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Surgical Pathology of the Conducting System of the Heart*

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I am most grateful for the honour of lecturing in this historic hall and for the opportunity it affords of publicizing an embarrassing but most important aspect of intracardiac surgery.

Almost exactly 3 centuries ago, the Apothecaries of London secured immortality when they stayed at their posts administering to the stricken during the great plague of London, when fashionable physicians had fled the capital to seek immunity in the countryside. And now today, you have a 20th century apothecary and pathologist come to plague the cardiac surgeon.

It is no coincidence that the amazing development of intracardiac surgery in the past few years has been accompanied by a no less astonishing succession of ingenious electrical machines for artificially pacemaking or restoring the heart beat, and for correcting disturbances of its rhythm. Although this has, without question, conferred great benefit to patients and brought relief to worried physicians and surgeons, it may have led to a somewhat conceited sense of false security that traumatic injury to the natural conducting system is of minor importance and easily remedied, despite a growing literature testifying the contrary. The cumbersome, and often troublesome man-made devices employed for these means, however, bear no comparison with the lasting perfection of the exquisite built-in mechanism which Nature has provided for the appropriate reaction of the heart beat in all circumstances. When this natural system is working normally, therefore, it seems elementary that every effort should be directed towards preserving its integrity.

The object of my lecture, therefore, is to present the histological anatomy of the conducting system in the various conditions amenable to modern cardiac surgery, to demonstrate the lesions that may be inflicted by operations in the area it occupies, and thence to define the danger zones to be avoided by the cardiac surgeon.

I have been interested in the conducting system of the heart for many years, and my modest efforts have, I think, helped to bring this somewhat obscure matter within the scope of routine histology. When I joined the National Heart Hospital in 1948, the system was under a cloud and people used to ask me if I believed it existed. This wave of uncertainty, initiated especially by the Glomsets and their colleagues in the 1940s (Glomset and Glomset, 1940) stimulated me and many other workers to restudy the area. It is now generally agreed that there *is* a well-defined neuromuscular system of impulse propagation and conduction in the heart, just as was defined in the brilliant pioneer studies of His (1893), Kent (1893), Tawara (1906), Keith and Flack (1907), Lewis, Oppenheimer, and Oppenheimer (1910), and other immortal contemporaries of that great era of discovery from 1893–1910. It is indeed astonishing that such fundamental revelations should ever have come under suspicion, or even downright disbelief.

Conducting System of the Normal Heart

The conducting system of the normal heart comprises 2 parts: first, the main generating station known as the sinu-atrial node (or pacemaker), and secondly, the atrio-ventricular system, which comprises the lesser generating station known as the atrio-ventricular or A-V node of Tawara, together with its forward extension as the bundle of His and its terminal subdivisions (Fig. 1).

Precisely how the impulse originating in the sinu-atrial node travels to the A-V node is not known; it is certainly via the atrial muscle, but whether by the *specific* myocardial pathways originally described by Wenckebach (1907), Thorel (1909), and Bachmann (1916), and more recently in studies by Robb and Petri (1961) and James (1963), has been disputed, for example, by Truex and Smythe (1965). All workers, however, including the writer, have noted the extensions from the 2 nodes into the atrial

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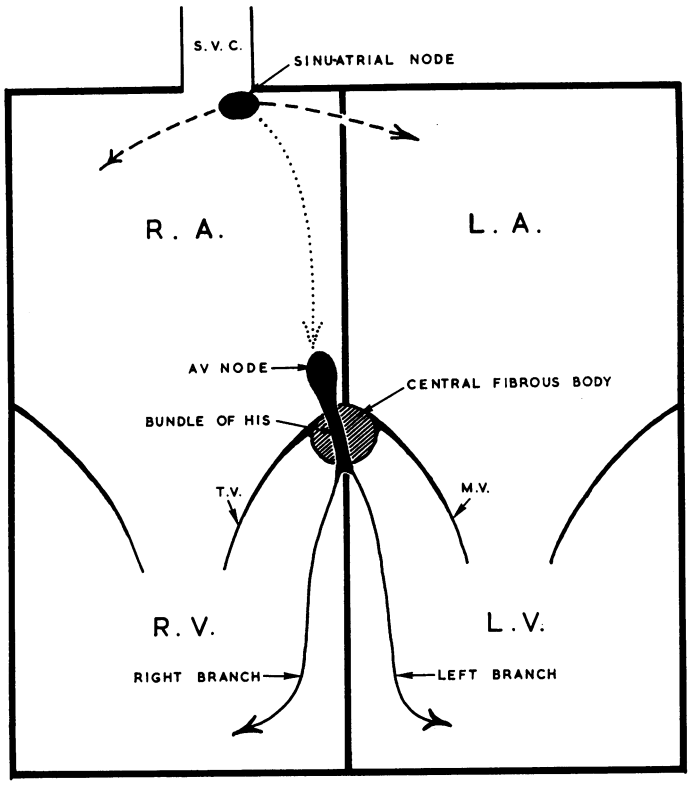

FIG. 1.—Diagram of conducting system. Note how the bundle of His penetrates the right side of the central fibrous body to reach the top of the interventricular septum.

myocardium. In general, the sinu-atrial node maintains sinus rhythm; if it should break down, the lesser station can take over, resulting in A-V nodal rhythm; if this node or its terminal branches are damaged, various types and degrees of heart block result. It would, however, be presumptuous to claim that histological study can always explain an electrocardiographic arrhythmia, and, in this, the writer fully agrees with Rossi (1964). It seems evident that any discrepancies are the result of our incomplete knowledge of the system, due in turn to the virtual impossibility of histological distinction between conducting cells and ordinary myocardium in areas remote from the well-defined pathways known to all workers.

The whole system is adequately supplied with blood and by autonomic nerves. Fig. 2 shows how the blood supply is arranged. The sinu-atrial node is nourished by the arterial circle at the entry of the superior vena cava, which derives from the right (55%) or left (45%) circumflex coronary arteries. The A-V system is fed by penetrating septal arteries, arising anteriorly from the anterior descending branch of the left coronary artery, and posteriorly from the U-loop made by the right (90%) or left (10%) circumflex artery as it dips beneath the interventricular vein at the posterior crus of the heart, made by the junction of the four chambers. The right circumflex artery thus supplies the S-A node in 55 per cent, and the A-V node in 90 per cent of hearts, and could more reasonably be called the "artery of sudden death" than the anterior descending artery (James, 1965). An injection *x*-ray microscopic study by Clarke (1965) showed that capillary densities were greatest in the two nodes.

Sympathetic innervation derives from the upper 5 thoracic dorsal nerve roots via the paravertebral and stellate ganglia; stimulation causes acceleration of the pacemaking impulse. Parasympathetic innervation is via the vagi, the right vagus supplying the sinu-atrial node and the left vagus the A-V node; stimulation causes decreased activity of the nodes (Truex, 1961).

Sinu-atrial Node. The sinu-atrial (S-A) node of Keith and Flack (1907), also known as Lewis's pacemaker (Lewis *et al.*, 1910), lies at some point around the arterial circle at the junction of the

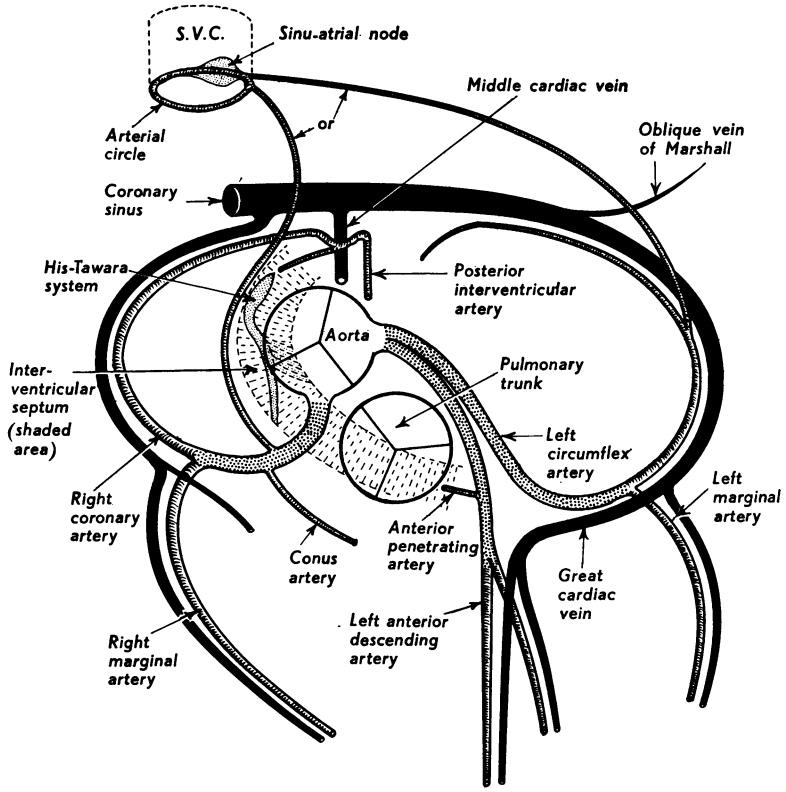

FIG. 2.—Diagram of coronary circulation to show the sinu-atrial node fed by branches from either right or left circumflex arteries, and the His-Tawara system by anterior penetrating branches from the left anterior descending coronary artery and by posterior penetrating branches from the U-loop which the right (usually) circumflex artery makes around the ascending interventricular vein at the posterior crus of the heart. [Reproduced from the author's book *Cardiovascular Pathology* (1965), by courtesy of Edward Arnold (Publications) Ltd.]

superior vena cava with the right atrium (Fig. 3). A reliable landmark to it, which I described in 1959, is the summit of the right atrium, that is, the highest point of its junction with the superior vena cava. This point also corresponds with the upper end of the crest of the right atrial appendage. The node most commonly lies in the epicardial fat just below and to the right of this summit. Occasionally the main part of the node lies more medially or laterally, but with the sole exception of single atrium, I have found the summit to be a reliable guide to its location in all hearts (Hudson, 1960). In mirror-image dextrocardia, as might be expected, the node lies in the precisely corresponding situation at the root of the left-sided superior vena cava (Fig. 4).

Fig. 5 illustrates the histological appearances of the node and its essentially myocardial structure; it also shows the node extensions downwards into the right atrium. Recent electron-microscopic studies by James and his colleagues in Detroit have shown that there are three types of cell in the human and canine pacemaker. First, principal or P cells, which have a relatively primitive structure with scanty myofilaments, and which may be the actual pacing cells; secondly, typical ordinary (working) myocardium, with abundant myofilaments and mitochondria, lying mainly at the node periphery; and thirdly, transitional cells, with a structure somewhere intermediate between these two (James *et al.*, 1966).

It is unfortunate that the pathologists' old custom of opening the right atrium at necropsy by a conjoined cut through both venæ cavæ usually makes adequate study of the pacemaker more difficult, and I would urge interested workers to preserve the shape of the superior vena cava intact by light wool-packing if they wish to investigate the node.

It is unfortunate too that the right atrial appendage should be a favourite site for surgical manipulations, cannulation, and sutures, which commonly

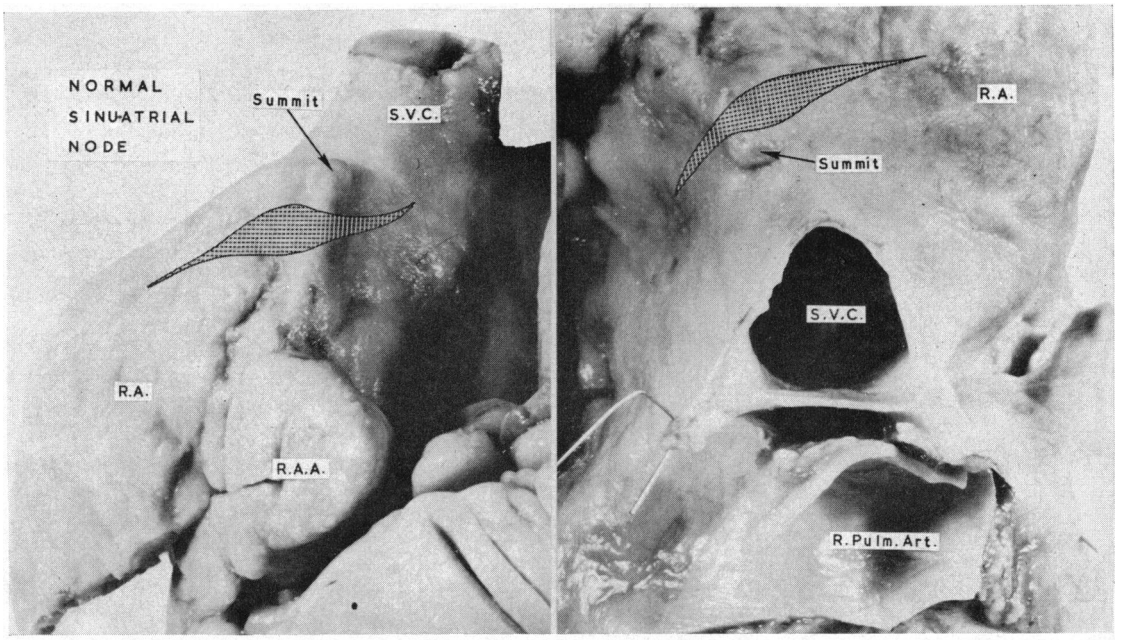

FIG. 3.—Anatomy of sinu-atrial node in relation to the summit of the right atrial junction with the superior vena cava. R.A., right atrium; R.A.A., right atrial appendage; R.Pulm.Art., right pulmonary artery; S.V.C., superior vena cava.

inflict hæmorrhagic trauma in and around the node, as illustrated in the three examples in Fig. 6; in 6A, the node is virtually obliterated.

Trauma may also be caused by occlusive damage to the circumflex artery (left or right) which supplies the arterial circle about which the pacemaker is disposed.

