Dimensional Ratios of Normal Mitral Valve Structures: A Tool for Determining the Degree of Geometric Distortion in Individual Patients

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Background and aim of the study: **One objective of mitral valve repair is to restore the distorted mitral apparatus geometry to its normal dimensions specific for each patient. Because all dimensions of the normal aortic and mitral valves should be related, it was hypothesized that, in the presence of a normal aortic annulus, it would be possible to determine the dimensions of the structures needed for mitral valve repair.**

Methods: **In seven sheep, sonometric ultrasound crystals were implanted at the left and right trigones (T1, T2), lateral annulus (P1, P2), and the tips of the anterior and posterior papillary muscles (M1, M2). The distances T1-T2, M1-M2, T1-M1, T2-M2, P1-P2, P1-M1, and P2-M2 were measured at end-systole (ES), end-diastole (ED), and maximum and minimum lengths. Using these measured distances, fractional relationships were computed, and the average fractional relationship was used to determine a 'calculated' distance. The 'measured' and 'calculated' distances were then compared using a paired *t*-test.**

Results: **All fractional relationships were close to 1, with ED 1.00 ± 0.21, ES 0.99 ± 0.19, maximum length 0.99 ± 0.19, and minimum length 0.94 ± 0.21. The intertrigonal distance (T1-T2) expanded by 4.19 ± 3.81%, and the transverse diameter (P1-P2) contracted by -6.15 ± 3.69% from ED to ES. The interpapillary muscle distance (M1-M2) contracted -22.3 ± 6.5%. The two distances with the least amount of contraction were those of T1-M1 and T2-M2, with contractions of -3.06 ± 2.39% and -3.27 ± 1.37%, respectively. P1-M1 and P2-M2 expanded 5.60 ± 2.89% and 6.84 ± 3.60% from ED to ES.**

Conclusion: **The mitral valve dimensions and calculated fractional relationships were similar in all sheep. As shown previously, the ratio of aortic annulus diameter (easily measured echocardiographically) to the intertrigonal distance (T1-T2) is 0.79 and 0.80 in humans and sheep, respectively. This distance can be used to determine normal mitral valve geometry and, therefore, preoperatively to calculate the degree of geometric distortion present in individual patients.**

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After myocardial infarction, functional ischemic mitral regurgitation (IMR) is a frequent occurrence, its presence leading to a doubling of mortality. Mitral valve repair seems to achieve better results than mitral valve replacement in IMR, for which several approaches to treatment have been suggested. The current standard approach is reduction annuloplasty, whereby a small annuloplasty ring is implanted to re-approximate the free edges of the valve; however, although the patient's quality of life is improved, the survival rate is not changed (50% at five years) (1). An IMR recurrence rate of 30% at a mean of 3.5 years' follow up has also been demonstrated (2).

Besides mitral valve annuloplasty, which reduces the always-present annulus dilatation, other subvalvular surgical maneuvers appear to be necessary (3). Several such intracardiac techniques have been suggested, including sectioning the anterior basal chords (4), placing a sling around the papillary muscles (5), or re-approximating the papillary muscles to the annulus (3,6). The objective of these maneuvers is to reduce or avoid continuous lateral displacement of the papillary muscles. All of these techniques are hampered by a lack of information on the degree of anatomical restitution required for the individual patient. Clearly,

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there is a need for easily obtainable, precise geometric parameters of the remodeled left ventricle and mitral valve compared with normal, for each individual patient. These data should guide the surgeon in his or her attempts to restore the normal geometry of the left ventricle and mitral valve. Intraoperative transesophageal echocardiography (TEE) should be the preferred method of identifying and quantifying these geometric distortions before surgery, and the TEE measurements should then serve as a roadmap for the precise surgical maneuvers necessary to restore normal mitral valve geometry.

In the present study, using an acute ovine model, sonomicrometry was employed to search for obtainable and reliable normal geometric parameters that could then be used to determine the degree of anatomic distortion present in individual patients.

Materials and methods

Animals

The mitral valve apparatus was studied during the cardiac cycle in seven adult sheep (mean body weight 68.7 ± 8.8 kg), using digital, three-dimensional sonomicrometry (Sonometrics, Inc., London, Ontario, Canada). For these investigations, six ultrasonic crystals were implanted onto the mitral valve of each animal while maintained under cardiopulmonary bypass (CPB).

