Steps, Arches, and Struts Supporting the Aortic Leaflet of the Mitral Valve

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Background and aim of the study: **The study aim was to re-examine the form and function of the cords exclusive to the aortic leaflet of the mitral valve.**
Methods: **The ventricular surface of the leaflet was exposed by a longitudinal incision between the coronary sinuses of the aorta. The cords exclusive to the leaflet, in between the so-called commissural cords on either side shared with the mural leaflet, were inspected visually in 75 human hearts obtained at autopsy.**
Results: **The cords were found to form two groups: (i) cords to the free edge, which support the gossamer-thin free edge of the leaflet, and provide a low-pressure, bloodtight seal; and (ii) belly cords, which insert into the ventricular surface of the leaflet, usually forming graceful steps and arches between the lateral and medial groups of cordal support. Among these belly cords were found strut cords, which course perpendicular to the steps and arches.**
Conclusion: **The so-called cords to the rough zone, better considered as belly cords, must be distinguished from cords supporting the free edge of the leaflet, as they have different forms and subserve a different function. The belly cords usually form steps, arches and struts, which facilitate the distribution of stress, whereas the cords supporting the free edge function to provide a blood-tight seal. An understanding of the pattern and variations in cordal support is necessary to appreciate the pathology, and to tailor restoration in the surgical repair of diseased valves.**

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The mitral valve, including its cordal pattern, is as unique to each person as are the fingerprints. In the present study, the cords that support exclusively the aortic leaflet of the valve were examined in order to reconsider their physical form and function.

Materials and methods

A total of 75 normal human hearts, obtained at autopsy, was examined by exposing the ventricular aspect of the mitral valve through a longitudinal aortotomy between the left and right coronary arterial sinuses, and extending the cut into the left ventricle up to the apex, keeping close to the septum, and away from the mitral valve. A fiber-optic light source in the left atrium was used to transilluminate the aortic leaflet; this also aided visual inspection of the cordal insertions and both surfaces of the leaflet. An imaginary mid-mitral line (1,2), bisecting the leaflet, separated the lateral and medial cords. Both surfaces of the leaflets, and the mode of insertions on the ventricular surface of cords exclusive to the aortic leaflet, were visually inspected. Details of the so-called commissural cords, which have been previously described (3), were not included.

When describing the mitral valve, there is a clear need for scientific accuracy (4-6). In this respect, the cordopapillary support of the mitral valve is currently considered by surgeons to be supported by papillary muscles described as being *anterolateral* and *posteromedial*. The present authors have previously documented wide variations in the location of the normal papillary muscles as regards their size, configuration and location (1). Recent developments in tomographic techniques for diagnosis that place the heart in the context of the body, nonetheless, show that the current terms used by surgeons - though time-honored - are unequivocally inappropriate, as the so-called 'posteromedial' muscle is in reality anterior to its partner. The most appropriate term for description has still to be

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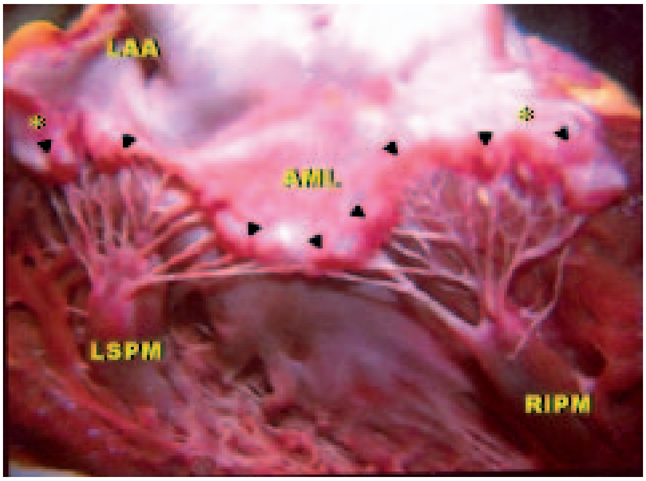

Figure 1: The mural leaflet of the mitral valve has been divided to view the atrial surface of its leaflets. Note the nodular thickenings (arrowheads) forming a narrow curvilinear rough zone of apposition of the leaflets. AML: Aortic leaflet of the mitral valve; LAA: Left atrial appendage; LSPM: Left superior papillary muscle; RIPM: Right inferior papillary muscle. The asterisks indicate the two halves of the mural leaflet.

