat basis relative to the reference.*

Effect amplifiers (input impedance $10^{12}$ ohms) to a set of high gain differential amplifiers. The overall frequency response of the system was 0.1–1200 Hz. A Hewlett-Packard 7 channel magnetic tape recorder was used to record all data at 3/4 to 7 1/2 inches/sec. The data were displayed on a Hewlett-Packard storage oscilloscope and could also be written out on a Honeywell 2106 ultraviolet oscillograph. The bipolar recordings from the reference and data electrodes were used to trigger a special digital timer which allowed on-line display of activation times on a beat-to-beat basis relative to the reference.*

Figure 1. Electrocardiogram in sinus rhythm (patient 1). The P-R interval is normal. $Q$ waves are present in leads II-III and $aV_1$.

Results

Case Report 1

The patient was a 25-year-old man admitted with a 2 1/2 year history of palpitations. Attacks had occurred 2 to 3 times per week and lasted from minutes to days, accompanied by dyspnea, diaphoresis, nausea, and chest pain. Syncope occurred on three occasions, resulting in 2 to 3 minute periods of unconsciousness. When attacks persisted despite therapy with propranolol 500 mg p.o. every 6 hours and propranolol 40 mg p.o. every 6 hours, he was referred for further evaluation. His clinical and laboratory exams were unremarkable except for his abnormal electrocardiogram.

Figure 2. Panel A) Electrocardiogram during reciprocating tachycardia. The previously noted $Q$ waves have disappeared. Panel B) Catheter map of retrograde atrial activation during reciprocating tachycardia. The ventriculo-atrial intervals are shown plotted on a cross-section of the heart at the level of the atroventricular groove. Earliest retrograde activity is initiated in the posterior left atrium.
FIGURE 3. Electrocardiogram during coronary sinus pacing. During pacing at a cycle length of 400 msec, pre-excitation becomes marked. The stimulus to delta interval remains long at 0.14 sec.

On May 31, 1976, after all drug regimens had been stopped, the patient underwent electrophysiologic study. During normal sinus rhythm his electrocardiogram (fig. 1) showed a P-R interval of 0.14 sec, QRS duration of 0.12 sec, and Q wave of 0.04 sec duration in leads II, III, and aV_{P}.

Reciprocating tachycardia (cycle length 355 msec) was readily induced with premature depolarizations of the atria or ventricle and was associated with a normal QRS complex (fig. 2, panel A). The His bundle electrogram recorded during tachycardia showed an A-H interval of 135 msec, an H-V interval of 45 msec, and a V-A interval of 175 msec.

Earliest retrograde atrial activation was recorded in the midcoronary sinus overlying the posterior left atrium (fig. 2, panel B). The appearance of left bundle branch block aberration during tachycardia resulted in a 30 msec prolongation of all ventriculo-atrial conduction intervals. No such change was observed with right bundle branch block aberration. This suggested that the accessory pathway was located in the left free-wall atrioventricular groove.

During atrial pacing, the A-H interval became progressively longer, resulting in increased pre-excitation and displacement of the His potential into the ventricular complex. The stimulus-delta interval was shortest and the degree of pre-excitation greatest when pacing the coronary sinus (CS) (fig. 3). One-to-one atrioventricular conduction over the accessory pathway was present during CS pacing until the cycle length fell below 280 msec; with right ventricular pacing, retrograde conduction was present with eccentric atrial activation until a cycle length of 220 msec was reached.

The patient was treated with quinidine, 300 mg every 6 hours (serum level = 2.9 mg/L), but this dosage caused diarrhea and episodes of reciprocating tachycardia continued. He was taken to the operating room on June 10, 1976. Following a median sternotomy and exposure of the heart, epicardial mapping was performed. During sinus rhythm (fig. 4) pre-excitation was found on the lateral free wall of the posterior left ventricle adjacent to a small branch of the circumflex at the level of the A-V ring. Atrial mapping showed origin of atrial activation in the region of the sinus node.

FIGURE 4. Epicardial mapping of a patient with a variant form of pre-excitation. During sinus rhythm, posterior left ventricular pre-excitation is present. Fusion is manifest by the epicardial breakthrough over the low anterior right ventricle. The atrial and ventricular data are related to the onset of the delta wave (0 time).
node with arrival at the atrial site contiguous to the site of ventricular pre-excitation occurring 90 msec later (P-A = 90 msec) (fig. 5, panel A).

