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ORIGINAL RESEARCH ARTICLE

Left ventricular chamber geometry in cardiomyopathies: insights from a computerized anatomical study

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Abstract

Aims Some authors have hypothesized that left ventricular chamber dilatation in ischaemic and idiopathic cardiomyopathies results in spherical transformation. Aiming to characterize how this transformation occurs, a study was performed by comparing normal and dilated specimens regarding sphericity and proportionality in left heart chambers. It is important to provide data for the development of therapeutic strategies in these diseases.

Methods and results An anatomical study was performed by comparing normal (n = 10), ischaemic (n = 15), and idiopathic (n = 18) dilated human cardiomyopathic specimens regarding left ventricular chambers and their segmental proportionality to normal hearts. It was performed by capturing and processing images with proper software in three different levels of left ventricular chamber (basal, equatorial, and apical). These obtained data were analysed based on sphericity and proportionality by two dedicated indexes. *Spherical shape*: Calculated segmental indexes showed that dilated specimens were not spherical because they were smaller than as expected for a spherical shape (all values were <70% of a perfect sphere). *Proportionality*: There was no difference between basal index perimeters among groups, but apical index was lower in dilated specimens than in normal hearts, and so dilatation was not proportional to normal hearts.

Conclusions Left ventricular chambers of anatomical specimens with dilated cardiomyopathies did not display a spherical shape and were not proportional to normal hearts.

Keywords Left ventricle remodelling; Ventricles; Cardiomyopathy; Heart failure

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Introduction

Dilated cardiomyopathies, as ischaemic and idiopathic, cause ventricular chamber transformation.

Although spherical and proportional left ventricular dilatation has been an accepted paradigm,[1–3] some authors such as Gibson and Brown[4] believe that ventricular dilatation does not result in a spherical shape and is not proportional to normal hearts.

One of the cornerstones for surgical treatment of dilated diseases is understanding how this geometrical distortion in left ventricular chamber occurs.

Several morphometric indexes have already been proposed. Some of them are based on dilatation at equatorial ventricular area; others on whole or segmental ventricular weight or even on the relationship between these measures and patient height.[2,4–6]

Anatomical studies concerning apical and basal segmental ventricular remodelling or focusing on how proportional to normal heart the ventricular chamber dilatation occurs are not so common.

Aiming to characterize how spherical or proportional to normal hearts the left ventricular chamber dilatation is, this anatomical study was performed by comparing normal and dilated specimens in order to verify the following hypotheses:

(1) Left ventricular chambers in dilated specimens display a spherical shape.
(2) Left ventricular chamber dilatation in dilated cardiomyopathies is proportional to normal hearts.
(3) It is possible to suggest a general model for chamber and ventricular walls dilatation.

Methods

Ethics approval

This study was approved by the Ethics Commission of Medical School of São Paulo University, ID 501/06.

Study design

An anatomical study was performed.

Inclusion criteria

Inclusion criteria were pathologic diagnosis of dilated ischaemic and idiopathic cardiomyopathies for the dilated groups and normal diagnosis in the control group.

Exclusion criteria

Exclusion criteria were previous cardiac surgery, acute myocardial infarction, pacemaker or resynchronization therapy, and ventricular aneurysm.

Material

Forty-three cadaver heart specimens, previously fixed in 10% formalin solution and the inside of the left ventricular chambers stuffed with cotton balls, were classified into one of the following three groups: normal or dilated (ischaemic and idiopathic), based on the diagnosis of the pathology department.

Demographic data by group:

(1) Normal: 10 specimens, weight average of 280.4 g, ranging from 212.0 to 338.0 g.
(2) Idiopathic: 18 specimens, weight average of 595.4 g, ranging from 358.0 to 942.0 g.
(3) Ischaemic: 15 specimens, weight average of 606.4 g, ranging from 400.0 to 840.0 g.

Methods

Longitudinal axis measurement and transversal specimen slicing

First of all, the measurement of the longitudinal axis length (in centimetres) from the posterior atrioventricular sulcus to the ventricular apex (AV-AP length) was performed.

Second of all, three segmental transversal slices were measured from the atrioventricular sulcus to the apex: at 20% (basal point), at 50% (equatorial point), and at 80% (apical point) (*Figure 1A*).

Digital image capture of transversal slices

Digital pictures were taken from the basal face of three segmental transversal ventricular slices (*Figure 1B*).