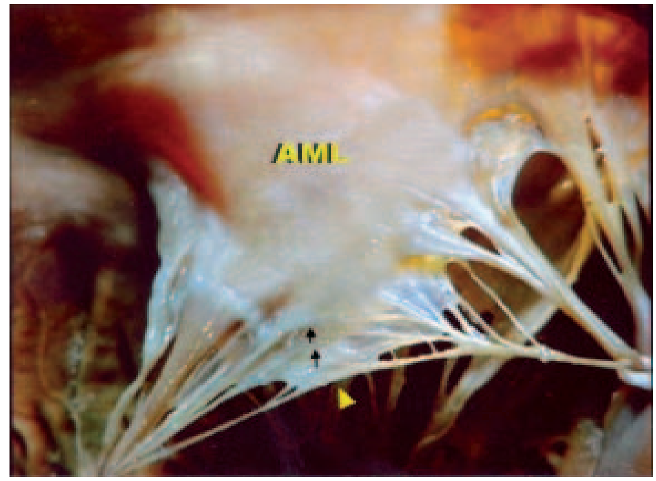

Figure 2: Note the thin, delicate narrow strip of leaflet tissue at the free edge of the aortic leaflet (AML). The tendinous free edge cords from either side meet across the mid-mitral line supporting a tongue-like extension of the leaflet (arrowhead). The cords also join each other on either side to form faint cordal arches (arrows).

determined. Some authors have suggested that the terms posterosuperior and anteroinferior would be better (4-6), but these are unfamiliar to most surgeons. For descriptions in the present report, therefore, we have opted to use the terms *left superior* and *right inferior*.

Results

The mitral valve is viewed as possessing two leaflets, closing along a single curved zone of apposition. At either end of this zone, the so-called commissural cords support the edges of both leaflets. In between these commissural, or linking cords, the aortic leaflet has medial (*right*) and lateral (*left*) groups of cordopapillary support, separated by the mid-mitral line which bisects the leaflet (1,2).

Rough zone

A curvilinear rough ridge was visible on the atrial surface, about 2 mm away from, and parallel to, the free edge. This is best observed in fresh hearts (Fig. 1). The ridge, itself about 2 mm wide, is composed of small irregular endocardial thickenings. This forms part of the curvilinear commissural zone of apposition between the leaflets.

Thin translucent free edge

Between this ridge and the free edge of the leaflet there is a smooth narrow strip of gossamer-thin, translucent tissue, again best seen in fresh specimens (Fig. 2). Fixing in formalin causes the delicate free edge to shrivel up.

Cords and arches supporting the free edge

Cords inserting into this free edge formed arches with each other, giving the free edge a crenellated or notched character. These cords on either side of the mid-mitral line effectively joined hands to support a tongue-like extension of the free edge at the mid-mitral line (Fig. 2). This extension apposed a similar tongue-like extension in the middle scallop of the mural leaflet.

Steps

Between the free edge and the aortic-mitral curtain, cords are inserted on the ventricular aspect of the belly of the leaflet, usually in a stepwise fashion. In 25 hearts, up to four steps were well defined (Fig. 3A), whilst in a further 28 hearts the steps were identifiable but not clear-cut. At each step, there was progressive thickening of the leaflet from the free edge to the base, the leaflet becoming increasingly opaque to transillumination at each step (Fig. 3B), until it merged with the opaque aortic-mitral curtain. Cords emanating from the papillary muscle inserted into one, two, or more of the steps without dividing, or after dividing up to five times.

Cordal insertions without steps

Steps were not identifiable in 22 hearts. Rather, the cords inserted in a crowded fashion in a curvilinear

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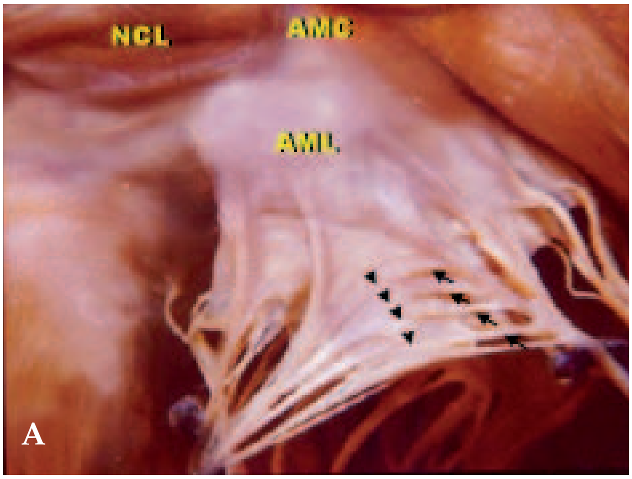

