Electrophysiology of ventricular inversion¹

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Electrophysiological studies were carried out in 7 subjects with angiographically proven ventricular inversion in order to determine if this technique could be used in the study of arrhythmias in such subjects. Three subjects with normal PR intervals on the electrocardiogram had normal low right atrium to His (LRA-H) and His to ventricle (HV) intervals at rest. With atrial pacing, 1 of these 3 with normal PR interval developed Mobitz II second-degree atrioventricular block. Of 2 subjects with first-degree atrioventricular block 1 was found to have prolonged LRA-H and HV intervals, and the other had only LRA-H prolongation. In both subjects with complete atrioventricular block, the block was below the His bundle recording site. One of these patients with complete AV block was found to be able to conduct through his AV conducting system during the supernormal period. This study found that useful information can be obtained by recording the His bundle potential in patients with ventricular inversion. Conduction abnormalities were found from the AV node through the His-Purkinje system. This technique may be useful in making clinical decisions in patients with ventricular inversion and complex arrhythmias.

Ventricular inversion with a laevo-transposition of the great arteries usually occurs with one or more intracardiac anomalies and in 30 to 60 per cent of the cases, an atrioventricular conduction disturbance is present at birth or develops later (Walker *et al.*, 1958). Complete atrioventricular block, one of the frequent arrhythmias (Walker *et al.*, 1958), may be a major factor in the morbidity and mortality in these patients, sometimes necessitating an artificial pacemaker. In evaluation of patients with atrioventricular conduction disturbances from several causes, the bundle of His electrogram has proved to be a helpful new technique (Scherlag *et al.*, 1969; Brodsky *et al.*, 1971; Damato *et al.*, 1969; Roberts and Olley, 1972). Since the arrhythmias of patients with ventricular inversion are frequently complex, it seems likely that recordings of His bundle potentials would be helpful in their management. However, there is a theoretical difficulty in recording and interpreting the His bundle electrogram in patients with ventricular inversion because of inversion of the conduction

system as well as other anomalies in the structure and course of the AV node, His bundle, and bundle-branches (Lev, Licata, and May, 1963; Hudson, 1970). Wolff, Freed, and Ellison (1973) have reported success in only 2 of 8 patients with ventricular inversion in whom they attempted to record His bundle electrograms.

The purpose of this study was to evaluate the technique of His bundle recording in the study of atrioventricular conduction in patients with ventricular inversion in sinus rhythm as well as with partial and complete AV block.

Subjects and methods

The His bundle potential was recorded in 7 patients with ventricular inversion during diagnostic cardiac catheterization, using the percutaneous sheath femoral vein approach. The patients were sedated with meperidine, promethazine, and chlorpromazine. None was receiving digitalis or other cardioactive medications. Bi- and tripolar electrode catheters were used with inter-electrode distances of either 2 or 10 mm. The technique was the same as that used in subjects with non-inverted ventricles. The tip of the catheter was positioned in the apex of the right-sided morphological left ventricle and withdrawn with clockwise rotation (Narula *et al.*, 1971). During this withdrawal several potentials could be sequentially recorded between the low right atrium and

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ventricle potentials. As the catheter was withdrawn, the middle potential became closer to the low right atrium potential. The discrete sharp potential closest to the low right atrium potential was taken as the His bundle potential. Because of the difficulties of inserting multiple catheters in children, atrial pacing was carried out only once. His bundle pacing was not attempted. The catheters were connected to a photographic recorder through an Electronics for Medicine junction box. Records were made at 100 and 200 mm per second with 0.02 sec or 1 sec time lines. The frequency band widths used were 40–500 Hz. Principles of electrical safety in the laboratory were followed closely, since the electrode catheter creates a conduction of potential electrical hazard.

All measurements were made from the first rapid deflection of one potential to the first rapid deflection of the next. Three different intervals were searched for and measured when possible: the low right atrium to His (LRA-H), the His to ventricle (HV), and the morphological left (right-sided) bundle-branch to ventricle (LB-V). The left bundle-branch is defined as the first division of the common bundle, which in ventricular inversion is found in the morphological left (right-sided) ventricle.

Subjects ranged in age from 22 months to 29 years (Table). Ventricular inversion was identified by cardiac catheterization and angiography, and each patient had the characteristic leftward initial deflection of the QRS complex on the transverse plane of the surface electrocardiogram. Two of the subjects had congenital third-degree atrioventricular block and the other 5 were in sinus rhythm at the time of the study. One of these 5 had only recently recovered from surgical third-degree atrioventricular block. Atrial pacing was carried out in this patient in order to elicit a potential atrioventricular block.