An unusual electrogram was recorded at the site of ventricular pre-excitation. We believe this represents activation of the accessory pathway (AP). The interval from local atrial activation to the onset of the AP electrogram was 22 msec (fig. 5, panel B) (A-AP = 22 msec), and to the rapid component was 28 msec. The interval from the AP electrogram to the onset of the delta wave and earliest ventricular activation was 38 msec (AP-V = 38 msec) when the probe was placed immediately below the A-V groove. However, the AP electrogram could be recorded a full 1 cm distal to the A-V ring, a site that was unquestionably on the ventricle. As the probe was moved from the A-V ring toward the apex, the interval from the AP to the ventricular electrograms gradually shortened until the two merged approximately 1 cm distal to the A-V ring (fig. 5, panel C). The AP electrogram could be recorded only in an area within 2 mm on each side along the course of the pathway. Detailed measurements along this apparent course of the accessory pathway showed a delay of 30 msec occurring over a distance of 10 mm, suggesting a conduction velocity of 0.3 m/sec. The AP electrogram had an amplitude of 2.3-4 mV compared to ventricular complexes of 20-40 mV. It is unlikely that this electrogram represents atrial depolarization since it (1) occurred after inscription of the P wave and later than all contiguous atrial sites; (2) was recorded on the ventricle below the A-V groove, merging distally with the local ventricular electrogram; and (3) could no longer be recorded after freezing the site of ventricular pre-excitation.

The left ventricle was then paced at a cycle length of 550 msec, and the retrograde atrial activation sequence recorded. Earliest activation occurred on the posterior left atrium. The ventricular site where earliest antegrade pre-excitation had been noted was explored during ventricular

**Figure 5.** Epicardial recordings from the area of pre-excitation. Tracings in panels A-C are, from above down, ECG leads I-III, a ventricular reference and bipolar and unipolar recordings from the mapping probe. In panel A, the probe is placed over the atrium contiguous to the site of ventricular pre-excitation, and records an atrial electrogram (A). In panel B, the probe is on the ventricle and records an electrogram thought to arise in the accessory pathway (AP). In panel C, the probe has been moved 1 cm distal to the A-V ring. The previously noted electrogram (AP) merges with the ventricular electrogram. A 10 mV calibration signal is shown to standardize all the unipolar recordings.
pacing and an electrogram thought to arise in the accessory pathway was recorded (fig. 6). This deflection occurred during ventricular depolarization and thus the designation of a retrograde AP deflection cannot be made with certainty. No similar deflection, however, could be recorded at any other ventricular site, and the deflection disappeared after production of the lesion described below. Assuming the deflection resulted from depolarization of the AP, the events underlying retrograde conduction can be roughly quantitated. Local ventricular activation occurred +110 msec after the stimulus (delivered near the apex), followed by the AP electrogram at +135 msec; the contiguous atrial point activated at +170 msec. Thus, the ventriculo-atrial conduction time at this site of the A-V ring was 60 msec and composed of a V-AP interval of 25 msec and an AP-A interval of 35 msec.

Local pressure in the region of the AP electrogram during antegrade excitation caused the QRS complex to become normal. It was impossible therefore to determine the effect of cooling to 0°C since the slightest pressure of the probe would normalize the QRS. Therefore, the probe was immediately cooled to −60°C in this area for 90 sec. The diameter of this lesion was 7 to 8 mm. A contiguous area along the course of the AP electrogram was also cooled to −60°C for 90 seconds, producing a lesion 1.5 cm in length. During this time, cardiopulmonary bypass was initiated to allow manipulation of the heart and to reduce the amount of blood in the left ventricle so that a deeper lesion might be obtained. The left side of the heart, however, was never opened. After freezing, the AP electrogram could no longer be recorded. Pre-excitation was gone and no arrhythmias could be provoked. Repeat epicardial mapping during left atrial pacing showed a normal sequence of ventricular activation (fig. 7, panel A). Ventricular pacing resulted in ventriculoatrial dissociation at paced cycle lengths of 700–300 msec.

The patient recovered without complications and was completely restudied nine days postoperatively. At this time, there was no evidence of antegrade or retrograde pre-excitation and no arrhythmias could be induced. His electrocardiogram during coronary sinus pacing (fig. 7, panel B) showed a normal morphology identical to that observed preoperatively during reciprocating tachycardia. He has remained asymptomatic.

**Figure 6.** Retrograde mapping during ventricular pacing. The left ventricle is being paced at a cycle length of 350 msec. In panel A, the mapping probe is situated on the ventricle over the area of earliest pre-excitation. An electrogram arising from retrograde conduction over the AP is recorded. In panel B, the probe has been moved to the contiguous atrium (A).
A 23-year-old female was admitted for evaluation of intermittent paroxysmal atrial tachycardia. Tachycardias began at age 15. Previous regimens included quinidine 400 mg every 6 hours (serum level = 2.9 mg/L), propranolol 120 mg every 6 hours, and digoxin 0.375 mg daily (serum level = 1.0 ng/ml) administered alone or in combination. Attempts to further increase dosage of these medications resulted in untoward side effects. Tachycardias continued with increasing frequency and DC cardioversion was required on a number of occasions. Two weeks prior to admission, tachycardia resulted in pulmonary edema before it could be terminated with direct current cardioversion using 400 W-sec. Physical exam was unremarkable except for obesity. Her electrocardiogram during sinus rhythm showed a P-R interval of 0.14 sec. Left axis deviation was present. The QRS duration was 0.12 sec and was identical in morphology to that observed during reciprocating tachycardia (fig. 8).