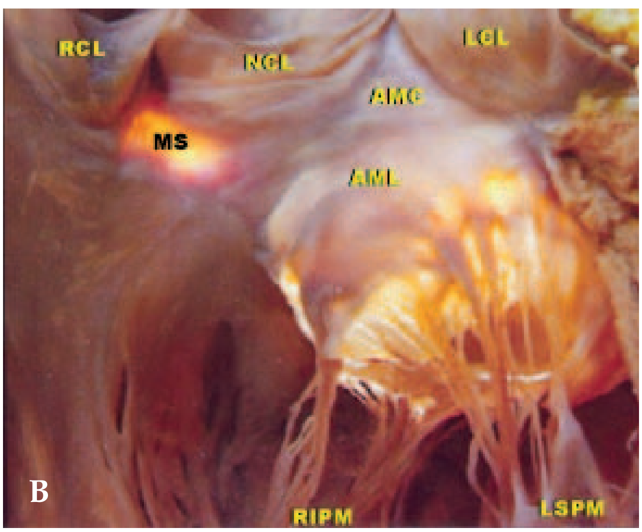

Figure 3: A) Note the cordal steps (arrows) and arches (arrowheads) tying up both groups of cordopapillary support. B) Stepwise decreasing translucency of the aortic mitral valve leaflet (AML) from the free edge to the aortic-mitral curtain (AMC). LCL: Left coronary leaflet; LSPM: Left superior papillary muscle; MS: Membranous septum; NCL: Non-coronary leaflet; RCL: Right coronary leaflet; RIPM: Right inferior papillary muscle.

zone parallel to the free edge, leaving a central zone which was clear on transillumination (Fig. 4).

Arches

As with the arches formed by the cords attached to the free edge, at each step the cords from each side formed arches across the mid-mitral line (Fig. 3A), and between each other. When inspecting the ventricular surface of the mural leaflet, which is usually divided into a central mural scallop and varying number of scallops on either side (3), it is also possible to recognize similar steps and graceful arches crossing the central scallop (Fig. 5).

Figure 4: Note the clear translucent central zone and outer opaque curvilinear zone (arrows) of insertion of cords in the aortic leaflet of the mitral valve (AML). LCL: Left coronary leaflet; NCL: Non-coronary leaflet.

Strut cords

The strut cords, which are stouter and thicker than the other belly cords, were identifiable medially in 68 hearts, and laterally in 49. They were double in three hearts medially, and in six hearts laterally. They took their origin from the tip of the *right inferior* papillary muscle in 68 hearts, and from the *left superior* muscle in 41 hearts. In seven hearts laterally, they originated from the slope of the *left superior* papillary muscle, while in one heart there was an exclusive papillary muscle supporting the strut cord. The termination of the struts varied (Table I). When steps were identifiable, varying number of steps were reinforced by branches of these strut cords (Table II).

Criss-cross cordal insertions in two planes

The free edge cords, and the cords supporting the ventricular surface in steps, usually exhibited webs which were parallel to the surface of the leaflet, before blending with the tissue of the leaflet, and adding to its thickness. Among the strut cords, some extended

Table I: Termination of strut cords.

Insertion	Medial struts	Lateral struts
Only annulus	1	1
Annulus + basal third		1
Basal third	03	03
Middle third	29	31
Free edge + outer third	35	10

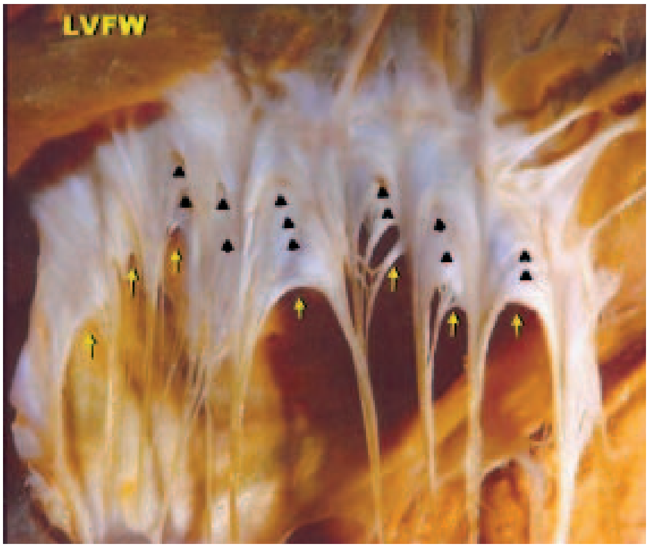

Figure 5: Note the multiple arches in the free edge (arrows) and belly (black arrowheads) of the multiscalloped mural leaflet, the ventricular surface of which has been exposed by removing the mural wall of the left ventricle. LVFW: Left ventricular free wall.