Atrio-ventricular (A-V) System of His-Tawara. The A-V system comprises the A-V node of Tawara, the bundle of His, its terminal branches, and their subendocardial ramifications ending in Purkinje cells.

The node and bundle lie between the ostium of the coronary sinus in the right atrium and the root of the membranous septum (pars membranacea) at the septal commissure of the tricuspid valve (Fig. 7). Soon after its formation, the bundle usually starts yielding a thin sheet of left fascicles which fan down in the left ventricular subendocardium from below

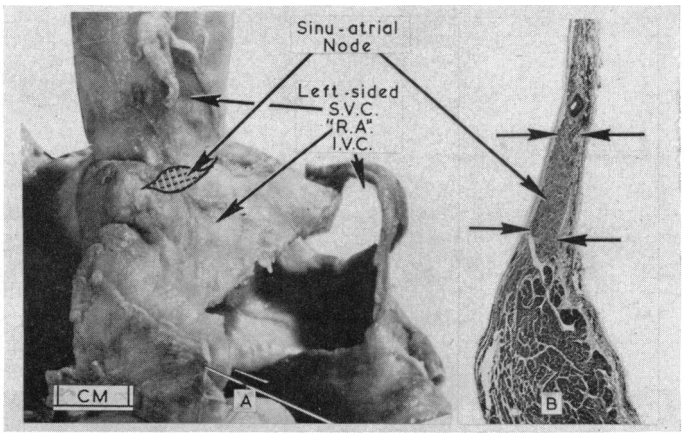

FIG. 4.—(A) Anatomy of sinu-atrial node in mirror-image dextrocardia; allowing for the inversion, its relation to the right atrial summit is normal. (B) Longitudinal section. (H. and E. × 6.)

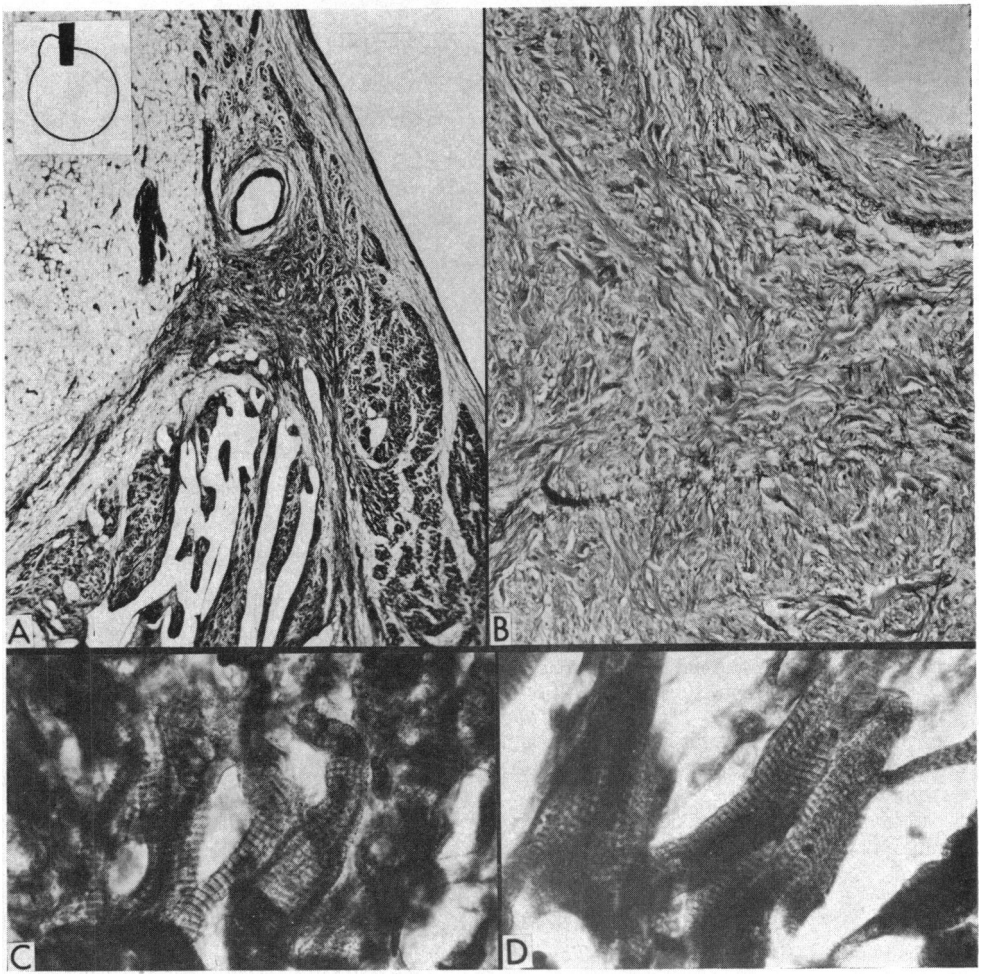

FIG. 5.—General histology of the sinu-atrial node. (A) Node lying around and below the node artery. Note the extensions upwards towards the superior vena cava and downwards into the right atrium. (Holme's silver method. × 12.) (B) Detail of an area near the node artery (top right). The muscle is paler than the wavy fibrous tissue. The elastic fibrils stain black (elastic—Van Gieson. × 66.) (C) Individual muscle cells of node which are interwoven. (D) Myocardium of adjacent right atrium. (C and D stained by Holme's silver method. × 474.) [Reproduced from the author's book, *Cardiovascular Pathology* (1965), by courtesy of Edward Arnold (Publishers) Ltd.]

the pars membranacea, which fills in the area between the right and non-coronary aortic valve cusps. What is left of the bundle, after these fascicles cease, continues as the right branch, descending near the endocardial surface just behind and below the crista supraventricularis. It is believed by some that the impulse may also be conveyed across the cavity of the left ventricle by "false tendons" which are sometimes found as delicate threads linking the septum to the bases of the papillary muscles of the mitral valve; the writer has certainly identified muscle in these cords, but cannot state whether or not this is conducting tissue.

In passing from atrium to ventricle, the bundle of His must penetrate the valve rings of the heart somewhere. It does so in the most protected and convenient situation, that is, through the right fibrous trigone, which is the right part of the central fibrous body made by the contiguous fibrous annuli of the mitral, tricuspid, and aortic valves (Fig. 8). During this course, the bundle may become disrupted and this is the lesion underlying congenital heart block; it is obvious, too, that this situation makes the bundle and branches highly vulnerable in valve surgery, as will be shown later.

Fig. 9 illustrates the histological appearances of

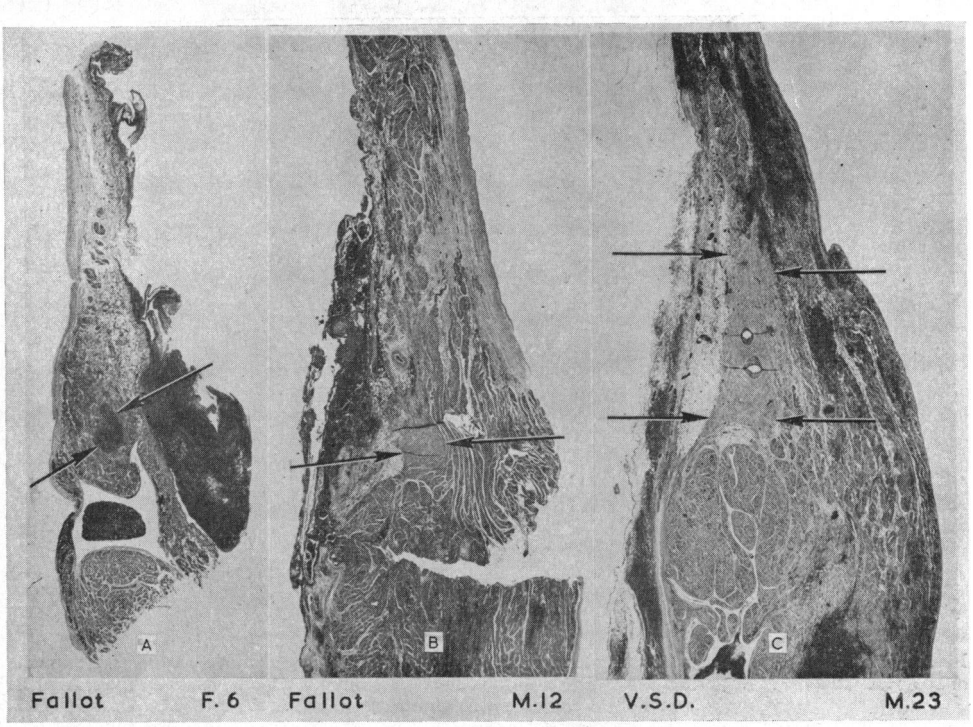

FIG. 6.—Three examples of surgical trauma in or near the sinu-atrial node (arrows). In A, the node is virtually obliterated by hæmorrhage. In B and C, there are dark areas of hæmorrhage near the node. (All stained by hæmatoxylin-eosin. ×5·7.)

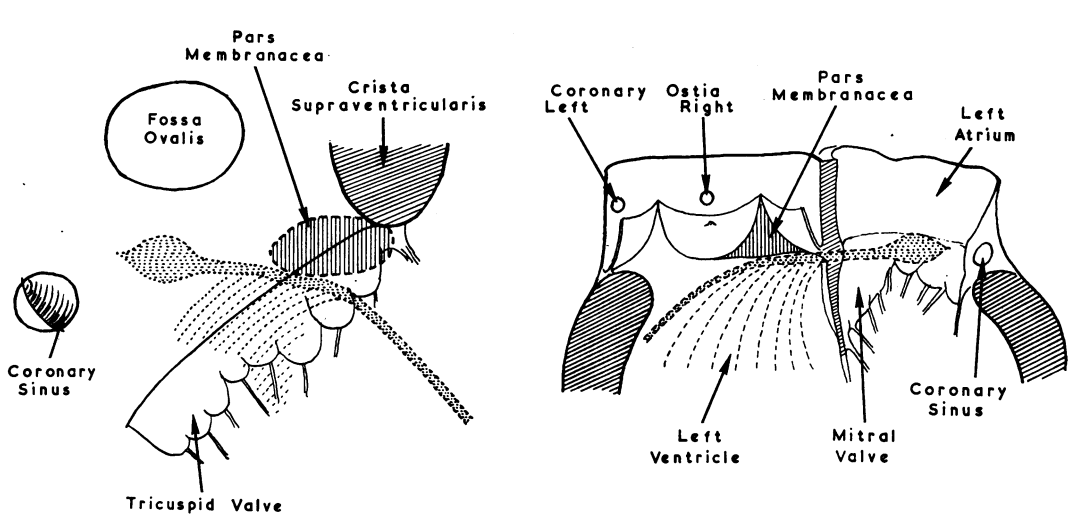

FIG. 7.—Diagram of atrio-ventricular system of His-Tawara. The left-hand drawing shows the A-V node adjacent to the coronary sinus, extending forward as the bundle of His in the base of the membranous septum (which is divided into right-atrial—left-ventricular and interventricular portions by the tricuspid valve attachment). The bundle gives off left fascicles and, when these cease, proceeds as the right branch. The right-hand drawing shows the bundle of His in the base of the membranous septum between the right- and non-coronary aortic valve cusps; from it, left fascicles fan down the left side of the interventricular septum. The relation of the A-V node to the mitral valve ring is indicated, though it lies on the far side of this part of the septum.

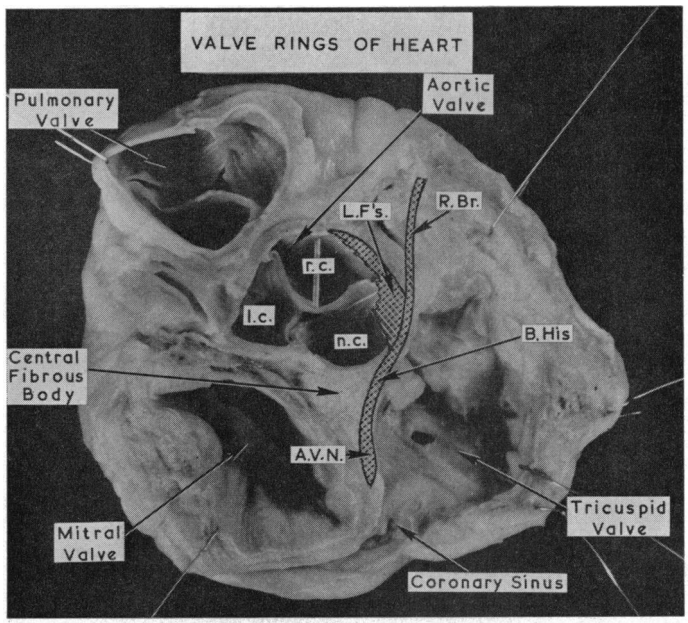

FIG. 8.—Dissection of valve rings of heart seen from above, and the relationship to the A-V system; the bundle of His penetrates the right portion of the central fibrous body (right fibrous trigone) made by the contiguous annuli of the mitral, aortic, and tricuspid valves.

the normal A-V system transected at intervals from node to branches. The A-V node (A) lies just under the right atrial endocardium, hugging the central fibrous body, which is black in the pictures. At its widest, it is about 5 mm. or more high, and from it, fine muscle fibres can be traced upwards into the right atrium; superficial fibres usually connect with the tricuspid valve ring. In (B), the node is becoming more compact and starting to penetrate the central fibrous body to form the bundle of His (C) which lies on the crest of the muscular septum in the base of the membranous septum. The bundle usually starts giving off the sheet of left fascicles which run down in the endocardium just beneath the endocardial plain muscle (D), and at some point, these fibres take on the appearance of Purkinje cells, large, vacuolated-looking fibres with scanty peripheral fibrils (D—right picture). Left fascicles continue to spring from the bundle and fan down over the left side from the region of the membranous septum. Eventually, these left fascicles cease, and just before this the system will appear to bifurcate (E). During its course, the bundle sends Mahaim fibres (Mahaim, 1947) direct into the top of the muscular septum. From this point forwards, the main bundle, less its left fascicles, continues as the right branch, which moves over towards the right side of the septum eventually emerging in the subendocardial zone (F). Left fascicles will still be seen as they are cut running forwards and downwards from above but they appear lower in each succeeding section and eventually only the right branch will be seen, often as a quite distinct cord of myocardium, which can sometimes be identified in a casual section of the septum.