On June 15, 1976, the patient underwent electrophysiologic study. No pre-excitation could be elicited with pacing of the right atrium or left atrium (via coronary sinus). One-to-one A-V conduction via the A-V node continued until the cycle length fell below 260 msec. The A-H interval increased from 60 msec to a maximum of 90 msec, suggesting

**Figure 7.** Panel A) Normal epicardial map following cryoablation of the accessory pathway. The map was obtained during left atrial pacing at cycle length 450 msec. The ventricular data are referenced to the onset of the QRS. Panel B) Postoperative electrocardiogram during coronary sinus pacing. This normal tracing was obtained during restudy 9 days postoperative while pacing at cycle length 400 msec.

**Figure 8.** Patient 2. Electrocardiogram during reciprocating tachycardia.
enhanced A-V node conduction. The differential diagnoses were reciprocating tachycardia due to re-entry in the A-V node or re-entry utilizing an accessory atrioventricular connection capable of only retrograde conduction. Premature right ventricular depolarizations were therefore introduced during reciprocating tachycardia. A premature ventricular depolarization was programmed to occur 10 msec before the His bundle deflection. The H-H interval remained constant, but the subsequent atrial cycle length was shortened 30 msec (fig. 9). Since the His bundle was refractory at this time, the premature beat must have traveled up an accessory pathway with conduction properties independent of the normal conducting system. The area of earliest atrial activation, during tachycardia as well as premature ventricular beats during tachycardia, was the atrial septum. During mapping of the atrial septum during cardiac catheterization, tachycardia suddenly stopped. No ventriculo-atrial conduction or ability to induce tachycardia was present for several hours, presumably due to trauma to the accessory pathway.

On July 2, 1976, she was taken to the operating room where exposure of the heart was accomplished following median sternotomy. Atrial mapping was performed during reciprocating tachycardia (fig. 10, panel A) and during RV pacing (fig. 10, panel B) first externally, and later by intracavitary recording when the patient was on cardiopulmonary bypass. Both techniques established that the site of earliest retrograde atrial activity was on the anterior limit of the membranous septum, 5 mm (or one probe diameter) from the recorded His bundle deflection. Epicardial mapping of the ventricle during reciprocating tachycardia in sinus rhythm demonstrated an activation sequence compatible with a nonspecific intraventricular conduction defect.

Sustained reciprocating tachycardia was difficult to maintain during cardiopulmonary bypass. Therefore, the right ventricle was continually paced at a cycle length of 400 msec and an atrial reference electrode monitored. When cooling (0°C) was applied to the site of earliest retrograde atrial activity (fig. 11), V-A dissociation appeared. One-to-one V-A conduction was established after rewarming. This same area was then frozen to −60°C for 90 seconds two times. The diameter of the lesion was approximately 1 cm. Subsequently, during ventricular pacing, retrograde conduction to the atria was impossible and no reciprocating tachycardia could be induced. Antegrade conduction remained intact.

The patient’s postoperative course was unremarkable. Retrograde conduction continued to be absent on a restudy nine days postoperative, and the patient has remained free of arrhythmia in follow-up evaluations.

**Discussion**

The presence of delta waves with normal P-R intervals has been previously described. One group has postulated Mahaim tracts arising from the His bundle and entering the

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**FIGURE 9.** Validation of the presence of an accessory atrioventricular pathway participating in tachycardia.

**FIGURE 10.** Intraoperative map of retrograde atrial activation. Ventriculo-atrial conduction intervals recorded by epicardial and intracavitary mapping during reciprocating tachycardia (panel A) and right ventricular pacing (panel B). The circle labeled His bundle indicates the location of the recorded His deflection on the membranous septum. The circle labeled CRYOPROBE indicates the location where cooling was applied.
ventricular septum as an explanation. Rosen reported a case based on His bundle recordings in which he suggested that slow Kent bundle conduction was present. Patient 1 in this paper is the first reported case based on detailed catheter and epicardial mapping. Our findings suggest that interatrial conduction delay and conduction time over a long accessory pathway is another possible underlying mechanism for pre-excitation with normal P-R intervals. This case also demonstrates how pre-excitation can mimic old diaphragmatic infarction by producing Q waves in the inferior leads.