from the free edge for varying distances, perpendicular to the steps, running towards the annulus, either embedded in the substance of the leaflet, resembling the struts in an umbrella, or the cables of a suspension bridge, dropping branches perpendicular to the surface of the leaflets. Thus, cords are arranged in two groups, criss-crossing and perpendicular to each other, with cordal insertions in two perpendicular planes.

Redundant cords or accessory leaflet tissue

Some lax redundant cords attached to the leaflet were observed, but these seemingly were functionally superfluous. They were medial in three hearts and lateral in two. Accessory tissue was attached to the leaflet medially in one heart.

Table II: Relationship of branches of strut cords to the steps.

Steps supported by strut	Medial strut cords	Lateral strut cords
Free edge	01	05
Free edge + Step 1	-	01
Step 1	04	01
Step 1 & 2	04	02
Step 2	09	04
Step 2 & 3	03	02
Step 3	05	07
Step 3 & 4	01	-
All steps	04	04
Whole length of leaflet (umbrella strut)	02	01

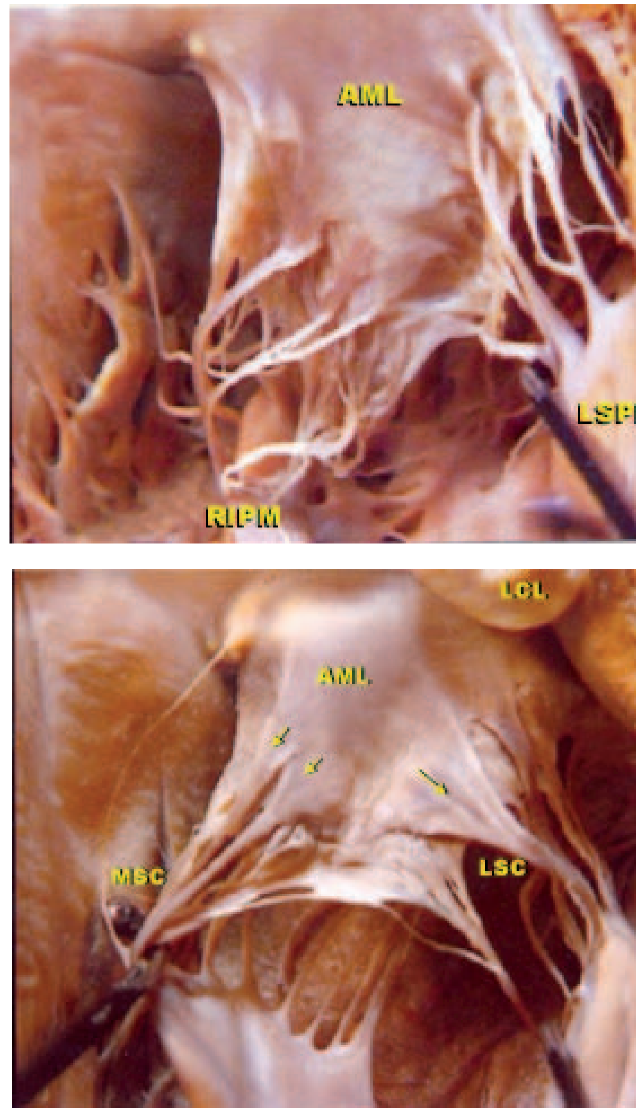

Figure 6: A) Note a suspension type of medial strut cord dropping branches to many steps. B) Prominent lateral (LSC) and medial strut cords (MSC) are seen (arrows). Note the web-like broad insertion perpendicular to the surface of the leaflet. AML: Aortic leaflet of the mitral valve; LCL: Left coronary leaflet; LSPM: Left superior papillary muscle; RIPM: Right inferior papillary muscle.

