Assessment of Left Ventricular Outflow in Hypertrophic Cardiomyopathy Using Anyplane and Paraplane Analysis of Three-Dimensional Echocardiography

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This study analyzes the alterations in size and geometry of the left ventricular (LV) outflow tract that occur in hypertrophic cardiomyopathy (HC) using transthoracic 3-dimensional echocardiography. Transthoracic 3-dimensional echocardiography was performed in 17 patients with HC (4 after myectomy) and in 10 normal subjects. Images were acquired with the rotational approach, with electrocardiographic and respiratory gating. From the 3-dimensional datasets, short-axis parallel slicing of the LV outflow tract at a 1 mm distance was performed at the onset of systole. For each slice, cross-sectional area and maximal and minimal diameter were calculated. Reconstruction of the LV outflow tract could be displayed in 3 dimensions in all patients, allowing orientation and clear definition of the irregular geometry. In patients with HC, the minimal LV outflow tract cross-sectional area was smaller than in normal subjects (2.3 ± 1.0 vs 5.0 ± 0.9 cm², p <0.0001). The ratio between maximal and minimal cross-sectional areas was higher in patients with HC than in normal subjects (2.6 ± 0.9 vs 1.4 ± 0.2, p <0.0001). The ratio between maximal and minimal diameter of the smallest cross section of the LV outflow tract was also significantly higher in patients with HC than in normal subjects (1.6 ± 0.3 vs 1.2 ± 0.1, p <0.001); a value of 1.36 separated normal subjects from HC patients without previous myectomy. In conclusion, precordial 3-dimensional echocardiography allows detailed qualitative and quantitative information on the LV outflow tract. Patients with HC are characterized by a highly eccentric and asymmetric shape of the LV outflow tract, and by a smaller minimal cross-sectional area than that seen in normal subjects.

METHODS

Study patients: We prospectively selected 17 patients (13 men and 4 women; mean ± SD age 39 ± 15 years, range 19 to 65) with HC referred to the outpatient clinic of our institution for routine transthoracic echocardiographic follow-up. High-quality images were a prerequisite for inclusion in this study. The diagnosis of HC was based on M-mode and 2-dimensional echocardiographic demonstration of a nondilated hypertrophic left ventricle in the absence of other cardiac or systemic disease that could produce LV hypertrophy. According to a previously established classification, the patterns of distribution of LV hypertrophy were: type I, 1 patient; type II, 3 patients; type III, 12 patients; and type IV, 1 patient. Systolic anterior motion of the mitral valve was present in 12 patients and its severity was evaluated semiquantitatively from 0 = absence, to 3+ = contact with the interventricular septum during systole. At the time of the echocardiographic study, a pressure difference was calculated from Doppler LV outflow tract velocity recordings, and obstruction (gradient >30 mm Hg under basal conditions) was detected in 4 patients. A septal myectomy had been performed in 4 patients. Ten asymptomatic subjects without evidence of LV hypertrophy were also studied for comparison. These controls were aged 20 to 49 years (mean 28 ± 8) and 8 were men.

Examination procedure: Two-dimensional echocardiographic studies were performed with a commer-
FIGURE 1. Analysis of left ventricular (LV) outflow tract in a patient with hypertrophic cardiomyopathy. From the 3-dimensional dataset, parallel slicing of the LV outflow tract perpendicular to the long axis (paraplane echocardiography) is performed at 1 mm intervals, at the onset of ventricular systole. In the left panel, 3 representative cut-planes are indicated. The corresponding cross-sectional 2-dimensional images with the manually traced endocardial contours are shown in the middle panels. The final wireframe mode display represented in the right panel can be rotated on the screen along the 3 main axes for versatile qualitative 3-dimensional evaluation. AML = anterior mitral leaflet; AV = aortic valve; IVS = interventricular septum.

Finally, reconstruction of the LV outflow tract at the onset of ventricular systole is displayed in wire frame mode and the representative image can be rotated on the screen for versatile 3-dimensional evaluation (Figure 1).

From analysis of the 3-dimensional datasets, the following measurements of the LV outflow tract at the onset of systole were considered: (1) minimal cross-sectional area; (2) ratio between maximal and minimal cross-sectional area (max/min cross-sectional area), as an index of the "eccentricity" of the LV outflow tract (the higher the value, the greater the variations of the cross-sectional area throughout the length of the LV outflow tract; (3) ratio between maximal (lateromedial) and minimal (anteroposteri...
ior) diameter (max/min diameter) at the level of the cross-section with the minimal area, as an index of the "asymmetry" of the LV outflow tract (a ratio of 1 indicates a circular shape, with the highest values corresponding to the more elliptical shape of the cross sections).

Inter- and intraobserver reproducibility for the measurements of LV outflow tract with 3-dimensional echocardiography was assessed in all 27 patients. To assess interobserver variability, two observers (A.S. and Y.N.) independently measured the outflow tract area from the 3-dimensional datasets without prior knowledge of clinical data and without preelection of cut-planes. In addition, LV outflow tract cross-sectional area measurements were performed by 1 observer (A.S.) on 2 occasions (3 months apart, without preelection of cut-planes from the 3-dimensional datasets) to assess intraobserver variability.