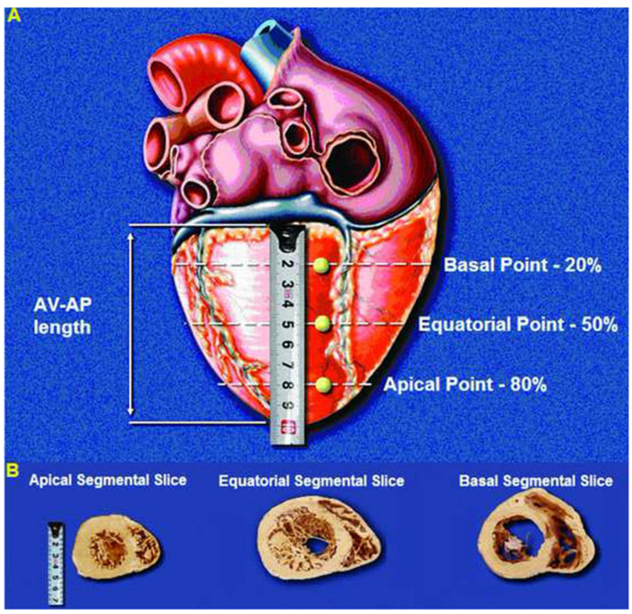
Digital image analysis: segmental perimeters and ventricular walls width measurements

Left internal segmental perimeters (without trabecular relief) and left ventricular walls width (anterior, posterior, lateral, and septal) were quantified by the Image Tool software (University of Texas, EUA) in the three segmental slices (basal, equatorial, and apical).

Ventricular relationships analysis

Spherical shape hypothesis In order to verify how spherical the dilated ventricles are, a geometrical model was proposed, based on a perfect sphere. In this geometrical model, the longitudinal ventricular axis was considered as a 'sphere diameter'. Based on this sphere diameter, through mathematical formulas, the expected perimeters were calculated in the three studied segments (basal, equatorial, and apical). The specimens of both dilated (idiopathic and ischaemic) groups were evaluated to check how spherical they were. All the three segmental perimeters observed (basal, apical, and equatorial) in each specimen were

Figure 1 (A) Posterior view of ventricular chamber. Schematic representation of the three predetermined points for ventricular slicing: basal, equatorial, and apical slices were performed at 20%, 50%, and 80%, respectively, from the atrioventricular sulcus to the ventricular apex. (B) Ventricular segmental slices from basal face view.



compared with their respective 'expected perimeters' for a perfect sphere. Based on this comparison, a segmental sphericity index (SSI) was proposed, in order to demonstrate, in percentage, how close each segment studied is a part of a perfect sphere. *Figure 2* demonstrates the basis of this sphericity hypothesis.

Expected segmental perimeters determination For a done longitudinal 'diameter', three expected segmental perimeters were calculated based on Formulas 1 and 2. As basal and apical segments are slices symmetrically placed from the equator, their expected perimeters should have the same length.

Formula 1

Expected equatorial segmental perimeter = 2π × ½ measured longitudinal ventricular axis.

Formula 2

Expected apical and basal segmental perimeter = $2\pi\sqrt{(R^2 - d^2)}$
R is ½ measured longitudinal ventricular axis.
d is the perpendicular distance from the equatorial plane to the segmental basal/apical plane = 30% of longitudinal axis (*Figure 3*).

Figure 2 Spherical shape hypothesis: the longitudinal axis (green arrow) of the left ventricle in dilated specimens is considered as the sphere diameter. The white lines refer to the calculated perimeters from this hypothetical sphere in the three levels (expected perimeters). These are compared with the blue lines measured in the same levels in that specimen (observed perimeters).