All animals received humane care in compliance with the principles of the Animal Welfare Act, the *Guide for Care and Use of Laboratory Animals* from the United States Department of Agriculture, and the Institutional Animal Care and Use Committee of The University of Montana.

Surgical protocol

Anesthesia was induced with intravenous ketamine (1.0 mg/kg) and propofol (4.0 mg/kg) and maintained with isoflurane (1.5-2.5%). Artificial ventilation was achieved with a volume-regulated respirator (North American Drager, Telford, PA, USA) supplemented with oxygen at 2 l/min. The heart was exposed by standard left thoracotomy through the fourth intercostal space. The left femoral (16 F) and left internal thoracic (10 F) arteries were cannulated, and a venous cannula (32 F) was inserted into the right atrium. The aorta and arch vessel were cross-clamped, and cold crystalloid cardioplegic solution was infused into the root. The ultrasonic crystals (1 mm) were implanted and secured with 5-0 polypropylene sutures. Through a left atriotomy, four crystals were placed on the mitral valve annulus at the left and right trigones (T1 and T2), and at the base of the two lateral scallops of the posterior leaflet (P1 and P2). Two crystals were placed on the tip of the anterior and posterior papillary muscles at the level of insertion of the two main anterior basal chords (M1 and M2). To reduce possible interference with valvular movements, the electrodes coming from each crystal on the annulus were exteriorized through the atrial wall, while those from the papillary muscles were exteriorized through the left ventricular wall. In order to avoid inter-operator variability, all of the crystals were implanted by the same surgeon. Two high-fidelity, catheter-tipped pressure transducers (model 510; Millar Instruments, Inc., Houston, TX, USA) were placed in the proximal ascending aorta and through the left ventricular apex. After discontinuing CPB, and when the animal was hemodynamically stable for at least 15 min, recordings were taken at 200 Hz. On completion of the experiment, the animal's heart was arrested with a lethal injection of potassium chloride, explanted, and the correct position of the crystals checked.

Phases of the cardiac cycle

Changes in the lengths of the various mitral segments were time-related to end-diastole (ED) and end-systole (ES), as defined by the aortic and left ventricular pressure curves (7). End-diastole, or the beginning of systole (isovolumic contraction), was defined as the beginning of increase of left ventricular pressure ($dP/dt > 0$). The dicrotic notch on the aortic pressure curve served to define ES.

Definition of anatomic regions

The mitral valve apparatus was studied throughout three consecutive heartbeats. Both, ED and ES distances were extensively evaluated to determine the relationship between the different landmarks. Using the mitral valve alphanumeric nomenclature described by Kumar et al. (8), the following distances were measured: intertrigonal (T1-T2); bases of the posterior leaflet lateral scallops (P1-P2); interpapillary muscles (M1-M2); and papillary muscle to mitral annulus (T1-M1, P1-M1, T2-M2, and P2-M2).

Two different mitral valve geometric planes were defined: an anterior mitral plane delineated by the two trigones and both papillary muscles (T1-T2-M2-M1); and a posterior mitral plane delineated by the two bases of the lateral scallops of the posterior leaflet and both papillary muscles (P1-P2-M2-M1). These two quadrilateral planes intersect at the interpapillary distance (Fig. 1).

Data acquisition

Sonometrics Digital Ultrasonic Measurement System TRX series 16 and 1-mm transmitter/receiver crystals were used to measure the displacements. A postprocessing program (SonoSOFT Version 3.1.4, Sonometrics Corp.) was used to examine each individual length between crystals. All crystal distances and