The direct recording of the accessory pathway has been infrequently noted in mapping of patients with pre-excitation. The recordings obtained in patient 1 conclusively demonstrated that recording of such pathways is possible. In most instances, the accessory pathways may be too deep or embedded in fat, preventing its recording from a surface probe. In some instances, it may be merged with the ventricular electrogram.

The same considerations suggest limitations in the cryoablation technique. If the accessory pathway is located close to a coronary artery, cryoablation may be inadvisable. The pathway must be superficial enough that the freezing lesion can be made within it at a sufficiently low temperature and thereby avoid the warming effect of intracavitary blood.

Previously reported efforts to approach accessory pathways bridging the left or right A-V grooves have required dissection of the atrium immediately above the involved anulus. Even with this technique epicardial pathways can be missed. External dissections are hampered by the risk of lacerating coronary arterial and venous structures. Cryoablation will allow, in selected cases, ablation of accessory pathways without necessarily instituting cardiopulmonary bypass.

We have previously reported difficulty in successfully dividing septal accessory pathways because there is always the danger that the normal conduction system, valvular structures, or the septum itself may be injured. The initial lesions produced by cryoa blation are reversible. The permanent lesions induced by irreversible freezing are homogeneous and well demarcated; they have no tendency to rupture, form aneurysms, or promote intracardiac thrombosis. In addition, vascular elements, collagen, and fibroblasts are resistant to hypothermal injury.

The use of local cryothermia to produce reversible lesions appears to be a useful adjunct to the surgical approach to ablation of accessory pathways. Ablation of other sites of arrhythmia (ectopic foci, re-entry circuits) may also become uses of this method.

Addendum

Since the preparation of this manuscript, the technique has been applied successfully in three further patients. The first had a true septal pathway ablated during complete cardiopulmonary bypass. The second was a 9-month-old infant with a ventricular septal defect and pre-excitation of the posterior RV free wall. External ablation was used during partial bypass. The last patient had pre-excitation over the posterior crux mimicking a true septal pathway. Ablation was accomplished externally with no cardiopulmonary bypass. Accessory pathway electrograms were recorded in the latter two patients.

References

Pre and Postoperative Ventricular Function in Infants and Children with Right Ventricular Volume Overload

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SUMMARY Hemodynamic and ventricular volume parameters were evaluated in 21 patients (24 studies) with total anomalous pulmonary venous return (TAPVR), 11 patients with secundum atrial septal defect (ASD), and eight patients who had complete correction of TAPVR or ASD. Right and left ventricular (RV and LV) volume parameters were calculated according to Simpson's rule and the area length methods, respectively.

In infants with TAPVR, RV end-diastolic volume was larger than normal, but RV ejection fraction was significantly less than normal.

LV end-diastolic volume and LV ejection fraction were all less than normal in infants with or without pulmonary hypertension, and the values did not correlate with the cardiorespiratory symptoms. In children with TAPVR or ASD, RV end-diastolic volume and output were higher than normal preoperatively and decreased to normal or near normal values postoperatively. The data suggest that pulmonary venous obstruction and/or RV failure are responsible for cardiorespiratory symptoms in infants with TAPVR and early surgical intervention is recommended in these patients.

INFANTS who present in the first week of life because of total anomalous pulmonary venous return (TAPVR) usually have respiratory distress and/or congestive heart failure. This could be related to the pulmonary venous obstruction observed in many of these infants, or to low left ventricular output associated with an interatrial restriction, or to right heart failure. In older infants, congestive heart failure is seen in the absence of cineangiographic evidence of pulmonary venous obstruction. Rarely, infants with ASD and a large left-to-right shunt develop congestive heart failure as well. However, congestive heart failure is rarely observed in older children with either TAPVR or ASD and is not observed in adults until the third decade and thereafter.

Previous work has shown that LVEDV and LV output were both normal or decreased in patients with ASD or TAPVR, but RVEDV and RV output were increased. These studies, however, did not delineate the relationship between the cardiorespiratory symptoms and the volume characteristics of both the left and right ventricles, nor did it describe the effect of corrective surgery on ventricular function. The purpose of this study, therefore, was 1) to determine the etiology of congestive heart failure and/or respiratory symptoms in infants and children with these lesions: is it a low left ventricular output or high output right ventricular failure? 2) to quantify ventricular volume characteristics after complete correction of total anomalous pulmonary venous return or atrial septal defect with large left-to-right shunt.

Methods

Patient Population

Hemodynamic and volume data were analyzed in 43 studies of 38 patients with cardiac defects which predispose the patient to right ventricular volume overload. These patients were divided into three groups according to the diagnosis. Group I consisted of 24 studies in 21 patients with TAPVR. In these patients, pulmonary venous flow returned to the vertical vein in 18 patients, the coronary sinus in two, and the portal vein in one patient. Right and left ventricular
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