Statistical analysis: Values are given as mean ± SD. Student’s unpaired t test was used to compare the differences between HC and control subjects. Values of p <0.05 were considered to be significant. Reproducibility of the LV outflow tract measurements was expressed in terms of mean differences and 95% confidence intervals.12

RESULTS

Three-dimensional acquisition could be performed successfully in all patients. Echocardiographic acquisition of the image of the LV outflow tract for 3-dimensional reconstruction was performed either from the parasternal (n = 20) or apical (n = 7) windows, according to the image quality. The examination including the calibration procedure, selection of the optimal axis of rotation, a number of test runs, and the actual image acquisition required approximately 10 minutes in addition to the time required for the standard 2-dimensional echocardiogram. Three-dimensional reconstruction of the images was possible and of good quality in all patients. The time required for post-processing the raw data, and reconstruction and analysis of the images was approximately 20 minutes. Demographics, echocardiographic characteristics, and measurements of the LV outflow tract in each patient with HC are reported in Table I.

| TABLE I Demographics, Patients Characteristics, and Measurements of the Left Ventricular Outflow Tract in Patients With Hypertrophic Cardiomyopathy |
|---|---|---|---|---|---|---|---|
| Patient Number | Age (yr) & Sex | Type LVH | Therapy | Gradient | SAM | CSA (cm²) | Max/Min CSA | Max/Min Diameter |
| 1 | 19M | III | V | 58 | 3+ | 2.9 | 2.0 | 1.9 |
| 2 | 21M | III | — | <10 | 2+ | 2.4 | 2.5 | 1.7 |
| 3 | 22M | III | — | <10 | 1+ | 3.0 | 2.8 | 1.8 |
| 4 | 24M | IV | — | <10 | 2+ | 2.9 | 2.4 | 1.6 |
| 5 | 25M | III | V | <10 | 2+ | 2.7 | 2.4 | 1.6 |
| 6 | 31F | II | S, V | 50 | 3+ | 1.3 | 4.2 | 2.0 |
| 7 | 38F | II | V | <10 | 0 | 3.2 | 2.1 | 1.6 |
| 8 | 41M | III | V | 20 | 1+ | 1.9 | 1.7 | 1.8 |
| 9 | 46F | III | A, V | <10 | 2+ | 0.7 | 4.1 | 1.4 |
| 10 | 53M* | III | — | <10 | 1+ | 1.5 | 3.8 | 1.9 |
| 11 | 63M | III | M | 100 | 3+ | 1.5 | 3.0 | 2.6 |
| 12 | 65M | III | V | 35 | 3+ | 2.0 | 3.0 | 1.6 |
| Mean ± SD | 37 ± 15 | 2.2 ± 0.7 | 2.7 ± 0.8 | 1.75 ± 0.3 |
| 14 | 31M* | III | — | <10 | 0 | 2.1 | 2.4 | 1.3 |
| 15 | 34M* | III | S | <10 | 1+ | 0.9 | 3.9 | 1.2 |
| 16 | 44M* | III | S, V | <10 | 0 | 4.7 | 1.5 | 1.3 |
| 17 | 59M* | III | V | <10 | 0 | 3.0 | 1.6 | 1.3 |
| Mean ± SD | 42 ± 12 | 2.7 ± 1.6 | 2.3 ± 1.1 | 1.27 ± 0.05 |
| Mean ± SD (overall) | 39 ± 15 | 2.3 ± 1.0 | 2.6 ± 0.9 | 1.6 ± 0.3 |

* Patients evaluated after myectomy.
A = amiodarone; CSA = cross-sectional area; LVH = left ventricular hypertrophy; M = metoprolol; Max./Min. = maximal/minimal; S = sotalol; SAM = systolic anterior movement; V = verapamil.

CROSS-SECTIONAL AREA: The values of minimal cross-sectional area of the individual subjects are plotted in Figure 2. The minimal LV outflow tract cross-sectional area calculated with 3-dimensional echocardiography was significantly smaller in patients with HC than in the control group (2.3 ± 1.0 vs 5.0 ± 0.9 cm², p <0.0001). Thirteen of the 17 patients with HC had a value smaller than controls, and 2 of the 4 HC patients (nos. 6 and 17) with higher values were evaluated after myectomy. After correction for body surface area the values were 1.3 ± 0.5 and 2.7 ± 0.6 cm², respectively (p <0.0001).