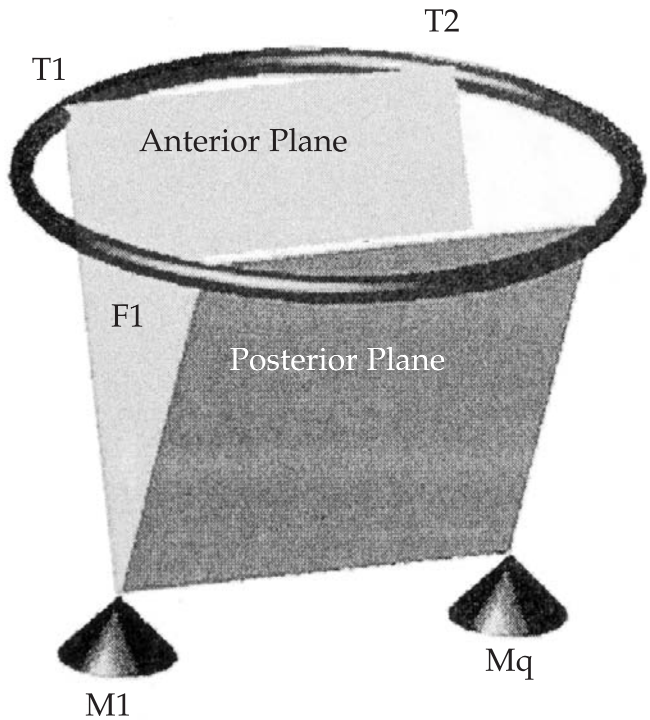

Figure 1: Anterior mitral plane defined as quadrilateral containing both trigones (T1, T2) and papillary muscles (M1, M2). The posterior plane contains both bases of posterior lateral scallops (P1, P2) and papillary muscles (M1, M2).

pressures were synchronized on the same timeline. Millar pressure transducer control units (TCB 600) and MIKRO-TIP pressure transducers (Millar Instruments, Inc.) were used to obtain the aortic and left ventricular pressures. All pressure readings were connected to the Sonometrics analog signal acquisition channels and zeroed. All calibrations and baselines were checked at the end of the experiment.

Measurements

After close examination of the data, three consecutive heartbeats with the least amount of noise were chosen for analysis. The data were filtered using an algorithm that employs the time-of-flight principle to detect the first peak of the ultrasound pulse as that pulse travels from transmitter to receiver.

The average 'measured' distances over three consecutive heartbeats of the seven sheep were computed at ED, ES, and at maximum and minimum lengths. One sheep did not provide a good trace for the reading between P1 and P2, and hence these data could not be used in the calculations. The calculations performed with P1-P2 used a sample size of six, versus the sample size of seven which was used for all other calculations. The percentage change from maximum to minimum lengths, and from ED and ES, was then calculated. The percentage changes for each measurement (i.e., T1-T2 at ED for seven sheep) were checked for outliers using a box plot. Outliers were found in five of the data sets. In order to correct this problem, without reducing the sample size, the individual trace for the distance measurement was re-evaluated to see if the average 'measured' distance could be improved by using a different heartbeat. In all cases, the outlier was replaced by using a different heartbeat. By using these 'measured' distances, fractional relationships were computed by dividing the following measured distances: T1-T2/M1-M2, T1-T2/T1-M1, T1-T2/T2-M2, T1-T2/P1-P2, M1-M2/P1-P2, P1-P2/P1-M1, and P1-P2/P2-M2. The averages of these fractional relationships were computed. Using the average fractional relationship, 'calculated' distances were determined by dividing the 'measured' distances by the average fractional relationship. The 'measured' and 'calculated' distances were then compared, assuming that the data were normally distributed between the sheep. A typical calculation, using T1-T2/M1-M2 as an example, is shown in Table I.

Table I: Fractional relationships determined by dividing T1-T2 by M1-M2 at end-diastole (ED).[*]

Sheep no.	Measured M1-M2 (mm)	Measured T1-T2 (mm)	Fractional relationship	Calculated M1-M2 (mm)
1	20.8	20.0	1.0	22.2
2	33.7	24.6	0.7	27.3
3	24.6	23.6	1.0	26.2
4	21.9	26.9	1.2	29.9
5	26.4	21.4	0.8	23.8
6	33.6	27.8	0.8	30.9
7	35.8	29.9	0.8	33.2
Mean ± SD	28.1 ± 6.2	24.9 ± 3.5	0.9 ± 0.2	27.7 ± 3.9

[*]The 'measured' T1-T2 was then divided by the average fractional relationship to obtain the 'calculated' M1-M2. This was done for all measured distances at ED, end-systole (ES), and maximum and minimum lengths to obtain the data in Table II.

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Statistical analysis

The summary statistics were reported as mean ± SD, and a two-tailed *t*-test for paired comparisons with a significance level of $p \leq 0.05$ was used to determine significance from ED to ES, and from maximum to minimum lengths.

Results

Model characteristics

During the surgical procedure the mean CPB time was 133.7 ± 3.9 min, and the mean cross-clamp time 86.7 ± 2.3 min. At the time of recording, hemodynamic conditions were as follows: heart rate 99 ± 6 bpm; aortic pressure 67/40 ± 2/3 mmHg; and stroke volume 33 ± 2 ml. All valves were shown competent on epicardial echocardiography. At necropsy, each of the sonographic crystals was in the correct position, in all animals.