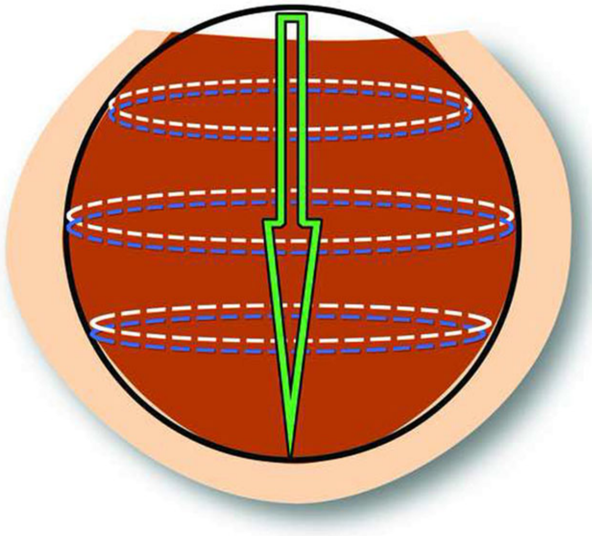
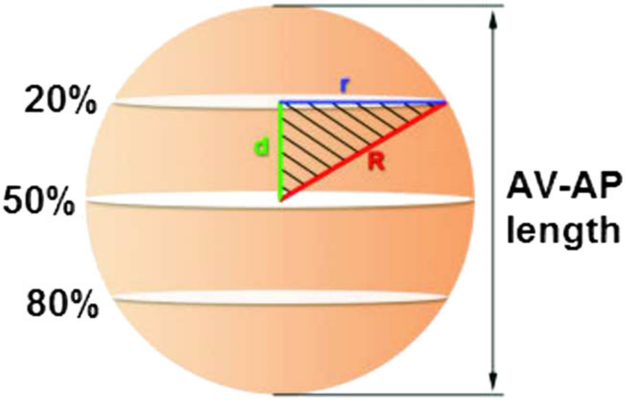


Figure 3 Graphic representation of one sphere with the variables of the equation for determination of expected segmental perimeters. AV-AP length: distance from the atrioventricular sulcus to apical ventricular extremity. *R*: ½ measured longitudinal ventricular axis = equatorial radius. *r*: basal and apical expected radius = $\sqrt{(R^2 - d^2)}$. *d*: the perpendicular distance from the equatorial plane to the segmental basal/apical plane = 30% of longitudinal axis.



Segmental sphericity index An SSI of each segment was established for each specimen:

- basal segment: SSI_{basal}
- equatorial segment: $SSI_{equatorial}$
- apical segment: SSI_{apical}

These indexes range from 0% (total imperfect sphere) to 100%, where the observed segmental perimeter must be identical to the expected one (a hypothetical perfect sphere).

The SSI was calculated based on the following formula:

$$\text{SSI} = \{1 - [(\text{Expected segmental perimeter} - \text{Observed segmental perimeter}) / \text{Expected segmental perimeter}]\} \times 100.$$

Proportionality hypothesis In order to verify if intersegmental perimeters relationships observed in the normal group were preserved in the dilated group, intergroups (normal × dilated) comparisons were performed.

For intersegmental perimeters relationships calculus, only the averages of perimeters were used.

Equatorial perimeter was defined arbitrarily as a basis for intersegmental perimeters relationships calculus. With this aim, an intersegment perimetral index (IPI) was established to quantify how much the basal and apical segmental perimeters were (in percentage) of the equatorial segmental perimeter.

The two IPIs of the normal group were considered as a 'control', for comparisons.

Intragroup intersegment perimetral index determination
For each group, the segmental average of basal, apical, and equatorial perimeters was calculated. Based on these averages, two IPIs were determined for each group:

- $IPI_{Basal/Equatorial}$ = Average Observed Basal Perimeter/Average Observed Equatorial Perimeter
- $IPI_{Apical/Equatorial}$ = Average Observed Apical Perimeter/Average Observed Equatorial Perimeter

Intergroup intersegment perimetral index comparisons
$IPI_{Basal/Equatorial}$ was compared among groups; the $IPI_{Apical/Equatorial}$ was compared as well. Initially, both dilated groups were compared with the normal one and was thus compared between them.

Statistical analysis
Descriptive analysis Data were described after Kolmogorov–Smirnov tests of normality with Lilliefors significance correction.

Comparisons and correlations related to morphometric data

- Longitudinal axis length comparisons: One-way ANOVA with Tukey's post-hoc test was used to compare means among the groups.
- Segmental perimeters comparisons: One-way repeated-measures ANOVA with Tukey's post-hoc test was used for comparisons among segmental perimeters of intragroups and intergroups.
- Segmental walls width comparisons (ancillary analyses): One-way repeated-measures ANOVA was used for segmental walls width comparisons. Basal, equatorial, and apical walls were considered as repeated measures within each group.