SHAPE: From the 3-dimensional datasets, the reconstructed LV outflow tract could be displayed as observed from different viewpoints. This simplifies visualization of the geometry and shape as well as the localization of the narrowing of the LV outflow tract in patients with HC (Figure 3). A similar display in a normal patient is shown in Figure 4. Some examples of 3-dimensional reconstruction of the LV outflow tract in normal subjects and in patients with HC are shown in Figure 5.
MAX/MIN CROSS-SECTIONAL AREA (ECCENTRICITY INDEX): The max/min cross-sectional area of the LV outflow tract derived from the 3-dimensional datasets are displayed in Figure 6. From this figure, it is apparent that patients with HC had higher ratios (2.6 ± 0.9), with a broad range of values (from 1.5 to 4.2) indicative of many irregular different shapes of the LV outflow tracts. In contrast, normal subjects had smaller ratios (1.4 ± 0.2), with a narrow range of values (from 1.1 to 1.6). In particular, each of the controls had a ratio of ≈1.6, whereas 15 of 17 patients with HC had a ratio of >1.6. The 2 patients...
DISCUSSION

Hypertrophic cardiomyopathy is a disease with a great individual variability and "no two hearts are alike." The results of the present study indicate that 3-dimensional echocardiography allows visualization of the varied complex geometry of the LV outflow tract in patients with HC. With quantitative analysis of the 3-dimensional datasets, we demonstrated that in patients with HC the minimal cross-sectional area is smaller than that in normal subjects. In addition, most patients with HC have an irregular shape of the LV outflow tract as demonstrated by an eccentricity index of $\geq 1.5$. In normal subjects, this area and diameter ratio were significantly higher than in patients with HC (1.6 ± 0.3 vs 1.2 ± 0.1, p = 0.001). Of interest, patients evaluated after myectomy had the lowest values; conversely, the highest values were found in patients with HC and LV outflow tract obstruction. An index of 1.36 appeared to separate normal subjects from patients with HC who did not undergo operation.

Reproducibility analysis of three-dimensional echocardiography: INTEROBSERVER VARIABILITY: The difference between the 2 observers for measurements of the LV outflow tract was compared with the average of the 2 measurements for each patient. The mean difference between the measurements of the 2 observers was $0.04 \text{ cm}^2$ (95% confidence interval $-0.08$ to $0.12 \text{ cm}^2$) for cross-sectional area.

INTRAOBSERVER VARIABILITY: The difference between the 2 measurements made by the same observer was compared with the average of the 2 measurements for each patient. The mean difference between the 2 measurements was $0.13 \text{ cm}^2$ (95% confidence interval $-0.01$ to $0.25 \text{ cm}^2$) for cross-sectional area.
index is always ≤1.6, indicating a uniform shape of
the LV outflow tract, without significant variation of
the cross-sectional area throughout its length. We
have also demonstrated that the cross-sectional shape
of the LV outflow tract is more elliptical in patients
with HC than in normal subjects, as indicated by a
higher ratio of max/min diameter measured at the
plane of the minimal cross-sectional area. This find-
ing is in agreement with the concept that in HC the
hypertrophic ventricular septum narrows the LV out-
flow tract mainly along its anteroposterior diameter.
Of interest, this asymmetry index was highest in pa-
tients with HC and obstruction of the LV outflow
tract at rest. In contrast, in HC neither the minimal
cross-sectional area nor the eccentricity index of the
LV outflow tract separated this subgroup. This find-
ing indicates that for similar cross-sectional area the
asymmetry of the LV outflow tract plays an impor-
tant role in determining the presence of significant
obstruction at rest.

Patients who had undergone myectomy had a
minimal cross-sectional area similar to other patients
with HC, including those with obstruction (Figure
2). However, from Figure 7 it is clear that after myectomy the asymmetry index was lowest, indicat-
ing that the surgical remodeling of the LV outflow
tract was adequate for the relief of the obstruction
despite the finding that the cross-sectional area re-
mained small compared with that in normal controls,
and remained in the same range as that of the other
HC patients without previous myectomy. Thus, in
patients with HC, precordial 3-dimensional echocar-
diography has the potential to play a major role in
tailoring the standard surgical resection of the inter-
ventricular septum to the individual patient’s anat-
omy, which is crucial for safe and efficacious per-
formance of myectomy, and also for evaluation of
the results of surgery.

Evaluation of left ventricular outflow tract using three-
dimensional echocardiography: Previous experience
with 3-dimensional echocardiography for the eval-
uation of the LV outflow tract was based on mor-
phologic analysis with volume-rendered display. In
contrast, for quantitative analysis of the LV outflow
tract performed in the present study, we selected a
multitude of cut-planes ("anyplane echocardiogra-
phy") and performed a parallel scanning of the LV
outflow tract at 1 mm intervals ("paraplane echo-
cardiography"). This rate of sampling of the dataset is
similar to the analysis done with magnetic reso-
nance imaging or computed tomography, and allows
detailed spatial information. While some display
modalities, such as volume rendering, are indicated
more for representation of anatomic details, the
wire frame display format appears particularly suited
to 3-dimensional reconstruction of the cardiac cavi-
ties, where areas, volumes, size, and shape can be
adequately evaluated.

Limitations of three-dimensional echocardiography:
In this study, patients were selected on the basis of
high-quality images at 2-dimensional echocardiog-
raphy, which yielded a success rate of 3-dimensional
reconstruction of 100%. The same results cannot be
expected from an unselected population where poor
quality precordial images may prevent adequate
quality of the reconstruction.

Echocardiographic images were acquired by an
experienced technician and reconstruction was per-
formed by a cardiologist after a learning period of
>50 studies. This previous experience of 3-dimen-
sional echocardiography prevented artifacts in the 3-dimensional datasets, limited the time required both for acquisition and reconstruction, and resulted in a minimal variability for the measurements.

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