Mitral valve changes from ED to ES

Comparing segment lengths at ED and ES, the mitral valve annulus underwent an asymmetrical pattern of contraction and expansion. The intertrigonal distance (T1-T2) expanded by 4.19 ± 3.81%, and the transverse diameter (P1-P2) contracted by -6.15 ± 3.69%. The interpapillary muscle distance (M1-M2) showed the largest contraction (-22.3 ± 6.5%). The anterior trigone to papillary muscle lateral lengths (T1-M1 and T2-M2) and posterior lateral lengths (P1-M1 and P2-M2) changed differently throughout the cardiac cycle. T1-M1 and T2-M2 experienced little contraction (-3.06 ± 2.39% and -3.27 ± 1.37%, respectively), while the posterior lateral lengths experienced larger changes during the cardiac cycle: P1-M1 expanded by 5.60 ± 2.89%, and P2-M2 by 6.84 ± 3.60%, from ED to ES. The similarities in the expansions of the posterior lateral lengths (ca. 6%) and contractions of the anterior lateral lengths (3%) should also be noted.

Mitral valve changes from maximum to minimum

As the maximum and minimum percentage changes did not occur precisely at ED and ES, the maximum and minimum values were also determined in order to obtain a greater understanding of the movements of the anterior and posterior planes throughout the cardiac cycle. The time-related changes in the anterior plane of one sheep (which was representative of the entire group) is shown in Figure 2. The interpapillary distance (M1-M2) showed the greatest change throughout the cardiac cycle (31.26 ± 6.65%). The intertrigonal distance (T1-T2) moved in the direction opposite to the motion of the papillary muscles, with less amplitude, and had maximum values of 12.85 ± 7.68%. The anterior lateral lengths showed a much more stable relationship, with a maximum change of 3.58 ± 1.91% and 3.33 ± 2.01% for T1-M1 and T2-M2, respectively.

The posterior plane showed a similar motion to that of the anterior plane, with the lateral lengths remaining relatively stable and the most movement occurring in the annulus and papillary muscles throughout the cardiac cycle. The maximum change of the transverse diameter (P1-P2) was 15.11 ± 4.49%, with a greater change apparent in the posterior segment of the annulus than in the anterior segment (T1-T2). The relationship of the posterior lateral lengths was 6.83 ± 3.09% for P1-M1, and 7.48 ± 2.70% for P2-M2. These relationships are shown in Figure 3.

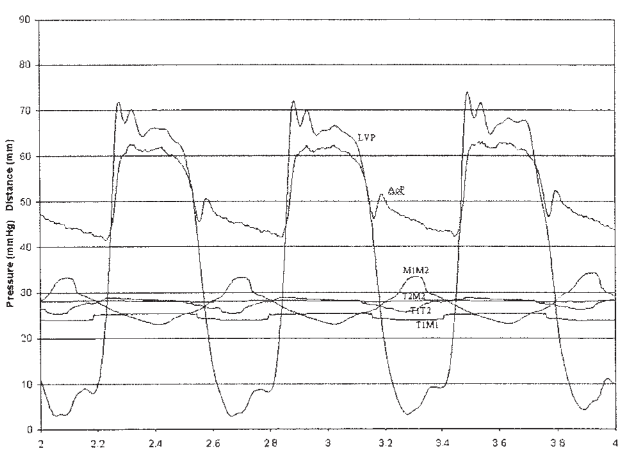

Figure 2: The anterior plane of the mitral valve apparatus. The greatest movement occurs in the papillary muscle distance (M1-M2), followed by the intertrigonal (T1-T2) and anterior lateral lengths, T1-M1 and T2-M2.