Comparison between groups for proportionality One-way ANOVA with Tukey's post-hoc test was used to compare means among the groups.

Significance level Statistical significance level for Type 1 error was established at 5%.

Results

Initially, we present the main results, and thus, results of ancillary analyses are presented.

The main results are presented in parts.

Longitudinal axis length (AV-AP) intergroup comparisons
The AV-AP was similar between dilated groups (P = 0.8), but their AV-APs were longer than the AV-AP of the normal group ($P < 0.001$).

- Normal: AV-AP ranged from 7.0 to 10.0 (average 8.4, standard deviation 0.9 cm).
- Ischaemic: AV-AP ranged from 9.0 to 13.0 (average 10.6, standard deviation 1.1 cm).
- Idiopathic: AV-AP ranged from 8.5 to 12.5 (average 10.4, standard deviation 1.1 cm).

Segmental sphericity index descriptive results

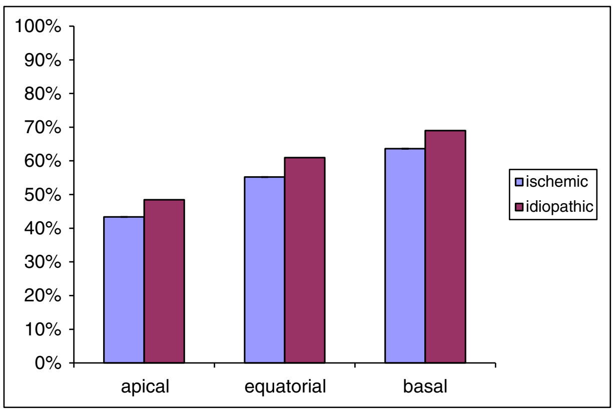
- Basal
  - SSI_{basal} mean: ischaemic group 63.6% and idiopathic group 69.0%.
  - SSI_{basal} standard deviation: ischaemic group 8.1% and idiopathic group 10.7%.
- Equatorial
  - $SSI_{equatorial}$ mean: ischaemic group 55.2% and idiopathic group 61.0%.
  - $SSI_{equatorial}$ standard deviation: ischaemic group 7.5% and idiopathic group 7.5%.
- Apical
  - SSI_{apical} mean: ischaemic group 43.3% and idiopathic group 48.5%.
  - SSI_{apical} standard deviation: ischaemic group 7.0% and idiopathic group 8.3% (*Figure 4*).

Intergroup intersegment perimetral index comparisons for proportionality
$IPI_{Basal/Equatorial}$: Normal group, 91.1%; ischaemic group, 91.9%; and idiopathic group, 90.2%.

$IPI_{Basal/Equatorial}$ was similar among groups (P = 0.892).

$IPI_{Apical/Equatorial}$: Normal group, 79.4%; ischaemic group, 63.0%; and idiopathic group, 63.4%.

Figure 4 Each segment (apical, equatorial, and basal), in ischaemic and idiopathic groups, represented (in percentage) of the same segment in the hypothesis of a perfect sphere (spherical dilatation).



$IPI_{Apical/Equatorial}$: Normal IPI was higher than that of both dilated IPIs ($P < 0.001$). $IPI_{Apical/Equatorial}$ was similar between dilated groups ($P = 0.99$) (*Figure 5*).

Ancillary analyses results

Intragroup comparisons of segmental perimeters for symmetry verification

For each group, segmental perimeters along the longitudinal axis were considered as a repeated measure. Neither normal group specimens nor dilated ones were symmetric in relation to the equator. All the specimens had basal perimeters longer than apical ones.

Normal group

- Basal and equatorial segmental perimeters were similar ($P = 0.128$), but both of them are longer than the apical perimeter ($P = 0.05$ and $P = 0.001$, respectively).

Dilated groups

- Equatorial segmental perimeter was the longest one, but the basal remained longer than the apical:
- Ischaemic group equatorial × basal ($P = 0.06$); equatorial × apical ($P < 0.001$); basal × apical ($P < 0.001$).
- Idiopathic group equatorial × basal ($P < 0.001$); equatorial × apical ($P < 0.001$); basal × apical ($P < 0.001$).

Comparison of the three segmental walls width

(1) Anterior wall: There were no differences among groups ($P = 0.32$), but there were differences among segments. Basal segment had the most width wall, and the apical segment had the less width wall in the three groups ($P < 0.001$).