SURGICAL LESIONS OF A-V SYSTEM

The present study may be divided into two main parts, the first dealing with lesions associated with valve surgery in otherwise normal hearts, and the second with lesions resulting from the repair of congenital malformations; in the latter group, a few non-surgical examples are included to make the range of abnormalities studied more complete.

Valve Surgery

As has been noted already, the central fibrous body and membranous septum (which are really a continuous structure) are formed by the contiguous tricuspid, mitral, and aortic valve rings. The bundle of His penetrates the right part of the central fibrous body in passing from atrium to ventricle, and is therefore at risk in operations on these valves, especially the aortic valve. Indeed, a growing literature has been accumulating ever since open-heart surgery became possible, recording the various

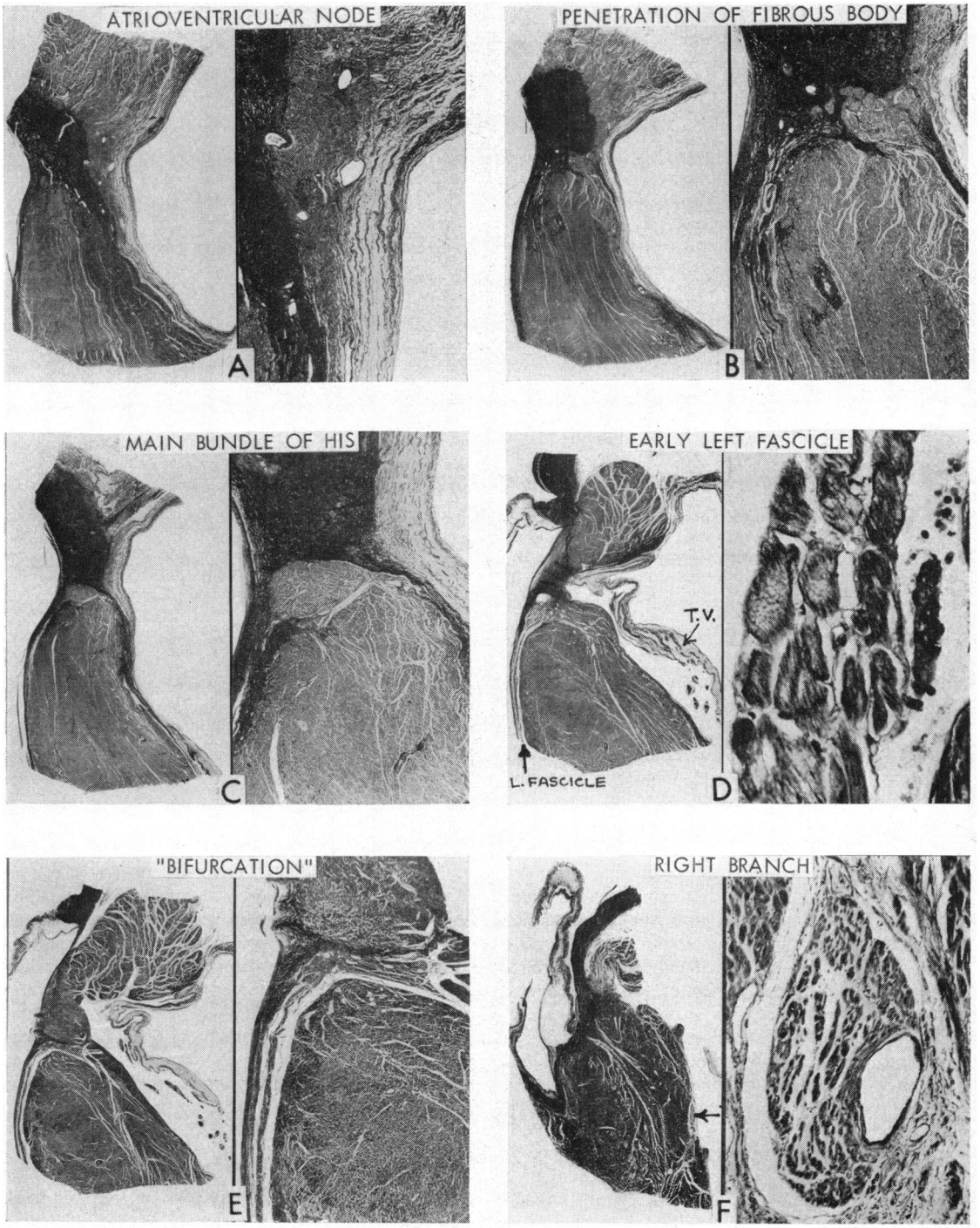

FIG. 9.—Histology of A-V system at intervals from the A-V node to the branches—see text. [Reproduced from Hudson, R. E. B. (1963). The human conducting system and its examination. *J. clin. Path.*, **16**, 497, by courtesy of the Editor and Publishers.]

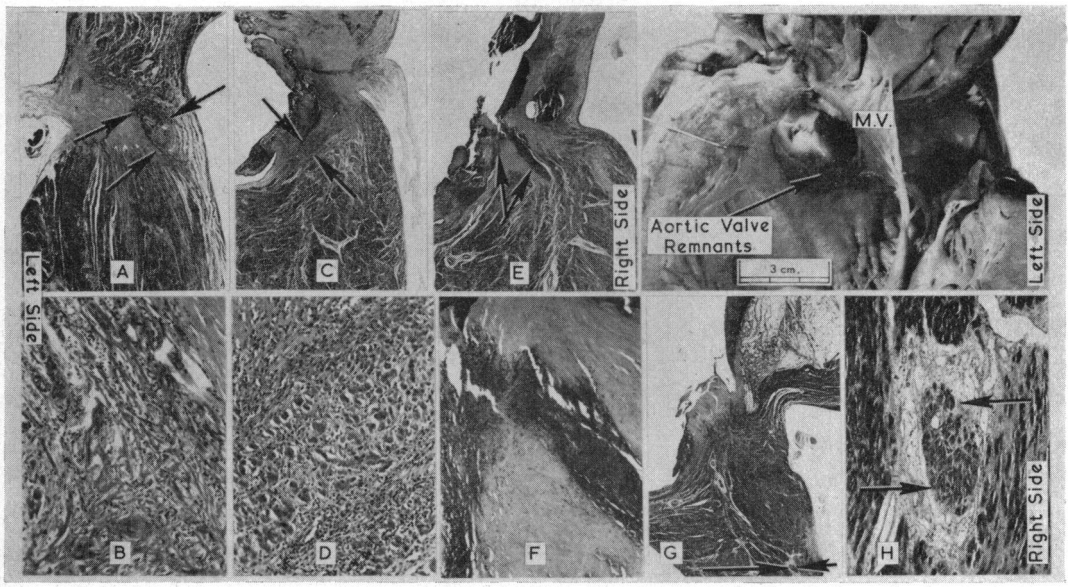

FIG. 10.—Heart block following replacement of a calcified congenital bicuspid aortic valve by a Starr-Edwards prosthesis in a man of 37 years; atrial fibrillation was present before operation. The prosthesis became partly detached. Top right is a view of left heart chambers after removal of the prosthesis. (A) and (B) A-V node showing lymphocytic infiltration. (×3 and ×18.) (C) and (D) Bundle of His showing lymphocytic infiltration. (×4 and ×18.) (E) and (F) Bifurcation—virtual destruction by hæmorrhagic necrosis and inflammation. (×4·5 and ×18.) (G) and (H) Right branch—slight lymphocytic infiltration (×1·9 and ×18.) (All sections stained by hæmatoxylin-eosin.)

arrhythmias which have followed surgical trauma to the system. Earlier reports sometimes registered aggrieved surprise at this natural complication; it certainly stimulated the current resurgence of interest in the anatomy of the A-V system in normal and malformed hearts (Hudson, 1965).

Probably the commonest lesion reported has been heart block following aortic valve replacement. The procedure of removing the original valve cusps and the suturing of the ring of a prosthesis or of the aortic rim of a homograft into the subcoronary position, all occur dangerously near to the bundle of His and its branches. The frequency with which this complication occurs varies, of course, with the skill and knowledge of the surgeon; fortunately, many of the lesions are temporary, due usually to hæmorrhage, and will probably resolve, with disappearance of the heart block. In other cases, persistent heart block may play its part in a fatal outcome. In a recent report, Gannon *et al.* (1966) found post-operative complete heart block in 16 of 124 patients who had aortic valve replacement by a Starr-Edwards or Magovern prosthesis; 15 needed artificial pacing and 9 died.

The present study included 6 examples of complete heart block following aortic valve replacement, by a Starr-Edwards valve (1 case, Fig. 10) or homograft (5 cases). In one patient with homograft replacement of a calcified bicuspid valve, complete heart block was also present before operation (Fig. 11); in another, the mitral valve was replaced by a Starr-Edwards prosthesis (Fig. 12). All 6 patients were men, their ages ranging from 37 to 61 years.

In all 6 cases, serial histology disclosed hæmorrhagic trauma, sometimes with necrosis, concentrated in the bundle of His and left fascicles and often obscuring the origin of the right branch. The A-V node usually escaped serious damage though it showed infiltrative hæmorrhage. A feature of the series was the way in which the hæmorrhage tracked along the connective tissue of the left fascicles and right branch; this facilitated the tracing of the latter, which so often was difficult or impossible to define at its origin. Indeed, it was often easier to identify the more distal portion of the right branch by its hæmorrhagic "halo" and then to trace it proximally.

Congenital Malformations

The A-V system was studied in the following congenital malformations.

Atrial septal defect: atrio-ventricularis communis; ostium primum; and ostium secundum.

Sinus of Valsalva aneurysm.

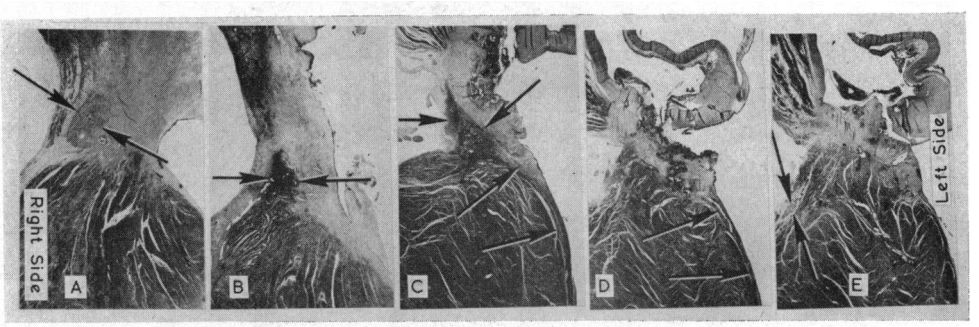

FIG. 11.—Pre- and post-operative heart block in a man of 60 who had homograft replacement of a congenital calcified bicuspid valve. He died in ventricular fibrillation 2 days after operation. (A) A-V node—no lesion. (B) Penetration segment of bundle of His, obliterated by hæmorrhage. (C) Bundle of His and left fascicles obliterated by hæmorrhage. (D) Virtual destruction of bifurcation area by hæmorrhage and calcification; the arrows indicate surviving left fascicles. (E) Right branch (arrows); left fascicles obscured by hæmorrhage. (Note the homograft at top right in D and E.) (All sections stained hæmatoxylin-eosin. ×2·8.)

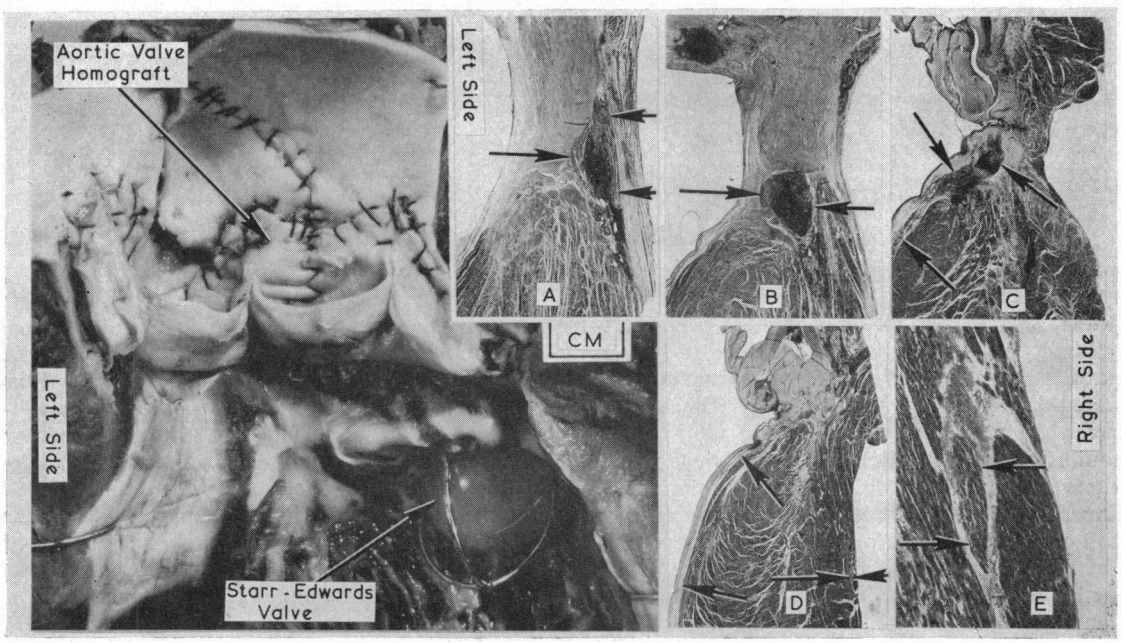

FIG. 12.—Post-operative heart block in a man of 44 years, following replacement of the aortic valve by a homograft and of the mitral valve by a Starr-Edwards prosthesis 3 days previously. The sinu-atrial node was normal. (A) A-V node hæmorrhage (dark areas). (×4.) (B) Bundle of His obliterated by hæmorrhage. (×4.) (C) Bundle of His; hæmorrhagic necrosis with abscess formation; the hæmorrhage is spreading along the left fascicles. (×4.) (D) Thick endocardium overlying the attenuated left fascicles (left arrows); right arrows indicate the right branch. (×1·6.) (E) Right branch with its hæmorrhagic "halo". (×20.)