Discussion

Leonardo da Vinci, steps, and arches

The images of the mitral valve as portrayed by Leonardo da Vinci (7) document steps and arches in the anterior leaflet of the mitral valve. da Vinci's illustration of the mitral valve evokes the awe and splendor of walking into a cathedral or a temple, like the Rameswaram temple in south India, also with pillars and arches arranged stepwise (7). Brock (8) compared the cordal insertions to a gothic column with fan tracery. Surgeons, who usually work on the atrial aspect of

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the leaflet, have not typically paid attention to the details of the cords on the ventricular side. Recent focus on transventricular remodeling of the left ventricle, however, should emphasize the need to pay more attention to the ventricular surface of the leaflets.

One commissure and two fans

The mitral valve is arranged in the form of a continuous veil of leaflet tissue, arbitrarily divided into aortic and mural leaflets (1) by imaginary commissural lines, which are the shortest perpendiculars from the free edge to the annulus, one to either side of the aortic leaflet.

Functionally, the surgeon is concerned not only about competent closure of the valve, but also about full diastolic opening. In the closed position, the two leaflets appose each other along a curved zone of apposition, which forms a true single commissure (5,6). During diastole, the leaflets splay out; this splaying, along with closing of the leaflets, is regulated by the fan-like arrangements of the cordopapillary support to each half of the valve (1,2). The lateral (*left*) and medial (*right*) fans can be identified by the surgeon from the transatrial view by retracting the middle of the leaflets (9). The hub of each fan is formed by the corresponding group of papillary muscles (1). The cords form the struts, while the corresponding halves of the two leaflets are the fabric.

By considering the wide variations of the papillary muscles (1), cords (2,3) and leaflets (3), the configuration of the fan will be unique to each heart (1). Nonetheless, viewing the entire cordal support as a fan on either side (2) facilitates assessment of pathology, as well as subsequent cordal reconstruction, especially when judging the length and lie of cordal substitutes. In each fan, there are cords exclusive to the leaflet, and so-called commissural cords which link the leaflets. These commissural cords would better be designated *linking cords*, thus circumventing potential controversy in using the term 'commissure'. The medial (*right*) and lateral (*left*) fans contribute cords to support the corresponding halves of the aortic leaflet. It is these cords which formed the focus of the present study.

Earlier classifications of cords

Roberts and Cohen (10) classified the cords based on the number of times they divided before inserting to the leaflets, whereas Quain (11) following the precedent of Tandler, divided the cords into three orders. The first and second orders took origin from the papillary muscles, and inserted into the free edge and ventricular surface, respectively. The third order arose from the ventricular wall, and inserted into the base of the mural leaflets. Lam et al. (12) grouped together the first two orders of Tandler and Quain, and labeled them as *rough zone* cords. Among these rough zone cords, Lam and colleagues identified thick stout chords, described earlier by Brock (8), and labeled them as *strut* cords. Subsequently, these authors (12) christened the third order of Tandler and Quain as *basal* cords. They also introduced the terms 'cleft cords' to account for the cords supporting the clefts or slits in the mural leaflet, and 'commissural cords' for the cords connecting the aortic and mural leaflets (12).

Rough zone cords

The genesis of the term *rough zone* (12,13) is possibly related to the curvilinear zone of apposition of the atrial surface of the leaflets, characterized by a ridge of multiple endocardial thickenings parallel and close to the free edge. During echocardiography, this narrow zone of apposition of the leaflets is easily identified. Looking from the atrium, the leaflets appear to adopt the 'namaste' sign of Indian greeting, with opposed palms forming the zone of apposition, the forearms the unapposed part of the bellies of the leaflets, and the fingers the cords. It has long been presumed that cords insert into a corresponding rough zone on the ventricular surface (12), making it opaque to transillumination, and leaving behind a clear translucent central zone (13). The findings of the present study revealed that the so-called rough area on the ventricular surface exhibits graceful steps and arches, as illustrated long ago by da Vinci (7).

Steps, arches and stress

Functionally, whether in a building or the mitral valve, the arrangement of support in steps and arches helps to distribute stress, ensuring participation from both sides. The multiple arches seen in the longer mural leaflet are equally graceful. The ventricular surfaces of both leaflets need to withstand the brunt of the systolic force generated by the ventricle. Studies relating to finite element analysis of mitral valve must consider the role of steps and arches in the distribution of stress.