(2) Posterior wall: There were no differences among groups ($P = 0.44$), but there were differences among segments. Basal segment had the most width wall, and the apical segment had the less width wall in the three groups ($P < 0.001$).

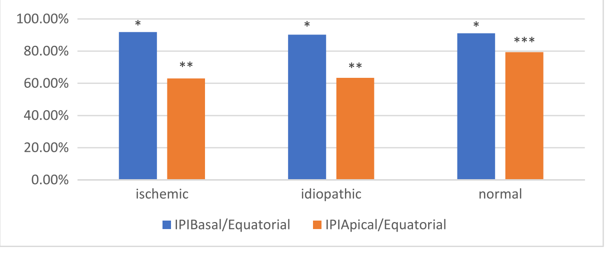
(3) Lateral wall: There were no differences among groups, nor among segmental walls width in the three groups ($P = 0.41$ and $P = 0.256$, respectively).

(4) Septal wall: There were no differences among groups ($P = 0.45$), but there were differences among segments. Basal and equatorial walls were similar, but both of them had more width than did the apical one ($P < 0.001$).

Schematic general shape model

In order to illustrate geometrical distortions in left ventricular chamber in dilated groups, a schematic model of segmental dilatation was proposed (*Figure 6A*). Similarly, regarding the ventricular wall around ventricular chamber in the three groups, a 'general shape model' for ventricular walls width was suggested (*Figure 6B and 6C*).

Figure 5 Apical and basal segments represented (in percentage) of the equatorial segment in each groups and a comparison of their relations among the groups. Differences among the groups: *$P = 0.89$; **$P = 0.99$; ***$P < 0.001$.



Discussion

Anatomical study and digital computer-assisted analysis

We have chosen an anatomical study instead of an *in vivo* one because we agree with Doblas *et al.*,[2] who support that anatomical study is the best design in order to collect morphometric data. We assume that retraction of fixed specimens is similar among the groups, and thus, a comparative study like this may provide important and valid information. The cotton balls used for filling the left ventricular chamber before fixation were important to maintain a more original form.

Digital computer-assisted analyses are widely and well established in medical literature, because in some instances, they can afford a more precise measurement of anatomical structures than do traditional manual methods.[7]

Ventricular morphometry

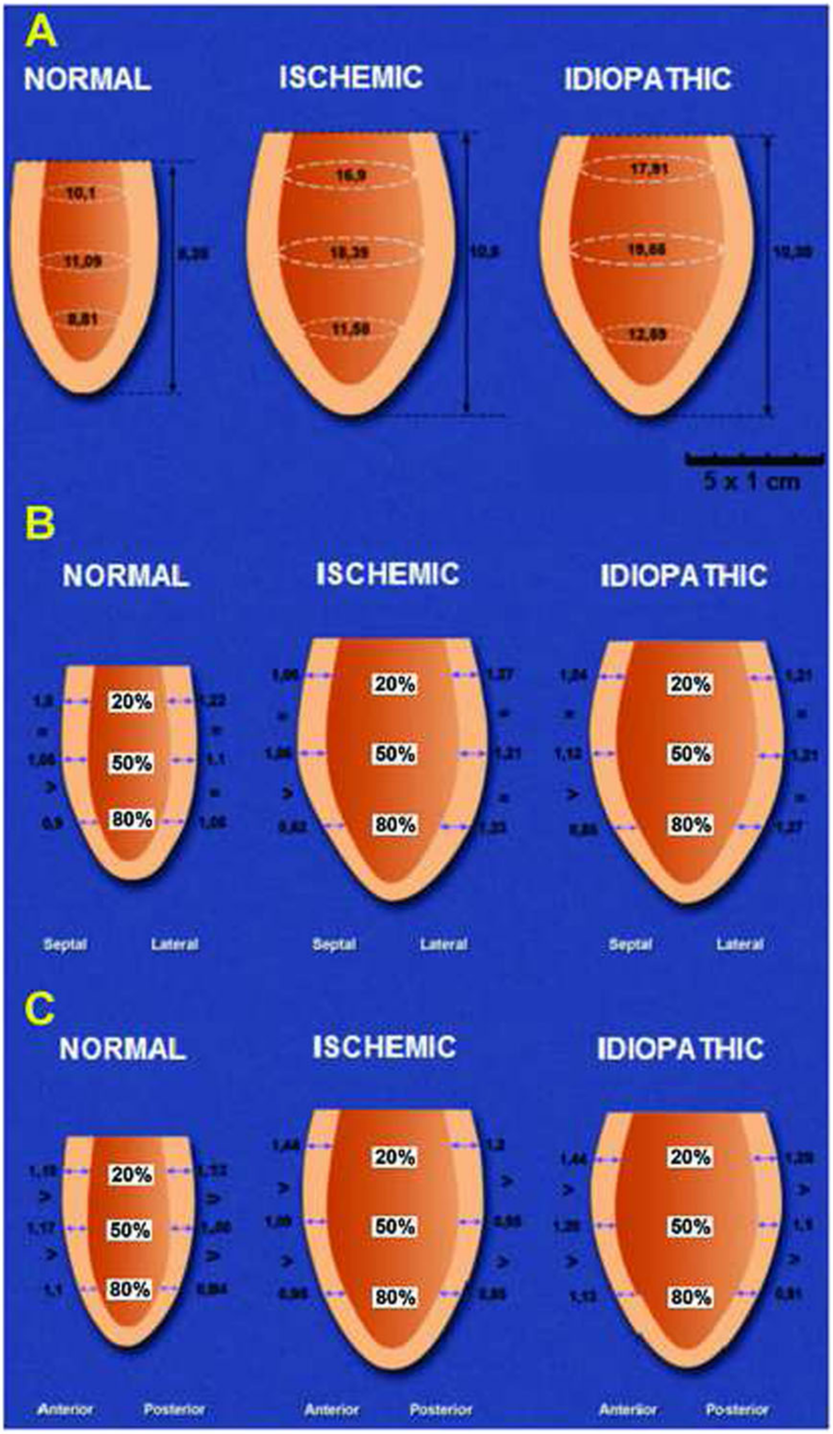
First of all, we will discuss the morphometric measurements: segmental perimeters and ventricular walls width.