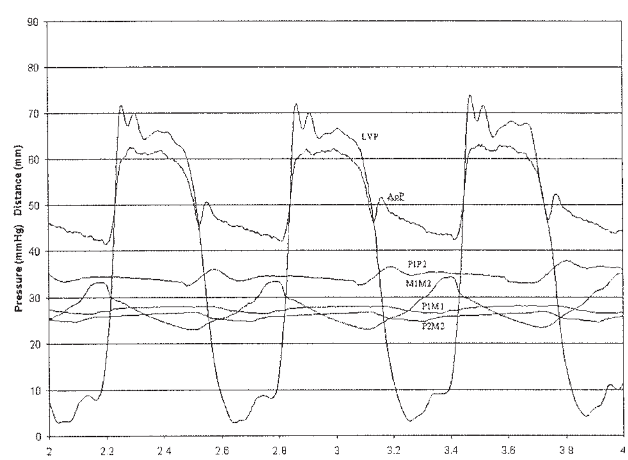

Figure 3: The posterior plane acts similar to the anterior plane, with the transverse diameter (P1-P2) showing a greater movement than the intertrigonal distance (T1-T2) of the anterior plane. The posterior lateral lengths move similarly to each other, and with very small amplitude.

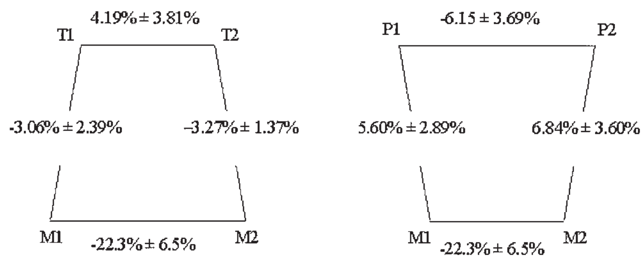

Figure 4: Length changes of the anterior (T1-T2-M1-M2) and posterior plane (P1-P2-M1-M2) from end-systole to end-diastole.

Fractional relationships of the mitral valve apparatus

The expansion and contraction of different landmarks of the mitral valve annulus and papillary muscles are key factors in understanding mitral valve dynamics. The fractional relationships between the measured distances were critically analyzed at ED, ES, and maximum and minimum lengths. The relationships between all segments were close to 1 in ED (1.00 ± 0.21), ES (0.99 ± 0.19), and at both maximum length (0.99 ± 0.19) and minimum length (0.94 ± 0.21). Using the 'measured' distances, fractional relationships were computed by dividing these measured distances, T1-T2/M1-M2, T1-T2/T1-M1, T1-T2/T2-M2, T1-T2/P1-P2, M1-M2/P1-P2, P1-P2/P1-M1, and P1-P2/P2-M2. The averages of these fractional relationships were calculated. Using the average fractional relationship, 'calculated' distances were determined by dividing the 'measured' distances by the average fractional relationship. The 'measured' and 'calculated' distances were then compared; these fractional relationships are listed in Table II.

A strong mathematical relationship was found between the different segment lengths of the mitral valve apparatus. Also, because all fractional relationships were very close to 1, the anterior and posterior planes were considered to take on a shape *similar* to that of an equal-sided quadrilateral. A simple schematic of the planes and the percentage change from ED to ES can be seen in Figure 4.

Discussion

The importance of annulopapillary continuity for left ventricular function is well established (9-13). For example, Gams et al. (11) proved that the left ventricle changed markedly in response to loss of the subvalvular apparatus, which led these authors to conclude that not only was the size and shape altered, but also that the ventricular wall thickness decreased, causing an increase in wall tension. However, the specific underlying mechanism responsible for this phenomenon is lacking. Komeda et al. (14) showed that, in normal sheep, the distance from the papillary muscles to the annulus remained constant throughout the cardiac cycle.

The present results showed little change between the tip of the papillary muscle and key points of the annulus. This constant length is most likely due to the presence of the main basal chords, which have been shown to be under constant tension during the cardiac cycle (15,16). Anteriorly, two thick stay chords connect the papillary muscles to the trigones through their insertion into the undersurface of the aortic curtain. These chords are wrongly called 'strut' chords; rather, they should be called 'stay' chords because a strut is defined as a member which is designed to resist longitudinal compression, whereas a stay serves as a support structure (17). The function of the anterior stay chords is critical to left ventricular function. In an acute sheep model, transection of these chords did not induce mitral valve regurgitation, but significantly decreased cardiac output and maximum dP/dt (9).

Although the dynamic geometry of the mitral valve has been extensively studied (18-25), to the present

Table II: Fractional relationships determined by dividing specific segment lengths at end-diastole (ED), end-systole (ES), and maximum and minimum lengths.