Aneurysm of the membranous septum.

Ventricular septal defect: isolated; and Fallot's tetrad.

Dextrocardia.

Corrected transposition.

The selected block of tissue, including the coronary sinus at one end and the supraventricular crest at the other, was first photographed from both sides after inserting marker threads of cotton to locate subsequent sections, and after trimming off one corner along the length of the right or left bottom side of the block to facilitate identical orientation of the serial sections on the glass slides. The block was then taken through a slow paraffin-embedding process, and in most cases, cut into serial sections

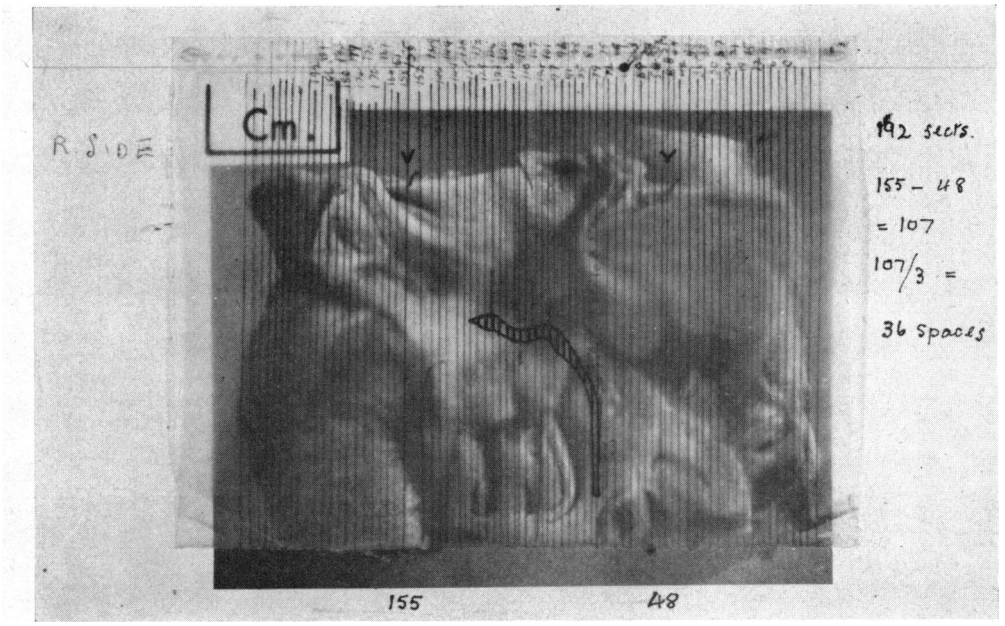

FIG. 13.—Method of plotting the A-V system (see text).

8 μ thick, starting at the anterior end (or in the middle with very long blocks). Every thirtieth section was numbered serially and stained with hæmatoxylin-eosin, yielding about 4 sections per millimetre. The sections containing the marker threads were located on the photographs, which were then covered by tracing paper. The area between the marker threads was then subdivided by equidistant parallel lines equal to the number of intervening sections; these subdivisions were continued over the whole photograph so that each section of the series could be plotted on its appropriate line. With a large series, every second to fourth section was plotted. The resulting series of plotted lines was then outlined into areas, so producing maps of the system (Fig. 13). These were then transferred to duplicate photographs for the illustrations which follow.

Atrio-ventricularis communis. Six examples were studied; one was a non-surgical case, a baby of 41 hours; the other 5 underwent operation, 1 for pulmonary artery banding (a girl of 6 weeks) and 4 for repair of the defect (a girl of 6 years, and 3 boys, ages 2½, 5, and 9 years). One of the latter 4 died during operation and the A-V system was undamaged (Fig. 14); the other 3 developed post-operative heart block and histology revealed severe hæmorrhagic necrosis of the bundle of His, the left fascicles, and the origin of the right branch; the findings in the 5-year-old boy are illustrated in Fig. 15.

In all 6 cases, the histological anatomy was similar. The A-V node was located at some point just below the orifice of the coronary sinus, and from it the bundle emerged to penetrate the central fibrous body and proceed along the upper rim of the ventricular septum immediately beneath the posterior atrio-ventricular valve attachments. As with normal hearts, the bundle soon gave off left-sided fascicles, and the right branch descended posterior to the crista supraventricularis. The point of "bifurcation" varied from case to case, but was usually behind the centre of the lower margin of the defect.

These findings confirm that it is impossible to insert sutures into the lower posterior half of the rim of the defect without damage to the main bundle of His; in addition, sutures in the corresponding area on the left side below the defect are bound to inflict trauma to some left fascicles, though this may be of less serious consequence.

Ostium primum is distinguished from A-V communis defect by having separate mitral and tricuspid valves; the mitral valve in all cases was cleft more or less deeply at its septal attachment.

Four examples were studied; one was a non-surgical case of a male infant of 13 days in whom there was a double superior vena cava, associated,

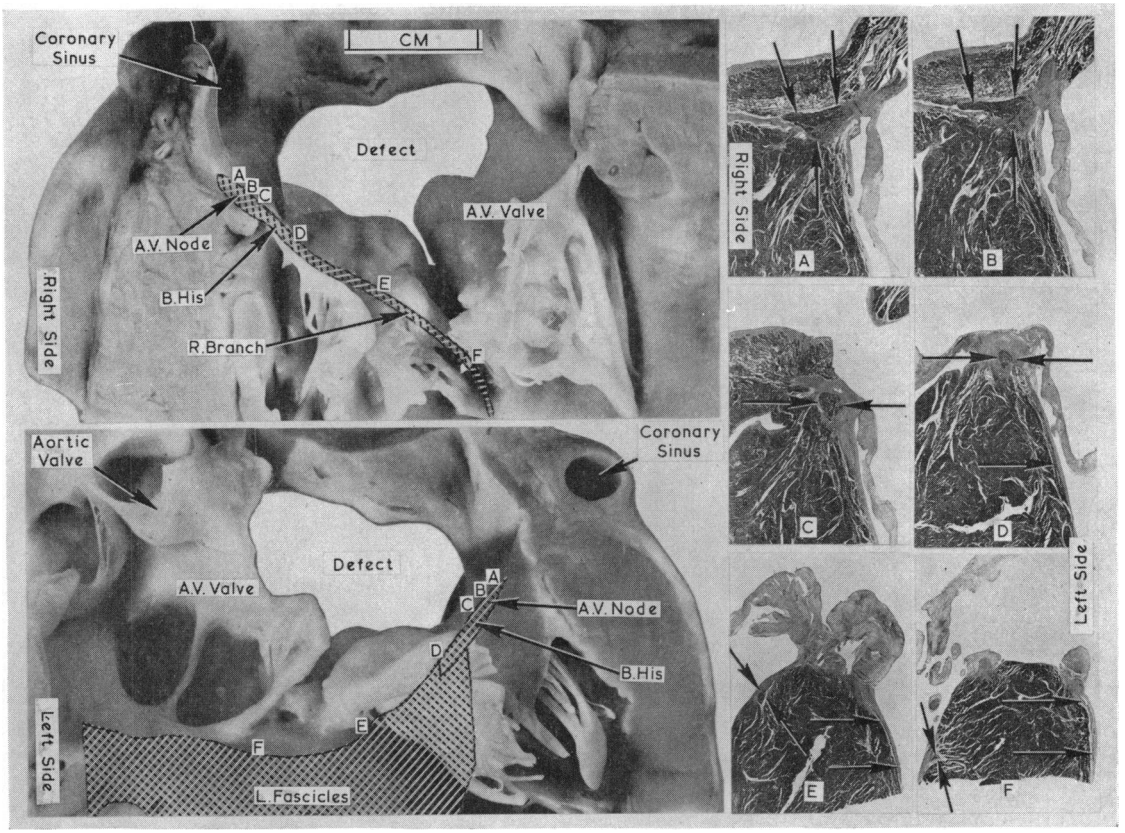

FIG. 14.—A-V communis, incomplete form, in a boy of 2½ years who suffered pulmonary hypertension and repeated chest infections; he had incomplete right bundle-branch block and left ventricular hypertrophy. He died at operation to close the defect. Necropsy disclosed an accessory orifice in the mitral valve; note the chordal attachment of the anterior atrioventricular cusp to the septum (lower left). (A) A-V node. (B) Penetration of central fibrous body. (C) Bundle of His. (D) Bundle of His and left fascicles; the bundle lies between the right and left atrioventricular valve cusps. (E) and (F) Right branch and left fascicles. (All sections stained hæmotoxylin-eosin. ×2·7.)

as is usual, with a greatly dilated coronary sinus which displaced the A-V node forwards (Fig. 16). Another was a male infant of 3 weeks who died after ligation of a patent ductus arteriosus; there was no lesion in the A-V system in either of these 2 patients. The third patient was a boy of 7 years who developed heart block after repair of the defect and suture of the cleft mitral valve (Fig. 17). The fourth patient, a boy of 12 years, had the defect repaired at the age of 6 years; the baneful effects of the cleft mitral valve eventually led to its replacement by a Starr-Edwards prosthesis. This was followed by heart block due to necrotizing damage to the bundle of His.

As expected, the histological anatomy followed the same pattern as in A-V communis defects.

Ostium secundum (*fossa ovalis*) defects lie in the floor of the fossa ovalis and therefore well above the A-V system. Rarely, congenital heart block may occur, as in the female infant of 57 hours reported by Lev and Cassels (1964) who made a serial section study and found a lack of cardiac muscle in the vicinity of a degenerate atrophic A-V node, the approaches being occupied by fibro-fatty tissue.

One example (Fig. 18) was studied, particularly because the defect was of the "inferior caval" type, with no posterior rim and separate from the fossa ovalis. The patient, a man of 55 years, had right bundle-branch block (almost invariably present with ostium secundum defects). He also suffered pulmonary hypertension with fatal massive thrombotic occlusion of the main pulmonary arteries. Histology revealed that the bundle of His, after giving off some left fascicles, ended in the central fibrous body; anterior to this was a considerable gap before the right branch was encountered. In

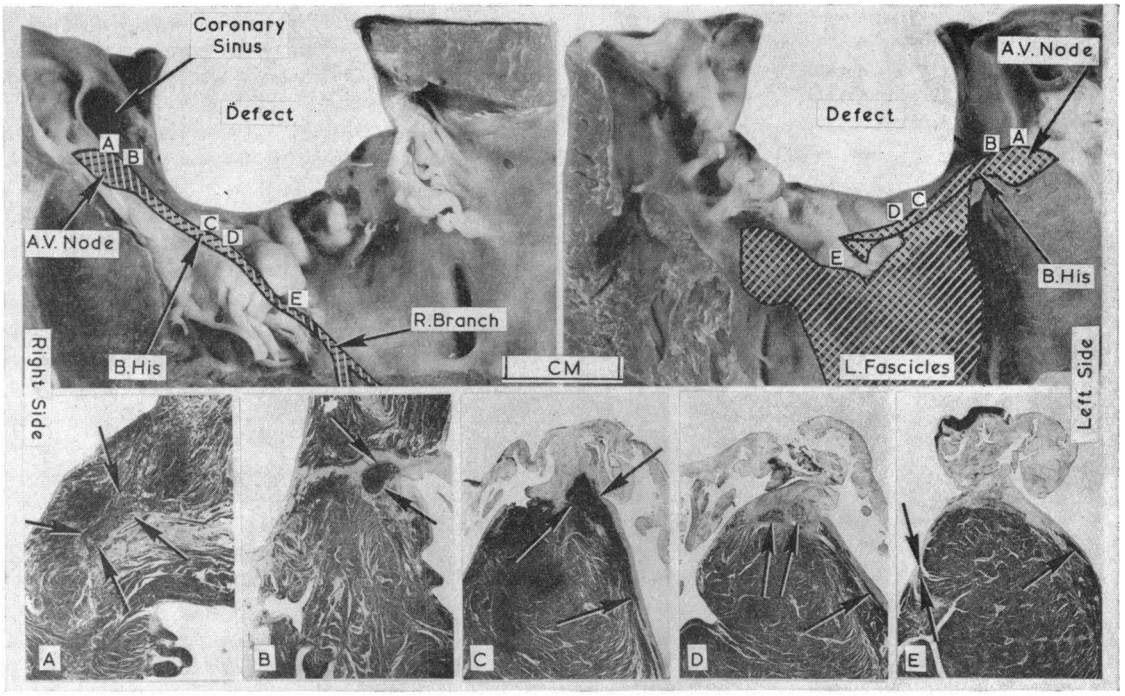

FIG. 15.—Heart block following a few hours after surgical repair of incomplete A-V communis defect in a boy of 5 years who had mitral regurgitation, sinus rhythm, incomplete right bundle-branch block, and left ventricular hypertrophy. Note the tethering of the anterior atrio-ventricular valve cusp to the ventricular septum by short chordæ tendineæ (top right). (A) A-V node; dark areas of hæmorrhage nearby. (×3·5.) (B) Bundle of His almost obliterated by hæmorrhage. (×3·8.) (C) Bundle of His and left fascicles obliterated by hæmorrhage. (×3·8.) (D) Bifurcation area; the bundle of His is double, and there is hæmorrhage along the left fascicles. (×3·8.) (E) Right branch, and hæmorrhage in left fascicles. (×2·7.) (All sections stained by haematoxylin-eosin.)

this heart at least, this break in the proximal portion of the right branch would explain the right bundle-branch block present in life.