Segmental perimeters

Morphometric data confirmed dilatation in all the three studied segments. Dilatation was more pronounced in the idiopathic group.

These measurements afforded data about basal and apical regions that are not as studied as equatorial region in literature. Moreover, these data were used to check the spherical and proportional hypotheses and to suggest the general model of dilated chamber.

Figure 6 Internal validity general model (with the observed measures). (A) Ventricular chamber in normal and dilated specimens. Scale is represented in the inferior right corner. (B) Septal and lateral ventricular walls width in normal and dilated specimens. (C) Anterior and posterior ventricular walls width in normal and dilated specimens.



This transversal dilatation has consequences. Torrent-Guasp *et al*.[8,9] demonstrated that myocardial fibres bands are displayed in a helical network in a normal heart. Furthermore, Buckberg showed that these fibres bands crossed in a 60° angle, which generates an optimal muscular traction axis from basal to apex region.

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Transversal dilatation would result in a loss of the original 60° angle between fibres bands, reorganizing them in a more transversal direction. That could result in a less effective blood flow in longitudinal axis.[1,3]

Segmental perimeters measurement: with or without trabecular relief?

In a preliminary analysis, IPI was compared among with and without trabecular relief, and it was observed that the percentages were similar.

Despite observations of Papavassilliu *et al.*,[10] who concluded that the difference between these two methods resulted in a change in estimated volume and mass, there were no data in medical literature about the influence of trabecular relief in the hypothetical geometrical shape of ventricular chamber.

So we decided to quantify segmental perimeters without trabecular relief.

Ventricular walls

Our results suggest that not only a muscular stretch occurs but an additional width gain was also observed, because of the maintenance of the original width of normal specimens even in a dilated heart.

Another interesting result that must be highlighted was the homogenous behaviour of all the four ventricular walls along the longitudinal axis in all the three groups.

Ventricular geometry: sphericity and proportionality

We preferred to describe and analyse ventricular geometry by segmental region instead of describing left ventricle as a spatial geometric figure.

Spherical or not spherical, proportional or not proportional: therapeutic implications

First of all, we aimed to verify if dilated ventricular chambers tended to have spherical shape. If not, we will verify if their final shape was proportional to that of the normal hearts. It was performed because some surgical therapies are based on the recovery of the 'anatomical and physiologic ventricular geometry' of dilated ventricle.[1,3,11–18]

Understanding the general shape of normal ventricular chamber is very important, but suggesting a general model for dilated chambers is essential for remodelling therapies as well.