Results

The His bundle potential could be recorded in all 7 subjects in which it was attempted by the method described above. No modifications in technique were necessary because of the ventricular inversion. The intervals recorded for LRA-H, HV, and LB-V are found in the Table.

Three subjects were in sinus rhythm with normal PR interval and normal QRS duration at the time of electrophysiological study (Cases 1, 5, and 7). In them normal resting LRA-H and HV intervals were found (Fig. 1). Case 5, who had recently recovered from surgical complete atrioventricular block, was stressed by atrial pacing to a rate of 133. Repeatedly at this rate he developed Mobitz II second-degree block by suddenly dropping a beat. The block was between the His and left bundle-branch potential (Fig. 2).

Two subjects in sinus rhythm showed first-degree atrioventricular block at the time of study (Cases 3 and 6). Case 3, whose surface electrocardiogram showed a complete bundle-branch block pattern (Fig. 3) demonstrated both LRA-H and HV prolongation on his His bundle electrogram (Fig. 4). When the catheter was advanced slightly farther into the right-sided ventricle, the His potential was much less well recorded, but a discrete potential could be seen after each ventricular depolarization (Fig. 5). The second subject (Case 6) with first-degree atrioventricular block had a normal QRS duration and showed only LRA-H prolongation.

TABLE Results of His bundle electrocardiogram study in patients with ventricular inversion

Case No.	Age (yr)	Associated lesions	Rhythm by electrocardiogram	QRS duration (msec)	LRA-H (msec)	HV (msec)	LB-V (msec)
1	5	Pulmonary stenosis	Sinus	80	60	45	25
2	1 $\frac{1}{2}$	Left-sided AV valve regurgitation	Complete atrio-ventricular block	90	150	Blocked	20
3	18	Double inlet left ventricle, pulmonary stenosis, post-operative Blalock-Taussig shunt	Sinus, first-degree atrioventricular block	120	150	100	Not recorded
4	29	Ventricular septal defect, pulmonary stenosis	Complete atrio-ventricular block	90	120	Blocked	Not recorded
5	9	Postoperative valve and subvalvar pulmonary stenosis	Sinus	70	80	50	20
6	14	Ventricular septal defect, valvar and subvalvar pulmonary stenosis	Sinus, first-degree atrioventricular block	80	140	35	Not recorded
7	13	Double inlet left ventricle, pulmonary stenosis	Sinus	85	100	50	30

FIG. 1 His bundle electrogram of Case 1 with simultaneous surface lead aVR showing normal LRA-H, HV, and LB-V intervals. During the tracing the catheter moved farther into the ventricle, moving from the region of the His bundle to that of the right-sided 'left' bundle-branch.

At the time of study, two subjects were felt to be in complete atrioventricular block (Cases 2 and 4). Both had documentation of their complete atrioventricular block at the time of their first electrocardiogram which was taken in the first year of life (Fig. 6). Neither had any history of Adams-Stokes attacks. Both had incomplete bundle-branch block of their QRS complexes. In both of these subjects the maximal block was found below the site at which the His potential was recorded (Fig. 7 and 8). The LRA-H interval was found to be prolonged in both subjects also.

On the tracings from Case 2, His potentials were seen only after atrial depolarizations which followed the preceding ventricular depolarization by more than 500 msec (Fig. 7). Two successive ventricular depolarizations were seen to follow atrial depolarizations which came close to 500 msec after the preceding ventricular depolarization (Fig. 8). Case 4 showed two sharp discrete potentials not associated with surface activity. One was temporally related to the low right atrial potential (H_1), following it by 120 msec. The second followed the ventricular depolarization by 150 msec (H_2) (Fig. 9). The H_2 deflection was recorded both by the proxi-

mal and distal electrode pairs while the H_1 was only recorded by the proximal electrodes pair.