Plane	ED	ES	Maximum length	Minimum length
Anterior				
T1-T2/M1-M2	0.9 ± 0.2	1.2 ± 0.1	0.9 ± 0.2	1.2 ± 0.2
T1-T2/T1-M1	0.9 ± 0.1	0.9 ± 0.1	0.9 ± 0.1	0.8 ± 0.1
T1-T2/T2-M2	0.9 ± 0.1	0.9 ± 0.1*	0.9 ± 0.1	0.8 ± 0.1
T1-T2/P1-P2	0.8 ± 0.1	0.9 ± 0.2	0.8 ± 0.2	0.8 ± 0.1
Posterior				
M1-M2/P1-P2	0.9 ± 0.1	0.7 ± 0.1	0.9 ± 0.1	0.7 ± 0.1
P1-P2/P1-M1	1.3 ± 0.1	1.2 ± 02	1.3 ± 0.1	1.2 ± 0.1
P1-P2/P2-M2	1.3 ± 0.2	1.1 ± 0.2	1.2 ± 0.2	1.1 ± 0.2

Values are mean ± SD.
*Statistically significant, p ≤0.05.

authors' knowledge no geometric relationship has been described between the different mitral valve structures. Defining the anterior and posterior planes has revealed new geometric relationships with significant clinical implications. The present findings show that the distances between the papillary muscle tips and annulus, between the trigones, and between the bases of the posterior lateral scallops, are substantially constant. The only significant change during the cardiac cycle was the distance between the papillary muscles. Therefore, determining any single distance should allow the remaining segments to be calculated, and the information acquired should provide a quantitative basis for mitral valve repair.

At present, mitral valve repair for functional regurgitation is based on stabilizing the annulus with an annuloplasty ring (26). This ring can be sized by measuring the intertrigonal distance, which previously was thought to be immobile. However, several studies, including the present investigation, have shown that this distance not only changes during the normal cardiac cycle but also dilates in disease, particularly in cases of ischemic and dilated cardiomyopathy (27). In these cases, heterogeneous dilatation of the whole annulus and apicolateral displacement of the papillary muscles is also found, resulting in leaflet tethering that leads to mitral valve regurgitation (28,29). An obvious need exists for precise - but easily obtainable - geometric parameters of the remodeled left ventricle and mitral valve compared to the normal situation for each individual patient. These data should guide the surgeon in his or her attempts to restore the normal geometry of the left ventricle and mitral valve. Intraoperative TEE should be the preferred technique by which to acquire and quantify these geometric distortions before surgery, and the measurements should serve as a roadmap for the precise surgical maneuvers necessary to restore normal anatomic geometry.

The standard treatment of a simple reduction annuloplasty is probably insufficient, and should be accompanied by other maneuvers at the subvalvular level (3,6). This approach requires a detailed preoperative knowledge of the degree of anatomical distortion present in the individual patient, and allows the surgeon surgically to redress the distortions with a reliable set of geometric guidelines. The data reported in the present study provide a set of ratios that should allow the surgeon to reconstruct all parameters based on any single parameter. As reported previously, the ratio between the normal aortic valve diameter (easily obtained with TEE) and the intertrigonal distance is 0.79 and 0.8 for humans and sheep, respectively (30). This relationship could then be used not only to select the appropriate size annuloplasty, but also to restore the distances between the papillary muscles themselves, and the distance between the annulus and the papillary muscles.

Study limitations

The main limitation of the present study was the invasive, acute, and open-chest nature of the animal model, and the deleterious effect of CPB and ischemia might also have resulted in abnormal valve behavior. Variability in the precise location of the crystals must also be considered, despite all implantations having been performed by the same surgeon to minimize this problem. Likewise, the presence of crystals and their attached electrodes is inherent to sonometric studies. Ideally, a larger number of sheep should be studied, as the small sample size might have adversely affected results. Additionally, it must be emphasized that findings in sheep are not necessarily applicable to humans, and although most dynamic valve studies have used an ovine model, variability between species might influence the results obtained. While the present data should be valuable for an understanding of the mitral valve, their validity in the clinical setting must await specifically designed echocardiographic studies.

In conclusion, the ratios between the lengths of the different basic structures of the normal mitral valve are close to 1. Knowing the intertrigonal distance makes it possible to calculate the correct annulopapillary and interpapillary lengths. Moreover, because the ratio between the normal aortic valve annulus (easily obtained with echocardiography) and the normal mitral valve intertrigonal distance is known, it is possible preoperatively to determine the degree of geometric distortion present in a particular patient and to plan the necessary corrective maneuvers.

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