Several authors have hypothesized that dilated chambers tended to have a spherical shape.[1–3,5,18–20] This hypothesis is based on Laplace's law. It postulates that the increase of internal tension against ventricular walls results in a dilated spherical chamber. But we agree with Gibson and Brown[4] and Hutchins *et al.*,[19] who refute this simplistic hypothesis. We believe that other variables can be implicated in the final shape of dilated chambers. A study about left ventricle dynamic geometry in dogs showed that in open chest, the left chamber tended have a more spherical shape, which is in contrast to that in dogs in conscious state.[21] Thus, studies or direct observation performed in open chests may not represent well the adverse chamber remodelling.

We suggested a sphericity index to quantify how spherical dilated chambers were. But we preferred to describe this sphericity index by segmental region, because we believe that each region can be considered a clinical entity. They can behave in a different way when compared with each other.

Perhaps when apical walls are submitted to longitudinal fibre tension, chamber blood flow and muscular traction perform in a different way when compared with those in basal walls, which are pulled to apical region during systole. Furthermore, basal chamber can suffer the impact of blood flow against its walls in a different way when compared with apical chamber.

Spherical shape and proportionality hypotheses

Dilated specimens were not spherical Dilated chambers shape was not spherical as suggested by some authors.[1–3,5,18–20]

All the observed SSIs were $<$70% of the expected one when considering the spherical shape hypothesis. Despite under 'geometric' language, we can declare that there is a tendency to a more spherical shape in both basal and apical regions; but these tendencies were not similar. This phenomenon resulted in an asymmetric tendency to sphericity in relation to the equator.

Moreover, as the basal segment had a more intense dilatation (proportional to equatorial segment) than does the apical segment, we could suppose that the chamber silhouette between basal and equatorial segments suffered a different curvature compared with the region between apex and equator.

It confers an asymmetric chamber silhouette, corroborating a no spherical shape for dilated specimens. If dilated specimens were symmetric, basal and apical perimeters would be similar, as their relation to the equatorial perimeter should be as well. It seems prudent to believe that because there are accentuated differences among polar regions in anatomical pieces, a similar deformation must occur *in vivo*, even if there is influence of blood pressure against the left ventricle walls. Probably the differences among apical and basal muscular arrangements contribute so much to this phenomenon.

Thus, another paradigm instead of a sphere would be pursued in order to describe dilated hearts.

Dilated specimens shape was not proportional to normal heart As dilated chambers were not spherical, we verified the second hypothesis: were they proportional to the shape of normal hearts, as suggested by Kono *et al.*[5] and other authors[7,20]?

When comparing relationships between segments perimeters (proportionality index) of dilated hearts to normal ones, it was found that they are not proportional to normal hearts.

We verified that compared with normal specimens, equatorial dilatation of ventricular chamber was the most accentuated. It was followed by basal and finally by apical segments, mainly in the idiopathic group, corroborating the hypothesis of other authors.[7,20]

We could hypothesize that this resistance of apical segment to dilatation, when compared with basal and equatorial regions, is due to its intrinsic arrangement of muscular bands. Apical bands arrangement composes a more complex network than that in equatorial and basal regions.[1,3,8,9]

Thereby, dilated specimens were not mere 'big' hearts, but they have a specific shape, different to that of normal heart.

The general model for chamber and walls dilatation

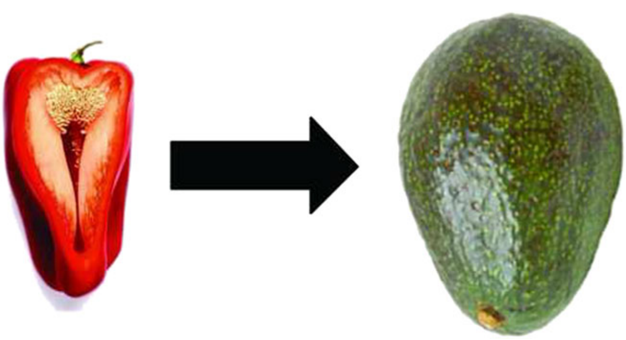
Sphere vs. 'avocado' theory

Thus, would it be possible to suggest a general model for chamber dilatation and for ventricular walls behaviour in dilated specimens?