Sinus of Valsalva aneurysm of the right or non-coronary aortic valve sinus may involve the A-V system, and, especially if of inflammatory nature, cause heart block. Fig. 19 illustrates an example from a man of 29 years with complete heart block, who died suddenly during a referred visit to the out-patient clinic. The aneurysm wall was composed of thick inflammatory tissue, and this infiltrated the A-V node and caused virtual destruction of the bundle of His.

Aneurysm of the membranous septum (*pars membranacea*) is a lesion somewhat similar to sinus of Valsalva aneurysm except that it lies *between* the right and non-coronary aortic valve cusps. Interference with the A-V system might be anticipated, because normally the bundle of His courses through the lowermost substance of the membranous septum. However, in an example studied, from a man of 71 years, the heart rhythm was normal. Histology (Fig. 20) explained this by demonstrating that the bundle of His coursed *below* the mouth of the aneurysm, on the left side of the muscular interventricular septum.

Ventricular septal defect. The A-V system was studied in isolated septal defect (2 cases) and in septal defect associated with Fallot's tetrad (5 cases).

(a) *Isolated ventricular septal defect.* Both patients were male infants (ages 10 days and 5 months), dying of non-surgical causes. In both, the defect was infracristal; in both, the A-V node was situated normally, but whereas in the younger patient the bundle and left fascicles lay on the very summit of the postero-inferior rim of the defect, in the older it coursed *below* the defect on the left side of the septum, its bifurcation forming an inverted-U shape in the muscular septum (Fig. 21).

(b) *Fallot's tetrad.* All 5 patients underwent operation; the defect was infracristal (the usual type) in 4 and supracristal in one.

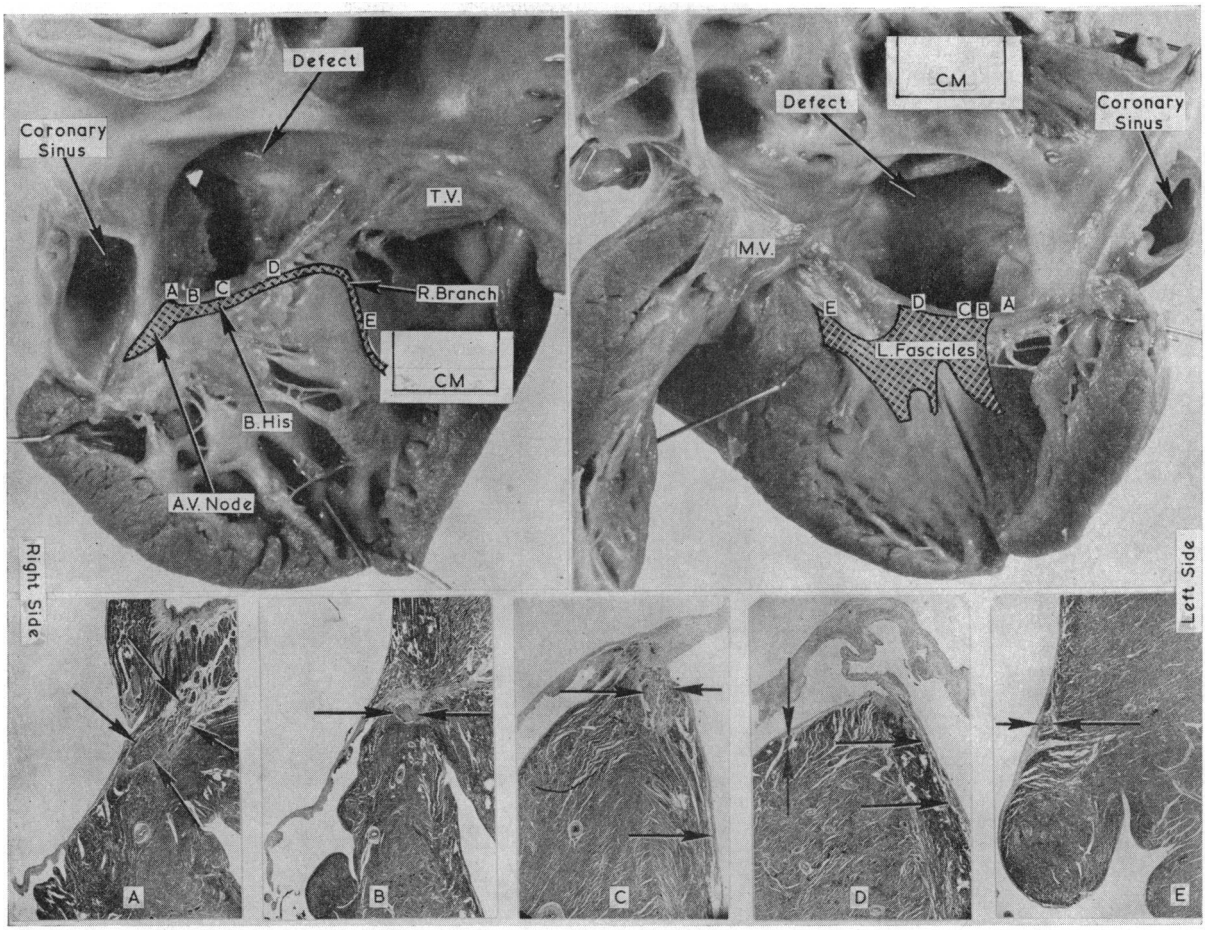

FIG. 16.—Ostium primum in the heart of a male infant of 13 days. The top left picture shows the enlarged coronary sinus associated with a left superior vena cava. The top right picture shows the deep cleft in the mitral valve (between M.V. and E). The selected block studied was limited below to the area shaded in. The A-V system was not well differentiated, but showed no lesion. (A) A-V node. (×4·3.) (B) Bundle of His. (×4·3.) (C) Bundle of His and left fascicles. (×7.) (D) Right branch and left fascicles. (×7.) (E) Right branch. (×7.) (All sections stained by hæmatoxylin-eosin.)

Infracristal defect. In all 4 cases, the A-V node was normally placed and the bundle of His coursed along the summit of the posterior half of the inferior muscular septum bordering the defect, or just below the summit on the left side.

Case 1. Male infant of 22 months in whom the infundibulum had been resected causing severe damage to the right branch.

Case 2. Acyanotic girl of 6 years with atrial septal defect as well as the tetrad (the "pentalogy"); an accessory tricuspid orifice was also present. Both defects had been closed by sutures, the infundibulum resected, and the pulmonary valve stenosis cut at operation. She died in ventricular fibrillation 3 days after operation. There was much hæmorrhage near the sinu-atrial node. The A-V node showed much hæmorrhage which had spread into the bundle and left fascicles. Traumatic inflammatory reaction had destroyed the origin of the right branch.

Case 3 (Fig. 22). Cyanotic mongol youth of 16 years; the stenosed pulmonary valve had been replaced by a homograft, the infundibulum resected, and the defect patched. Death occurred from ventricular fibrillation the day after operation. The sinu-atrial node showed gross hæmorrhagic trauma (see Fig. 6A); the A-V node was normal, but the bundle of His was virtually obliterated by hæmorrhage; a suture had penetrated the system near its bifurcation and the right branch was untraceable because of the resection trauma.

Case 4. Man of 23 years who had infundibular resection and closure of the defect by a teflon patch. On the tenth post-operative day, a systolic murmur re-

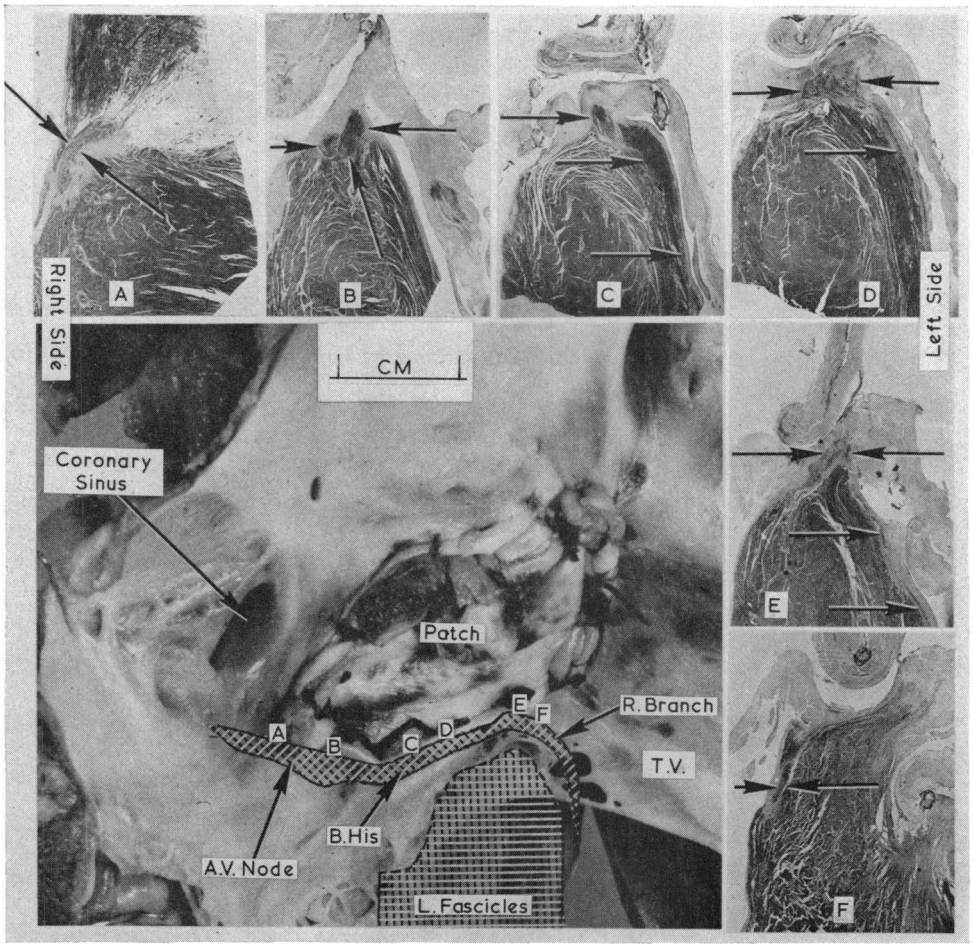

FIG. 17.—Ostium primum in the heart of a boy of 7 years. He had coarctation which was resected successfully. The following year, the defect was patched and the cleft in the mitral valve sutured. After operation, various arrhythmias, including heart block, occurred, and he died within 24 hours. The lower left picture shows the patched defect from the right side; note how the lower posterior sutures are adjacent to the bundle of His. For clarity the A-V system is shown as two separate components between C and E, the area from which left fascicles were arising from the bundle of His. (A) A-V node; dark area of hæmorrhage above it. (×3·3.) (B) Double bundle of His, much hæmorrhage in both. (×3·3.) (C) Bundle of His and left fascicles partly obliterated by hæmorrhage; note nearby suture in valve cusp. (×3·3.) (D) Bundle of His and left fascicles—note suture just beneath the bundle. (×3·3.) (E) Bifurcation—left fascicles attenuated. (×3·3.) (F) Right branch, with hæmorrhage above it; note suture in patch and in the root of the valve. (×5.) (All sections stained by hæmotoxylin-eosin.)

appeared, followed by complete right bundle-branch block. Blood cultures were sterile, but a downward course to right heart failure was pursued, leading to death in asystole 11 weeks after operation. At necropsy, the patch was found partly detached from the defect; some traumatic perforations were found in the cusps of the tricuspid valve and several chordæ tendineæ were ruptured. The A-V node was normal but the bundle of His coursed just below the postero-inferior rim of the defect on the left side, forming an inverted-U at its bifurcation in the substance of the muscular septum just below the defect. The right branch arose from the right limb of the bifurcation and soon was lost in an extensive area of inflammatory tissue just below the defect and in the extensive scarring of the healed infundibular resection.