Discussion

His bundle studies have contributed to the fundamental understanding of conduction disturbances and arrhythmias in adults (Scherlag *et al.*, 1969; Damato *et al.*, 1969). Such studies have also proved useful in evaluation of arrhythmias in children with normal hearts and relatively uncomplicated cardiovascular anomalies (Brodsky *et al.*, 1971; Roberts and Olley, 1972). It has been found that the His bundle electrogram is necessary to determine the site of surgical block after correction of tetralogy of Fallot (Anderson *et al.*, 1972). Theoretically, it might be difficult to record the His bundle electrogram with the usual techniques in complex cardiovascular anomalies, since the technique is sensitive to changes in relative catheter-conduction tissue position. We have found it possible to record the His bundle potential by the usual techniques in 7 subjects with simple ventricular inversion and with several associated lesions including two with double inlet left ventricle.

FIG. 2 His bundle electrogram from Case 5 during atrial pacing at a rate of 133 with accompanying ladder diagram showing intermittent block between the His bundle and the 'left' bundle-branch. The photograph is from a record taken at 50 mm/sec in order that several cycles can be shown; however, measurements were made from 200 mm/sec records.

In ventricular inversion it was not known whether the LRA-H and HV intervals, representing conduction time from the right atrium near the atrio-ventricular node to the proximal bundle of His and from the proximal bundle of His to the ventricular myocardium respectively, would be equal to the intervals observed in subjects with normally related ventricles. In Cases 1 and 7, who had no conduction abnormality on the surface electrocardiogram, we recorded normal LRA-H and HV intervals. Thus the inversion of the conduction system did not in these instances cause abnormal conduction through the atrioventricular node or the His-Purkinje system. Based on these observations, abnormal intervals in patients with ventricular inversion would be expected to be caused by abnormalities in their conduction system in addition to inversion.

Lev *et al.* (1963) have suggested that the bundle of

His in ventricular inversion is longer than in normal hearts. We found no electrophysiological evidence for this. More than half of our patients had normal HV intervals which measure conduction through the bundle of His and bundle-branches. In Case 3 with a prolonged HV, there was associated bundle-branch block which may have been the cause of the prolonged HV. Cases 2 and 4 probably did have block in their bundle of His since they had block between the H potential and ventricle, with almost normal QRS duration. At the time the studies on the subjects were carried out, the authors were not familiar with the phenomenon of the split His potential so it was not searched for.

Both subjects with first-degree atrioventricular block had prolonged LRA-H intervals: this is evidence for block in the atrioventricular node. Both subjects with complete atrioventricular block were

FIG. 3 Surface electrocardiogram of Case 3 demonstrating first-degree atrioventricular block, QRS prolongation, biatrial enlargement, right axis deviation, and Q waves in the right chest leads with none in the left.

FIG. 4 His bundle electrogram of Case 3 showing prolonged HV interval and prolonged LRA-H interval.

FIG. 5 His bundle electrogram at a different time in Case 3 demonstrating retrograde 'left' bundle-branch and His bundle activations, the last of which is conducted to the atria as an atrial echo beat.

found by His bundle electrocardiography to have block between the H potential and ventricular electrogram. Since they had relatively normal QRS complexes, the block may well have been in the bundle of His though trifascicular block is also possible. Case 3 was found to have LRA-H and HV prolongation as well as bundle-branch block pattern on the electrocardiogram. Thus, in 6 subjects with ventricular inversion before surgery studied without respect to conduction abnormalities, 2 had evidence for normal conduction throughout the conduction system, 4 had evidence of slow conduction through the atrioventricular node, 2 had evidence of slowed or blocked conduction in their bundle of His, and 1 had evidence of slowed conduction in his bundle-branches. We conclude, therefore, that the conduction system disease in patients with ventricular inversion is not limited to any one anatomical area, but is distributed with decreasing frequency from the AV node through the bundle-branches. Most patients with congenital or acquired complete atrioventricular blocks have had normal intervals in the segment not blocked (Narula *et al.*, 1971; Rosen *et al.*, 1971 a, b; Kelly *et al.*, 1972). The fact that additional conduction delay was found in

the non-blocked interval in our 2 patients favours the fact that the disease process in these patients is more widespread than in most other patients with conduction disturbances.

Our study demonstrates that in patients with ventricular inversion, as in other forms of congenital heart disease and in basically normal hearts, His bundle electrocardiography is often necessary to delineate the site of slowed or blocked conduction. It has been previously shown that in patients with congenital heart block who demonstrate narrow QRS complexes, the site of block is usually above the His potential (Rosen *et al.*, 1971). These studies did not contain any subjects with ventricular inversion. The 2 subjects in this study with complete heart block and similar electrocardiograms were found to have their block below the H potential. This fact could not have been shown without intracardiac recordings. One previous report of His bundle studies in a patient with ventricular inversion also produced unusual findings (Mobitz II block above the H) (Rosen *et al.*, 1971 a, b).