In dilated groups, both the chamber and the ventricular walls followed a homogenous geometrical behaviour. Despite that the idiopathic group suffered a more intense transversal dilatation, the same general geometric pattern of deformation of both chamber and walls was observed.

Based only on these observations, we cannot verify our third hypothesis: if it would be possible to suggest a general model for chamber and ventricular walls dilatation. It is due to our small casuistry, which does not allow us to apply these results in any external casuistry. But regarding only internal validity, in *Figure 6A*, we suggest the general model for chamber dilatation; and in *Figure 6B and 6C*, we suggest the general model for ventricular walls dilatation. Finally, in *Figure 7*, we show an analogy of the left ventricular chamber dilatation phenomenon, the sweet pepper–avocado theory.

Figure 7 Sweet pepper–avocado theory, the left ventricular chamber dilatation phenomenon.



Therefore, further studies based on a larger casuistry could verify if it would be possible to suggest a general model for chamber and ventricular walls with external validity.

Possible functional and clinical consequences of ventricular distortions

What could be the functional and clinical consequences of these morphometric changes traduced by chamber distortions in dilated hearts?

In normal hearts, during ventricular systole, a pressure gradient from apical to basal region generates a resultant vector propelling blood flow from the ventricle to aorta.[22]

The three major components of this resultant vector are the following:

(1) The longitudinal component: generated by the ventricular contraction from basal to apical region.
(2) The circumferential component from apical region: generated by the ventricular contraction of apico-equatorial region, propelling blood flow to the central point of ventricular chamber.
(3) The circumferential component from basal region: generated by the ventricular contraction of baso-equatorial region. This component result in a 90° vector in relation to the resultant vector of longitudinal and circumferential apical component.

In the basal region of dilated hearts, we observed a more acute angulation of ventricular silhouette. Moreover, we measured the ventricular walls width in this region, which indirectly supposes a higher density of muscular fibres bands. Additionally, as showed for Buckberg, these distortions could result in a more transversal angulation between muscular fibres bands. All these three variables could reduce systolic function.

The more acute angulations of baso-equatorial ventricular silhouette

The circumferential component vector of dilated basal region could be pathologically more oriented to the inverse sense of normal blood flow, resulting in a pathologic resultant vector that could have a component pushing blood from basal to equatorial region. This phenomenon could be one of those that concur to the pump failure.

The supposed higher density of muscular fibres bands in basal region

We observed a larger ventricular walls width in the anterior and posterior walls in basal region in both normal and dilated groups, as described by Greenbaum *et al.*[23]

If this higher density can signify a higher contractile reserve in basal area, then in dilated specimens, it can signify also a higher counterflow of blood, decreasing the amount of blood ejected to the ventricular output.

Transversal angulations between muscular fibres bands

In theory, as a consequence of the observed, more acute angulations of ventricular silhouette, we could infer that fibres bands are displayed in a pathologic, more transversal orientation[1,3] in both dilated groups.

This orientation could disturb the physiologic longitudinal traction vector from apical to basal region.

All these three characteristics in ventricular chambers and walls of ischaemic and idiopathic dilated hearts described earlier could take part in the mechanism of ventricular failure.

Final considerations

Of course, factors other than geometry contribute to ventricular failure. Among them, muscular fibres microscopic changes, pre-charge and post-charge, and disturbances of cardiac rhythm have already been described.[24]

But the major challenge to further studies can be how to establish the actual 'weight' of each of these known and unknown variables in the resulting ventricular failure. Thus, surgical and medical therapies can be tailored and targeted against each one of these components.[13–16,24,25]

Regarding surgical therapies, as ventriculectomy[1,17,26] and reshaping heart failure therapy devices (mesh),[14,15] the knowledge of normal and dilated shape of ventricular chambers could help surgeons to achieve a more physiologic anatomy remodelling dilated hearts. Ventriculectomy could be performed based on these morphometric data, and reshaping heart failure therapy devices could be tailored with differentiated tensions along its longitudinal axes.

In conclusion,

(1) left ventricular chamber in dilated cardiomyopathies did not display a spherical shape;
(2) transversal chamber dilatation in dilated cardiomyopathies is not proportional to normal heart because it is more accentuated in equatorial and basal regions; and
(3) a general model for chamber and ventricular walls dilatation was suggested, but without external validity.

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Conflict of interest

None declared.

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