Supracristal defect (Fig. 23). Boy of 12 years, cyanotic on exercise, who, in addition to the tetrad, had prolapse of an aortic valve cusp above the ventricular septal defect, causing aortic regurgitation. At operation, the aortic valve was replaced by a homograft which was also employed to help close the septal defect; the pulmonary valve was incised and the infundibulum

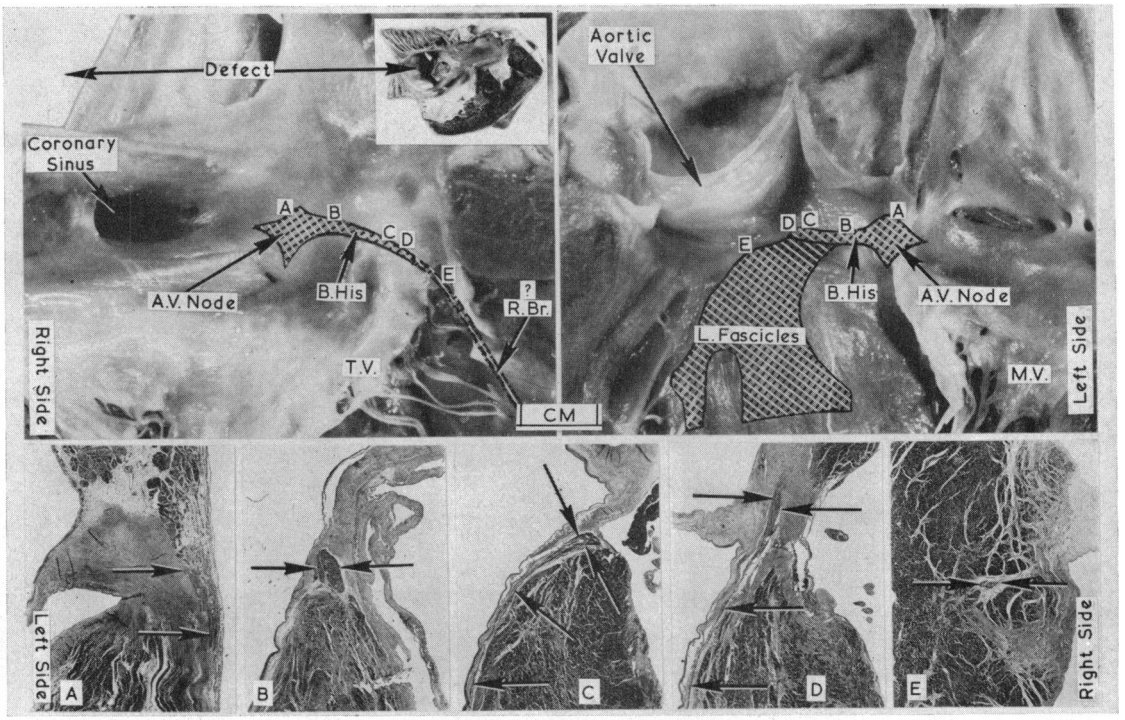

FIG. 18.—Inferior caval atrial septal defect in the heart of a cyanotic man of 55 years who had pulmonary hypertension with massive thrombosis of the pulmonary arteries, and right bundle-branch block. The small inset picture shows the large defect; only the anterior septum has developed and this shows a well-developed fossa ovalis. (A) A-V node. (×4·4.) (B) Bundle of His. (×4·4.) (C) Bundle of His and left fascicles. (×4·4.) (D) Bundle of His extending upwards and ending in the central fibrous body instead of bifurcating to form the right branch. The left fascicles are also attenuated. (×4·4.) (E) Right branch appearing again further forwards. The probable further course of the branch is indicated in the top left picture. (×10.) The disconnexion between the bundle and right branch and the interruptions beyond D correlate with the bundle-branch block present in life. (All sections stained by hæmatoxylin-eosin.)

resected. He died a few hours after operation. The A-V system pursued a normal course so that it ran well *behind* the defect. The bundle of His was duplicated at its origin and then ran quite low on the left side as a flattened band which formed an inverted-U at its bifurcation in the substance of the muscular septum. The right branch was readily followed by its hæmorrhagic "halo" until it was lost in the trauma of the infundibular resection.

A survey of the earlier literature shows that pioneers such as Keith (1909) not only elucidated the A-V system in the normal heart, but were aware of the essentially similar anatomy in ventricular septal defect; this was attributed to the fact that the system developed before complete septation had occurred (Mönckeberg, 1924), and was confirmed by numerous workers (e.g. Abbott, 1931; Yater, 1929).

The presence and importance of the A-V system was bound to become manifest when intracardiac repair of defects became possible, and this indeed was what happened, for in 1957, papers started to appear showing that heart block of various degrees could be produced in animals by creating experimental defects of the upper septum (e.g. Taufic, Lewis, and Bashour, 1957) and by surgical closure of septal defects in the human (e.g. Cooley, Kirklin, and Harshbarger, 1957; Kirklin *et al.*, 1957; Lillehei, 1957; Rodriguez and Wofford, 1957; Reemtsma and Copenhaver, 1958; Zimmerman *et al.*, 1958; Lev, 1958, 1959; and many later writers, see Hudson, 1965).

Truex and Bishof (1958) confirmed the position of the bundle of His and its branches in the postero-inferior margin of the high interventricular defect; in 15 hearts they also noted the variability in position of the bifurcation, and the occurrence of accessory bundles of Kent and of Mahaim's fibres into the top of the interventricular septum; they also found hæmorrhages in the system in 6 of 15 hearts, attributing them to agonal spasm of the numerous thin-walled venous channels traversing the system

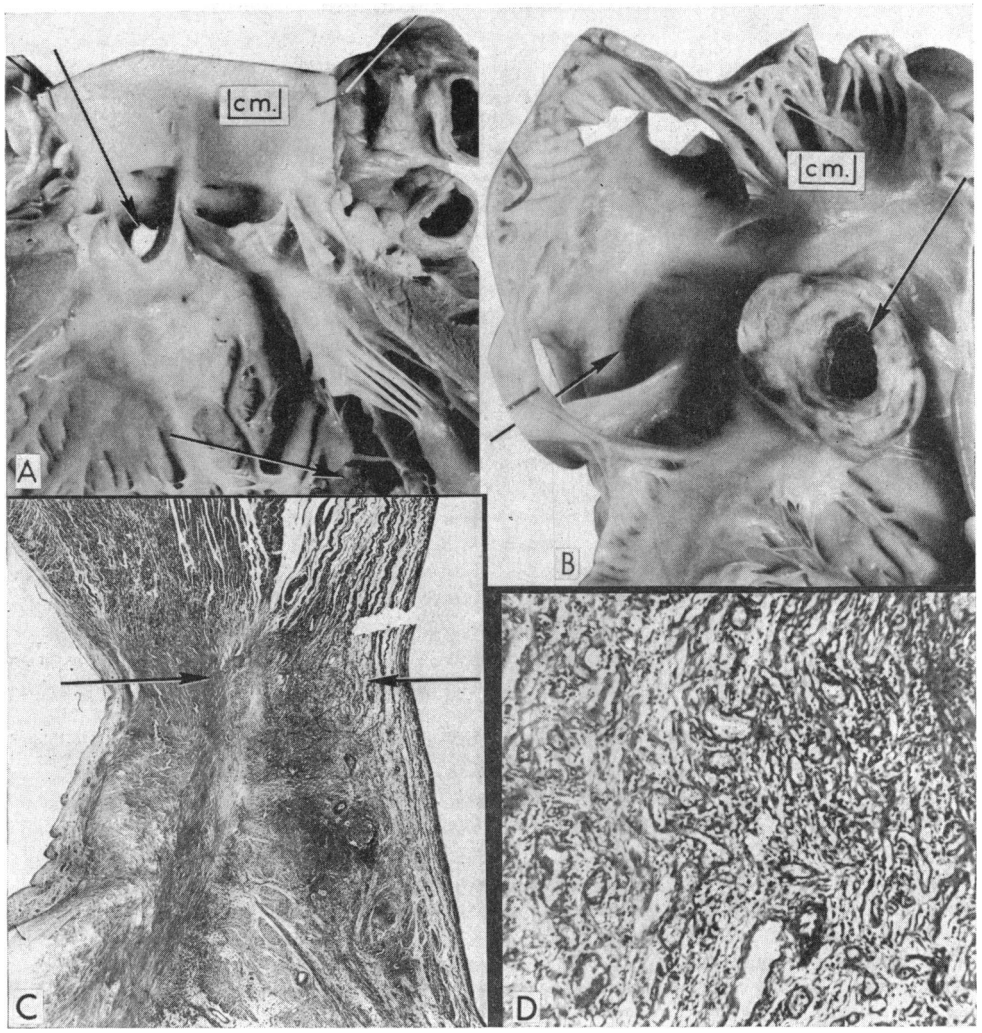

FIG. 19.—Infected aneurysm of the right coronary sinus of Valsalva in a man of 29 years, whose illness started with "influenza" 3 months previously and led to progressive dyspnœa and a pulse rate of 40 a minute. He died in the out-patient clinic on a referred visit. Necropsy showed evidence of congestive heart failure. (A) Aneurysm opening in right coronary sinus of Valsalva (upper arrow); the valve cusp is thickened and shortened. The lower arrow indicates massage trauma. (B) Aneurysm astride the tricuspid valve ring; the surface has been sliced away to reveal the thick inflammatory wall and hollow interior. Left arrow in inferior vena cava. (C) Inflammatory tissue at site of A-V node. (×4·25.) (D) Area between arrows in (C) showing the dense inflammatory infiltration between the muscle cells of the node. (×21.) (C and D stained by hæmatoxylin-eosin.) The bundle of His could not be identified further forwards, being virtually destroyed. [Reproduced from the author's book, *Cardiovascular Pathology* (1965), by courtesy of Edward Arnold (Publishers) Ltd.]

en route to the coronary sinus and right atrium, though none of the 15 patients had suffered any arrhythmia. In one heart, the right branch gave off an ascending ramus which passed upwards anterior to the defect towards the crista supraventricularis. (The writer observed a similar variation in a case of dextrocardia—see Fig. 24.) Rossi (1961) also stressed the vulnerability of the A-V system in the surgery of ventricular septal defect.

Occasionally, patients with ventricular septal defect or with Fallot's tetrad show electrocardiographic signs like those of A-V communis; Feldt, DuShane, and Titus (1965) found by comparison with ordinary septal defect and Fallot's tetrad, that

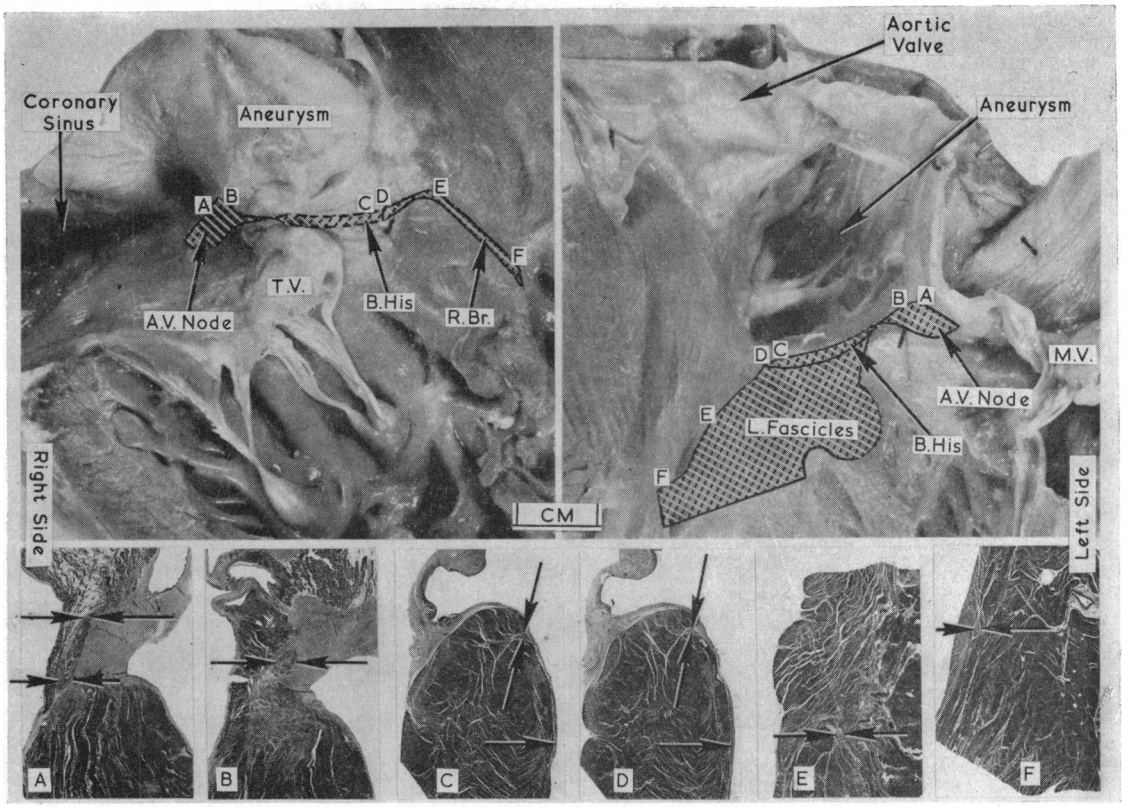

FIG. 20.—Aneurysm of the membranous septum in the heart of a man of 71 who had no arrhythmia. The A-V system courses below the aneurysm; it showed no lesion. (A) A-V node. (×2·3.) (B) Bundle of His. (×2·3.) (C) Bundle of His and left fascicles lying on the left side of the septum below the aneurysm. (×1·2.) (D) Bifurcation. (×1·2.) (E) and (F) Right branch. (×2·6.) (All sections stained by hæmatoxylin-eosin.)

the right branch arose late or was more circuitous, so that the left-sided stimulus was relatively earlier than usual, accounting for the electrocardiographic finding.

Dextrocardia. Two examples were studied, and both showed inversion of the A-V system.

Case 1 (Fig. 24). Cyanotic girl of 15 years with asplenia, midline liver, right-sided appendix and cæcum, inversion of the pancreas and lungs, dextrocardia, complete transposition of the great vessels, complete atrioventricularis communis, with ostium secundum defects, subvalvar pulmonary stenosis, and total anomalous pulmonary venous drainage into the left-sided superior vena cava. (These cardiovascular anomalies represent, in the main, the mirror-image of ordinary complete transposition with pulmonary venous drainage into a right superior vena cava.) She was investigated at the age of 4 years but the bewildering findings prohibited operation; she became more short of breath over the years and eventually a corrective operation was attempted, with partial success. The rhythm was normal before operation, but after it, atrial arrhythmia occurred, mainly nodal tachycardia with hypotension and pulmonary œdema. She also developed fits. She collapsed and died about 4 weeks after the operation. At necropsy there were thrombi in both internal carotid arteries, with cerebral softenings, and the complex heterotaxy and cardiovascular anomalies described above.

The sinu-atrial node was found at the root of the dextroposed superior vena cava and showed no lesion (see Fig. 4). The A-V system was inverted, the A-V node being on the left side; the bundle of His coursed along the upper rim of the A-V defect, extending downwards as a flat band on the left side and forming an inverted-U bifurcation at the rim; it was poorly defined for some distance, but then it appeared to continue as the left branch along the entire rim of the defect as 2 to 4 close-set tiny bundles. The thin sheet of right fascicles arose on the left side and coursed over the top of the muscular rim of the defect to fan out over the right side of the septum.