In Case 2 analysis of the His bundle electrograms showed that a His potential was seen only after atrial depolarizations which were greater than 500

FIG. 6 Surface electrocardiogram of Case 2 taken at 20 months of age, demonstrating complete atrioventricular block and Q wave in the right praecordium, with no Q waves in the left praecordium.

FIG. 7 His bundle electrogram recorded in Case 2 with leads aVF and II and a simultaneous ladder diagram. This demonstrates the complete block below the His and intermittent block in the atrioventricular node above the H.

FIG. 8 His bundle electrogram from Case 2 with simultaneous surface lead aVf and ladder diagram demonstrating two sequences in which the sinoatrial node captured the ventricles.

FIG. 9 His bundle electrogram recorded from Case 4 with a tripolar catheter with simultaneous ladder diagram demonstrating two distinct His bundle spikes, one activated from the atria and one activated in a retrograde manner from the ventricles.

msec after the preceding ventricular depolarization (Fig. 7). This suggested that there was concealed retrograde conduction into the His bundle, thereby indicating that conduction was still possible. A careful search of the electrograms demonstrated two conducted sinus beats (Fig. 8). That they are conducted beats is favoured by the following: 1) they were too early to be the regular ventricular rhythm; 2) they follow a normal sinus P wave; 3) they occur only when the atrial depolarization fell

close to 500 msec after a ventricular depolarization, i.e. the supranormal period of the retrograde depolarization of the bundle of His. The fact that this subject did have some conduction through his bundle of His and atrioventricular node might make it necessary to use a demand rather than a fixed rate pacemaker in him if he became symptomatic.

The His bundle recordings in Case 3 were important in two ways. They showed that he had advanced conduction system disease both in the AV junction

FIG. 10 Diagram of the proposed ventricular specialized conduction system in Case 4. Dashed lines show the direction of conduction for retrograde activation of the common bundle by way of the ventricular myocardium and left posterior division in Case 4.

and below. With this advance knowledge, a pacemaker could be inserted at the first sign of Adams-Stokes attacks. They also warned of the possibility of re-entry tachycardia by demonstrating the spontaneous atrial echo beat (Fig. 5). That this is an atrial echo beat is favoured by the following: 1) it is early; 2) its vector is reversed from the sinus P wave; 3) the low atrial electrogram precedes the beginning of the P wave; 4) there is a retrograde conduction system potential after each V electrogram and the V-LB_R interval slowly prolongs until the echo beat occurs. The proposed course of re-entry in this case is atrium, atrioventricular node, His bundle, right bundle-branch, ventricular myocardium, left bundle-branch, His bundle, atrioventricular node, atrium.

The His bundle recordings in Case 4 provided strong evidence that the block was in the bundle of His. Two separate 'His' potentials could be recorded with the catheter in one position, one associated with atrial and one with ventricular depolarization. It is postulated that the second His (H₂) was activated in a retrograde fashion by an impulse that originates in the ventricular specialized conduction system. To produce a narrow QRS with no preceding His potential but followed after 150 msec by a retrograde His potential, the right bundle-branch and left anterior fascicle would have to be activated normally followed by retrograde activation of the bundle of His by way of the ventricular myocardium. The complete findings in this sub-

ject could be explained by a block in the common bundle before the take-off of the left posterior division and one slightly below this which preserved continuity between the left anterior division and the right bundle-branch (Fig. 10).

Conclusions

His bundle recordings have been possible and helpful in studying the electrophysiology of ventricular inversion. It was found possible to have normal conduction intervals in association with ventricular inversion, possibly indicating that the frequent conduction abnormalities seen in this defect are not an inherent part of it. Many different areas of slowed or blocked conduction were found and these could only be accurately identified by the intracardiac recordings. The studies show potential usefulness in managing patients with ventricular inversion.

Addendum

We have studied two more children with ventricular inversion, one a 6-year-old boy with only a 20 mmHg gradient across his pulmonary valve, who had completely normal intervals. The other was a 2-year-old girl with associated large ventricular septal defect and severe pulmonary stenosis, who had congenital complete atrioventricular block (from at least 2 weeks). In her, the His recording clearly showed the block to be above the His bundle, which correlated well with her narrow QRS and fast resting rate of 100.

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