Clear and opaque zones

When steps are prominent, the leaflet becomes progressively thicker and opaque to transillumination, step by step, from the free edge to the aortic-mitral curtain. Only when the steps are indistinct, and cordal insertions form an arcuate band parallel to the free edge, is the central area of the leaflet clear and translucent (13,14) (Fig. 4). It needs to be determined whether such valves are more prone to disease processes such as prolapse.

Strut cords

Brock (8) showed that the central cords to each half of the aortic leaflet were strong and thick, and labeled the areas of insertion of these cords as *critical*. He described them as arising from the summit of the papillary muscle, and in the line of direct pull of the papillary muscle. On either side of the *critical cords* in each half, the cords were described as being obliquely set. It was Lam et al. (12) who subsequently re-named the critical cords described by Brock as the *strut cords*. These are the thickest and largest of the cords supporting the rough zone, and are found in more than 90% of hearts. Considering the wide variations among the papillary muscles (1,10), reliance cannot be placed on the origin of critical cords for their identity. There is also difficulty in identifying these so-called *strut cords* on the basis only of their thickness or classical location. In the present study, the strong cords eligible to be termed as struts were found to vary widely in number, size, location and morphology. Some of them ran along the ventricular surface of the leaflet for varying distances up to the aortic-mitral curtain, embedded in the leaflet, like a strut in an umbrella. Sometimes, cords of similar size and thickness were present beside each other, forming *double struts*, yet in other hearts the struts were absent. A few struts crossed the leaflet from the free edge to the annulus, like the cable of a suspension bridge, dropping branches to varying number of steps (Fig. 6A), often with web-like insertions perpendicular to the surface of the leaflet (Fig. 6B); these were unlike the web-like insertions of cords of steps and arches, which were in the plane of the leaflet. These suspension cords have been described in porcine hearts by van Rijk-Zwikker et al. (15). This criss-crossing cordal arrangement most certainly functions to distribute the stress imposed on the aortic leaflet. It was observed that, when the struts had wide perpendicular (Fig. 6B) insertions, or dropped prominent branches to varying number of steps (Fig. 6A), the belly cords were few in number. However, when the strut cords were not very prominent, or even absent, the belly cords were more numerous. This observation is likely to be relevant to the rupture of cords and cordal reconstruction.

Sealing of the apposed leaflets by cords to the free edge

The free edge cords insert into the margin of the leaflet (11). The extremely thin translucent free edge of the leaflet is devoid of any thickening; rather, it provides a blood-tight seal caudal to the curvilinear band of apposition of the two leaflets. This thin seal, which is best appreciated in fresh specimens, is clearly spared the primary impact of the force of apposition at the rough zone of apposition on the atrial surface. Gentle apposition of the thin free edge of the leaflets seals the orifice, without eversion of the free edge. Lomholt et al. (16) have shown experimentally that the cords to the free edge are less exposed to stress than the belly cords. There is a need to follow the proposals of Quain (11), therefore, and retain the distinction of the cords attaching to the free edge in any classification, because they are distinct in design, location, and function. They should be distinguished from the cords attached to the rough zone. The delicate free edge of the normal valve, and its related cords, are invariably thickened and shrunken or shriveled in diseased valves, and this might contribute to mitral regurgitation.

Muscular cords

Ranganathan et al. (14), in their study of 50 autopsy hearts, found five muscular cords in the lateral half, one cord at the lateral commissure, and two cords in the medial half. These muscular cords were considered as developmentally arrested cords that had retained their muscular embryonic structures. Cords, when muscularized, would extend a direct pull on the annulus, instead of transmission of the force through cords. Cords are possibly muscular when they are formed from the ventricular musculature, and later become fibrous (17).

Clinical significance

The arrangement of cordal support in steps, arches and struts helps to distribute the stress on the aortic leaflet. Becker and De Wit (18) found deficient cords, not compensated by adjacent cords, in eight out of 100 normal hearts, and in 36 of 40 hearts with billowing or prolapse of the leaflets. The aortic leaflet was involved in eight normal hearts, and in 26 abnormal hearts. The wide variations in the cordal support of the aortic leaflet found in the present study well supports the view of Becker and De Wit (18) that there could be gradations between normal valves and billowing or prolapsing valves due to subtle variations in cordal support.

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Sadly, Professor Solomon Victor died before this manuscript was accepted for publication. V. M. N. dedicates this report to Professor Victor's eternal memory, and thanks him for the outstanding support provided throughout their many collaborations.

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