Case 2 (Fig. 25). Cyanotic woman of 24 years with

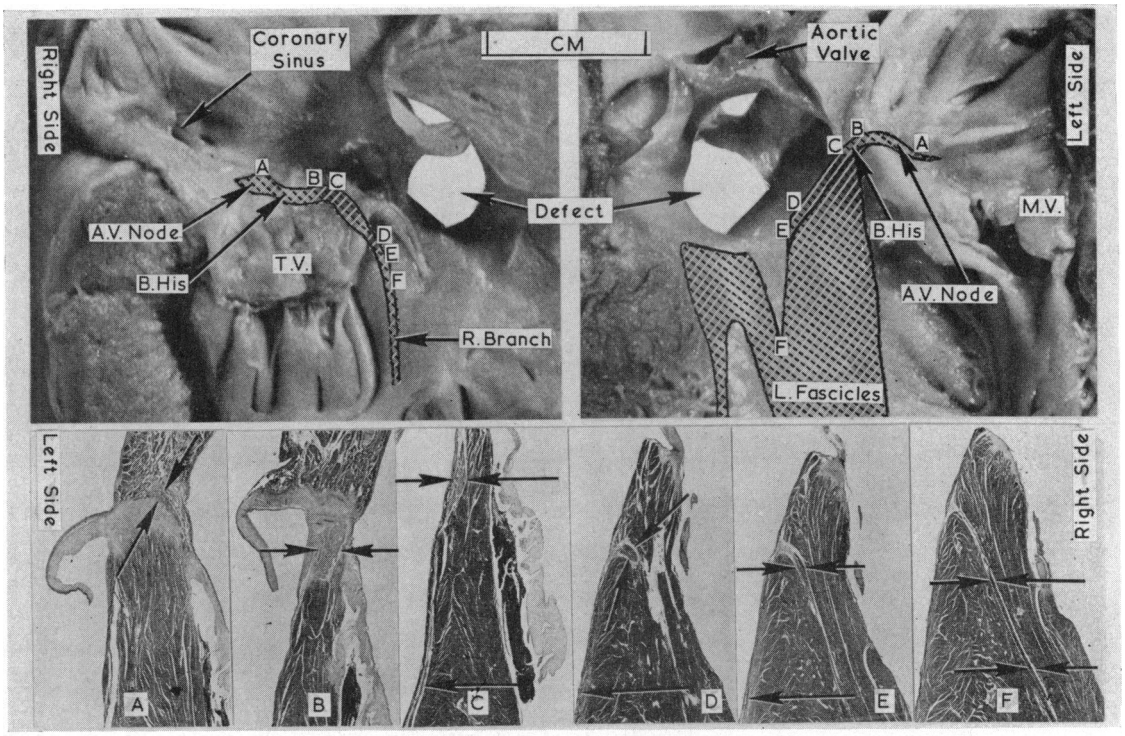

FIG. 21.—Isolated infracristal ventricular septal defect in the heart of a male infant of 5 months. (A) A-V node. (B) Bundle of His. (C) Bundle of His and left fascicles. (D) Bifurcation well down the left side of the septum. (E) and (F) Right branch traversing interventricular septum; it is cut longitudinally. Left fascicles still visible in E (lower left arrow). (All sections stained by hæmatoxylin-eosin. ×4·7.)

situs inversus totalis, single atrium with "cleft" mitral valve, and pulmonary hypertension; she died after a series of hæmoptyses. At necropsy, an extensive but unsuccessful search was made for the sinu-atrial node. The A-V system was inverted, but the bundle of His, in contrast to the first case, ran along the *top* of the muscular septum; it yielded a thin sheet of fascicles to the right side and continued as a left branch down the left side.

Corrected transposition (Fig. 26). A superb example of adult bulboventricular corrected transposition was found among a collection of specimens when the old mortuary of the Heart Hospital was cleared before rebuilding. It had been placed there presumably during the 1939–1945 war, but the writer was unable to trace its source, or any clinical details. The atria and great veins were normal, but the aorta arose anteriorly from a left-sided morphological right ventricle which was guarded by a left-sided tricuspid valve; there was a single coronary artery but no septal defect. Histology of the A-V system revealed that not only was it inverted, including the A-V node (though the coronary sinus entered the right atrium normally) but that the bundle of His was completely interrupted for a considerable distance, being lost in the central fibrous body. It reappeared much further forward down the right side of the septum, forming an inverted-U bifurcation into the musculature. Degrees of heart block are a common feature of this type of corrected transposition, and the writer would prophesy that, were clinical details available, they would establish that complete heart block was present in life in this patient.

Inversion of the A-V system in corrected transposition was noted by Uher (1935–36), Aschoff (1937), and by Lev, Licata, and May (1963). The last-named authors' findings were similar to those in the writer's case; however, the example they studied came from a patient with lævocardia; the coronary sinus entered the *left* atrium and there was no interruption of the bundle of His.

DISCUSSION

The present study highlights the surgeon's dilemma. Even fortified with the anatomical information presented, and alerted to the trauma which

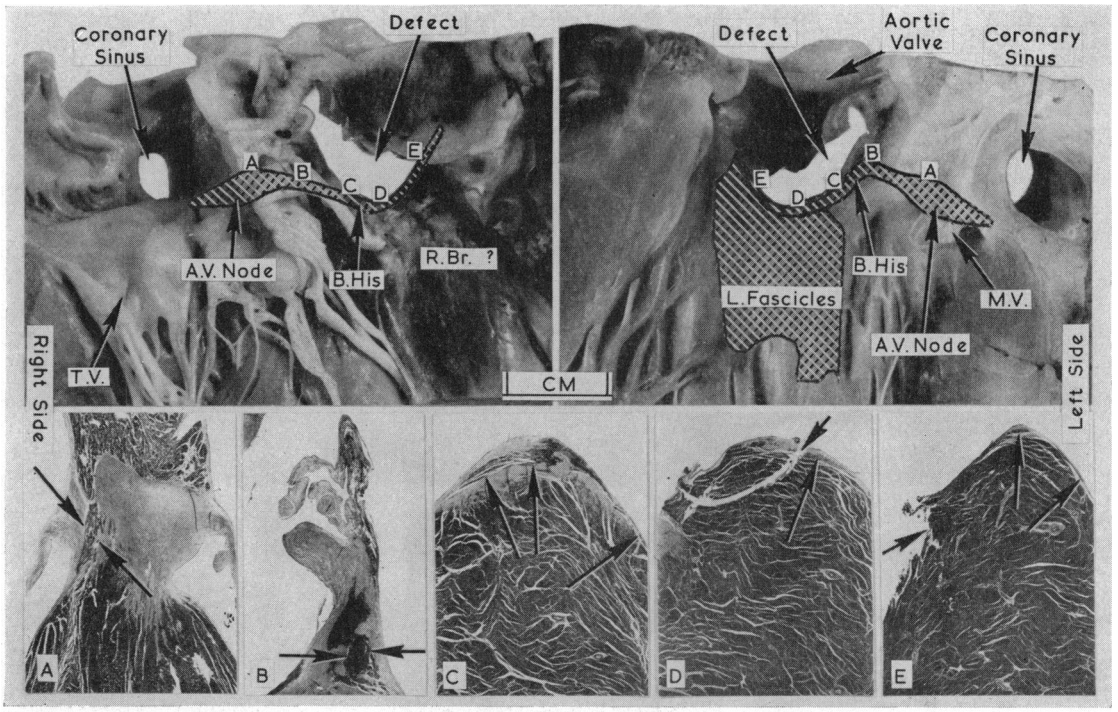

FIG. 22.—Fallot's tetrad in the heart of a cyanotic mongol youth of 16. At operation, the infracristal defect was patched, the infundibulum was resected, and the pulmonary valve replaced by a homograft. He died a few hours after operation from ventricular fibrillation. The sinu-atrial node showed severe hæmorrhagic trauma—see Fig. 6A. (A) A-V node. (×3·1.) (B) Bundle of His obliterated by hæmorrhage. (×4·75.) (C) Bifurcation, with hæmorrhage just above it at the rim of the defect. (×4·75.) (D) Suture track transecting A-V system. (×4.) (E) Trauma destroying right branch area (left arrow); left fascicles indicated by right arrows. (×3·1.) (All sections stained by hæmatoxylin-eosin.)

current intracardiac surgical procedures may sometimes inflict on the conducting system, how can valves be replaced or defects repaired without evoking this complication? No surgeon would wish to add an arrhythmia, even if temporary, to the hazards which every patient must face when undergoing intracardiac surgery; yet insecure anchoring of prosthetic valves and the incomplete closure of defects, which might result from zealous avoidance of the A-V system, may nullify the object of surgery and lead to complications just as formidable as conduction disturbances themselves.

With regard to the *sinu-atrial node* the writer will be forgiven for stating categorically that there is little excuse for surgical trauma; the landmark to the vital area should be widely known and is easily avoided. So often, this site seems to be a target for cannulation and extensive suturing which might well be performed in a safer area.

The *A-V system* presents a much more difficult problem. The danger areas in normally-formed hearts lie on the line between the coronary sinus ostium and the base of the membranous septum (medial commissure of the tricuspid valve) on the right side of the septum, and the whole of the left side of the septum, particularly in the area adjacent to the membranous septum (which lies between the right and non-coronary valve cusps) where the left fascicles are concentrated at their origin from the bundle of His, which courses in the lower posterior part of this structure. With a bicuspid valve, the coronary ostia provide alternative landmarks. Aortic valve prostheses must needs be inserted in the narrow space between the coronary ostia above and the membranous septum (between the right and non-coronary aortic valve cusps) below. This *can* be done successfully without damaging the A-V system, though it demands great surgical skill and experience, and an element of luck, even more so when using homografts. The writer believes that future developments in aortic valve repair will be along two lines. In the first, which the writer favours, the patient's own intact valve will be made efficient by relieving any stenosis (this is relatively easy) and inserting some new kind of small prosthetic device to prevent regurgitation, tailored to

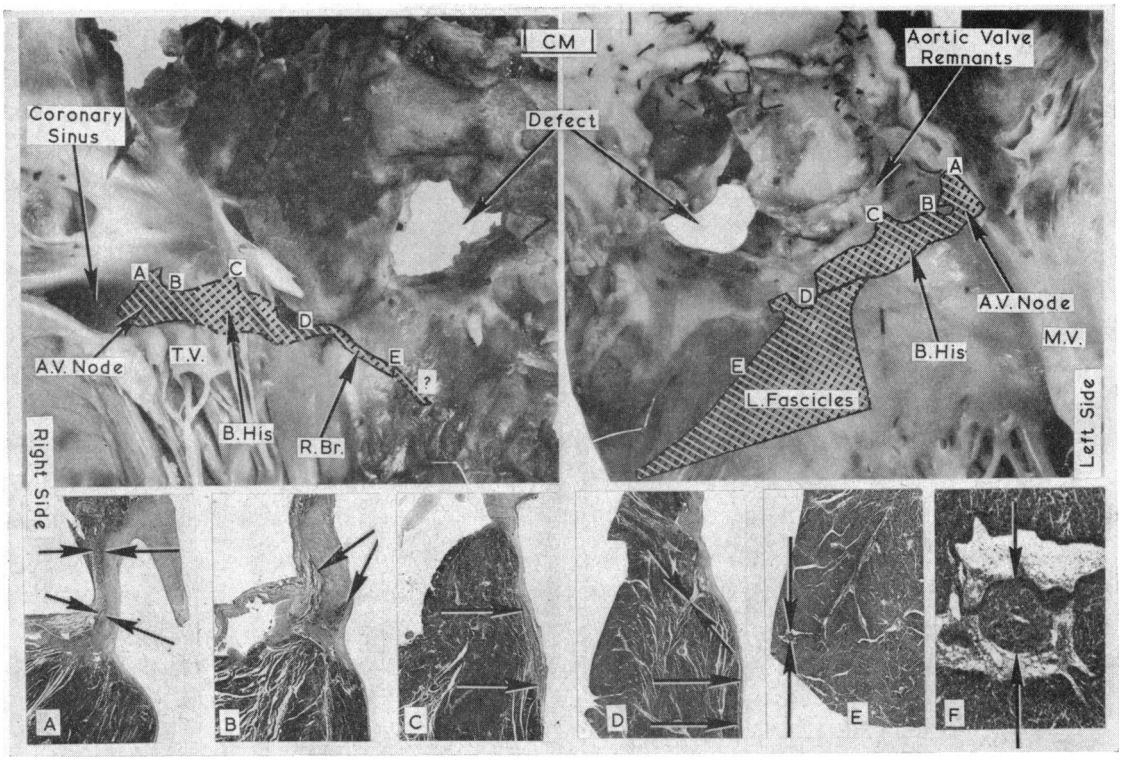

FIG. 23.—Fallot's tetrad with supracristal defect and aortic regurgitation due to prolapse of an aortic valve cusp in the heart of a boy of 12 years who was cyanosed on exercise. Pulmonary valvotomy was performed at the the age of 6. At the final operation, the defect was patched, the infundibulum resected, the valvar foramen ovale sutured and the aortic valve replaced by a homograft; he died within 24 hours of operation. The A-V system lies well clear of the defect. (A) A-V node—rather elongated and diffuse. (×2.) (B) Double bundle of His. (×2·7.) (C) Bundle of His down left side of septum. (×2·7.) (D) Bifurcation. The right branch (upper arrows) is very thin. (×1·7.) (E) and (F) Right branch with a hæmorrhagic "halo". It was destroyed beyond this point by the infundibular resection. (E×2·3, F×19) (All sections stained by hæmatoxylin-eosin.)

the patient's own valve at operation. The second line of approach will be the development of a durable trouble-free, flexible, and prosthetic valve, closely imitating the natural one, and designed for easy insertion in the subcoronary position by simple upper anchorage only, thus being well clear of the A-V system.

In hearts with cushion defects (ostium primum, A-V communis), and in those with infracristal ventricular septal defects, the danger areas are on a line from the coronary sinus ostium extending along the posterior inferior half of the rim of the defect, and the corresponding area of the left side of the upper septum adjacent to the defect. The "safe" areas thus appear to be the whole of the upper margin of a defect, and the lower anterior third of the rim on the right side, away from the actual summit where, rarely, conducting bundles may lie (as in Fig. 24). It is possible that valve cusps overlying the posterior part of the A-V system might provide sufficiently strong anchorage for sutures rather than the septum itself. With supracristal defects, the A-V system does not seem to be at great risk.

Infundibular resection should be confined to the outflow tract of the right ventricle and should not extend behind the crista supraventricularis because this may endanger the right branch.

A consoling feature of the present study is the relative constancy of the anatomy of the A-V system in all operable conditions; once the few salient features illustrated in this paper are mastered, the natural ingenuity and enterprise of surgeons should enable them to avoid the system, or at least ensure that any damage inflicted is purely accidental and minimal. I trust that my study, albeit imperfect and incomplete, will help to guide them in this praiseworthy but tantalizing endeavour.

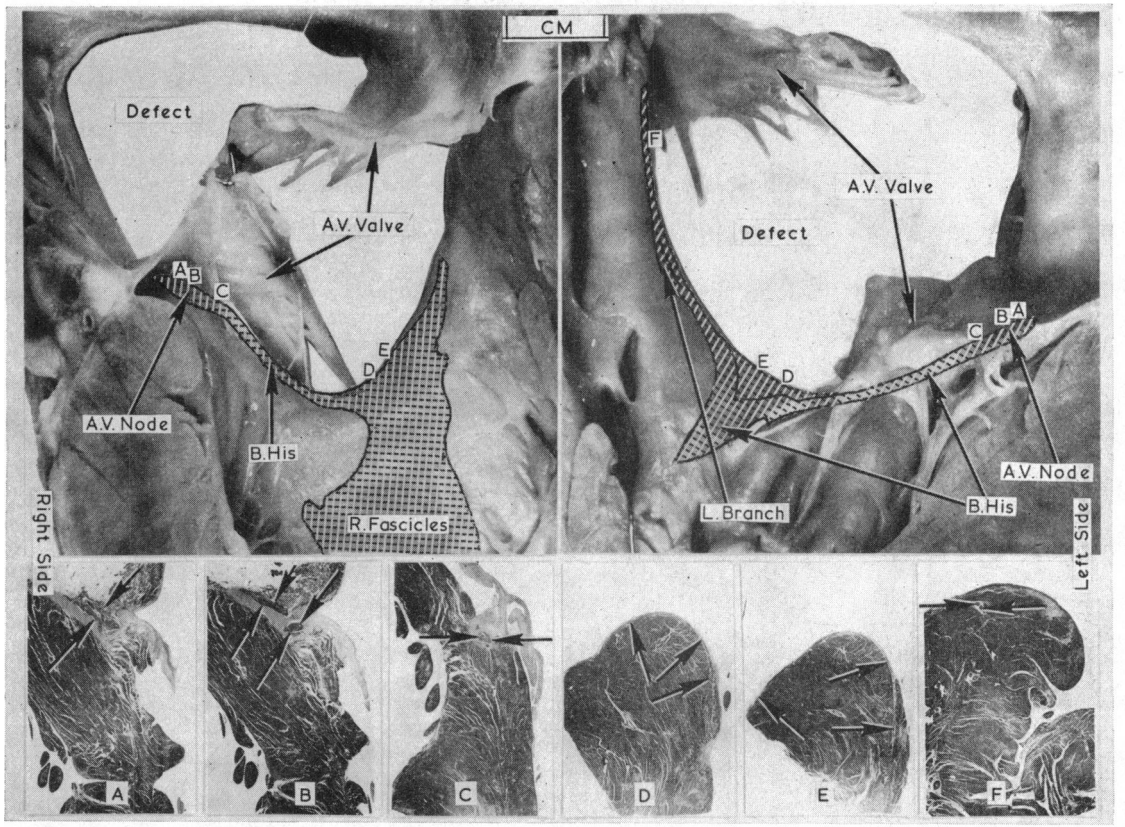

FIG. 24.—Dextrocardia in a cyanotic girl of 15 years who had asplenia, midline liver, inverted pancreas and lungs, transposition of the great vessels, complete A-V communis, subvalvar pulmonary stenosis, and total anomalous pulmonary venous drainage into the left-sided superior vena cava. Exploratory thoracotomy was carried out at the age of 5, and pulmonary valvotomy at 15; post-operatively she developed fits and atrial arrhythmias with pulmonary œdema, and she died 4 weeks after operation. Cerebral softenings associated with thrombosis of both internal carotid arteries were found at necropsy. The sinu-atrial node was inverted (see Fig. 4) and so was the A-V system. Note also how the anterior atrio-ventricular valve cusp can be lifted quite free of the ventricular septum. The upper left picture shows the smooth left ventricular surface of the right-sided left ventricle and the upper right picture shows the right ventricular appearance on the left side. (A) A-V node lying to the left of the central fibrous body. (×1·4.) (B) Penetration of central fibrous body. (×1·4.) (C) Bundle of His. (×1·4.) (D) and (E) Bundle of His and right fascicles appearing as a slender inverted-U over the rim of the ventricular septum. (D×1·75, E×1·4.) (F) Left branch appearing as two tiny bundles near the rim of the septum. (×2·1.) No left branch was found descending the left side of the septum. (All sections stained by hæmatoxylin-eosin.)

SUMMARY

An account of the histological anatomy of the conducting system in the normal heart and in the various congenital malformations amenable to open-heart surgery is presented, together with a description of the traumatic surgical lesions to the system which may result from valve replacement and from the repair of the common types of septal defects. In addition, the atrio-ventricular system has been studied in several other anomalies, including aneurysms of the sinus of Valsalva and membranous septum, dextrocardia, and bulboventricular corrected transposition; in the latter two conditions, complete inversion of the A-V system has been verified.

There is remarkable uniformity in the anatomy of the A-V system of His-Tawara in all the hearts studied, whether these are normally formed or congenitally malformed. It is demonstrated that the areas at risk to the system are, *on the right side*, on a line between the ostium of the coronary sinus and the base of the membranous septum in normal hearts, or the posterior half of the inferior rim in hearts with septal defects. It is also shown that

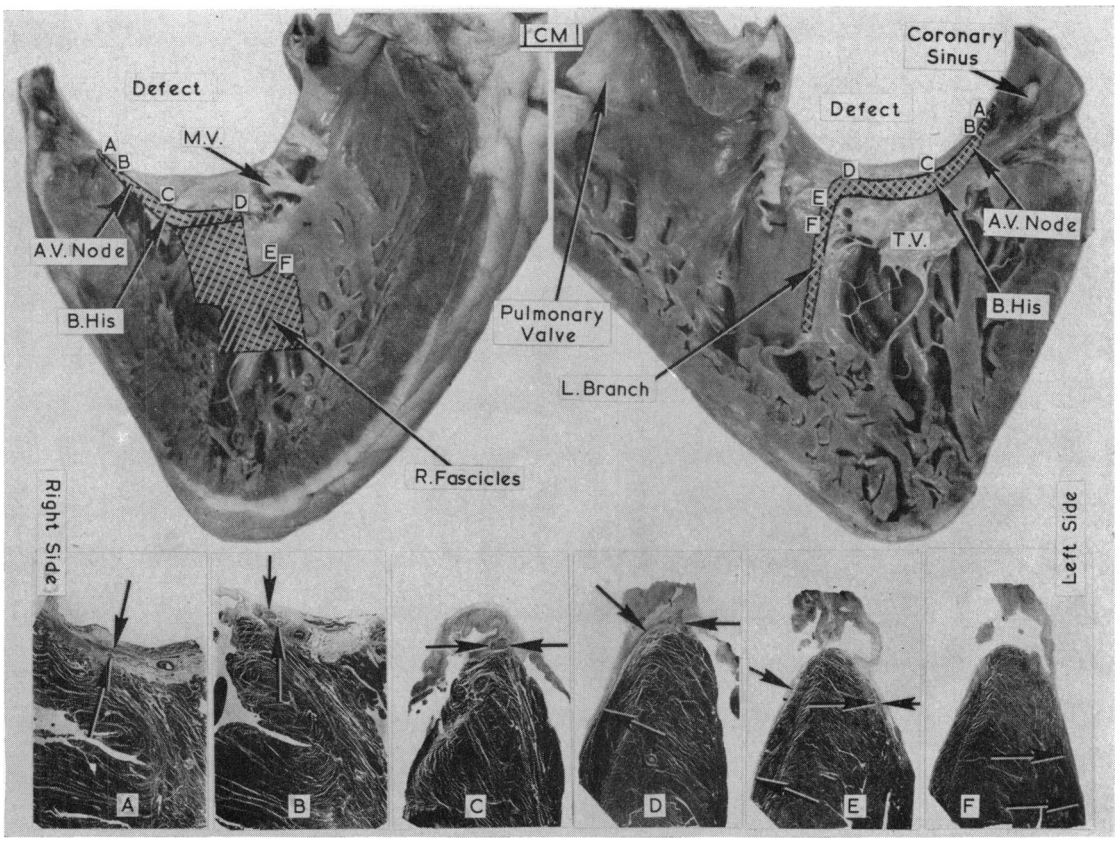

FIG. 25.—Situs inversus totalis (mirror-image) dextrocardia with single atrium in a cyanotic woman of 24 years who had pulmonary hypertension and died after a series of hæmoptyses. The upper left picture shows the smooth right side of the septum; the mitral valve was cleft. The upper right picture shows the muscular ridges of the left side of the septum. (A) A-V node on left side of central fibrous body. (×1·3.) (B) Penetration of central fibrous body. (×1·5.) (C) Bundle of His on summit of septum between the atrioventricular valve cusps. (×1·5.) (D) Bundle of His and right-sided fascicles. (×1·5.) (E) Bifurcation. (×1·5.) (F) Left branch cut longitudinally. (×1·3.) (All sections stained by hæmatoxylin-eosin.)

infundibular resection posterior to the crista supraventricularis may endanger the right branch. *On the left side* in normally formed hearts, the posterior half or more of the base of the membranous septum (between the right and non-coronary aortic valve cusps) and the endocardial surface of the neighbouring muscular septum is the area where the left fascicles are concentrated and therefore most vulnerable to trauma. In hearts with ventricular septal defects, the posterior two-thirds of the area adjacent to the rim of the defect should be considered vulnerable.

Knowledge of these facts may enable the cardiac surgeon to avoid damaging the system.

I am grateful to the Master and Wardens of the Worshipful Society of Apothecaries for the privilege of giving this lecture.

It is also my pleasure to acknowledge the enthusiastic and expert help in this intricate study, which I have received from my histology technicians, Mr. F. Dean and Mr. M. Blaszcynski, and from my medical photographer, Mr. B. Richards. I should also like to thank my secretary, Mrs. Joan Blow, who typed the manuscript.

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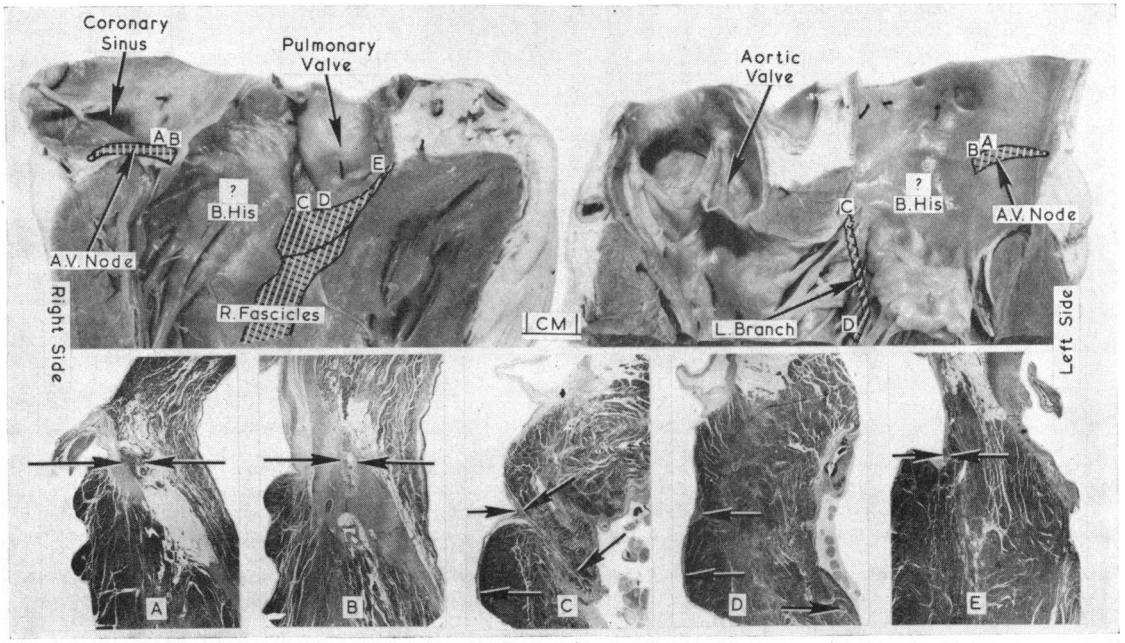

FIG. 26.—Bulboventricular corrected transposition in an adult heart; no clinical data available. The upper left picture shows the coronary sinus entering the right atrium, the posterior pulmonary valve, and the smooth "left ventricular" appearance of the right side of the septum. The upper right picture shows the anterior aortic valve in front of the crista supraventricularis, the single coronary artery ostium (the artery is transsected on the extreme left), and the muscular ridges on the left side of the septum. The A-V system is *completely* inverted, and also widely interrupted. (A) A-V node on *left* of central fibrous body. (×1·8.) (B) Bundle of His becoming faintly visible as it ends in the central fibrous body. (×3.) (C) Bundle of His reappearing down the right side of the ventricular septum (below the pulmonary valve) as a slender triangular wedge giving off right fascicles and left branch—the latter is traversing the septum. (×1·8.) (D) Bundle of His and right fascicles (left arrows) and left branch (right arrow). (×1·5.) (E) End of "bundle of His" which continued beyond the point at which right fascicles ceased. (×1·5.) (All sections stained by hæmatoxylin-eosin.)

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