ORIGINAL ARTICLES

Four-dimensional Reconstruction of the Left Ventricle Using a Fast Rotating Classical Phased Array Scan Head: Preliminary Results

Long Dang Nguyen, MD, Christophe Leger, PhD, *Orléans, France*

The evaluation of left ventricular function by noninvasive methods is still a major problem in cardiology. Two-dimensional echocardiography requires mental reconstruction of the heart by the physician and is always based on approximation of heart shapes and volumes. Three-dimensional echocardiography is promising but has rhythmic and function constraints because of the acquisition during many cardiac cycles. This article reports a study carried out to validate a new 4-dimensional echocardiography method. With the use of a classical phased-array sensor with a fast rotating motorized motion and a standard ultrasound system, many slices at different angulations are obtained in a single cardiac cycle. After manual endocardial delineation and computation, a representation of the left ventricle (beating heart) and a volume quantification are obtained at each instant of the cardiac cycle. This method has been tested on 11 healthy volunteers and the results are in agreement with those obtained with standard 2-dimensional echocardiography. Because of its simplicity of operation and short time acquisition, this new imaging modality is highly valuable in left ventricle evaluation, even if further studies on pathologic hearts need to be performed. (J Am Soc Echocardiogr 2002;15:593-600.)

Many invasive or noninvasive techniques can measure left ventricular (LV) volume and estimate ejection fraction. Most of these methods are based on geometric (Simpson method) or temporal (overlapping many cardiac cycles) assumptions of regularity. Although such assumptions are quite justified in the case of a normal healthy heart, they are not valid in the case of cardiac dysfunction or rhythmic irregularity.

The limits of 2-dimensional (2D) echocardiography in the evaluation of the left ventricle function are well known because of geometric regularity assumptions that are false on pathologic hearts, particularly in the case of segmental hypokinesia.[1] In these cases, quantification of the ejection fraction is not accurate, and the examinations give only qualitative results.

Classical 3-dimensional (3D) echocardiography uses step-by-step rotating probes[2]: Acquisitions are made during several cardiac cycles (mostly 45) with the probe spinning a few degrees every heartbeat. After automatic or manual endocardial border delineation, a computer program reconstructs the left ventricle volumes by mapping all the data on a single diastolic-systolic cycle. This method has several advantages. Lining up of the probe can be suboptimal to give a more precise estimation of cardiac volume (unlike 2D echocardiography, which needs precise cross sections to give accurate results). Less well-trained echocardiographers can use the method with benefit[3] because of its interoperator robustness. Numerous comparisons carried out between this method and standard 2D echocardiography,[4,5] scintigraphic,[6,5] angiographic,[7] and magnetic resonance imaging methods[7] have shown good correlation of results. Abnormal geometric ventricles (such as localized aneurysms) are well reconstructed.[8-10] Finally, complex equipment is not required: A simple sensor slowly rotated in a standard echocardiographic probe, and a computer to collect data and reconstruct the 3D ventricle are the only 2 elements needed. However, 3D echocardiography is based on the superposition of different cardiac cycles acquired at different instants. This implies not only a stable cardiac rhythm during image acquisition, but also a constant cardiac function and invariable measurement conditions during all the recording. These conditions are rarely met in practice, even though many precautions are taken throughout the acquisition: Patient and probe need to be strictly motionless. To

From the Service de Cardiologie, Centre Hospitalier Régional d'Orléans (L.D.N.), and Laboratoire d'Electronique, Signaux, Images (LESI), Université d'Orléans, Ecole Supérieure des Procédés Electroniques et Optiques (C.L.).

Reprint requests: Long-Dang Nguyen, Université d'Orléans, ESPEO/LESI, 12 rue de Blois, BP6744, 45067 Orléans cedex 2, FRANCE (E-mail: *nguyenld@valcofim.fr*).

0894-7317/2002/$35.00 + 0 **27/1/117563**
doi:10.1067/mje.2002.117563

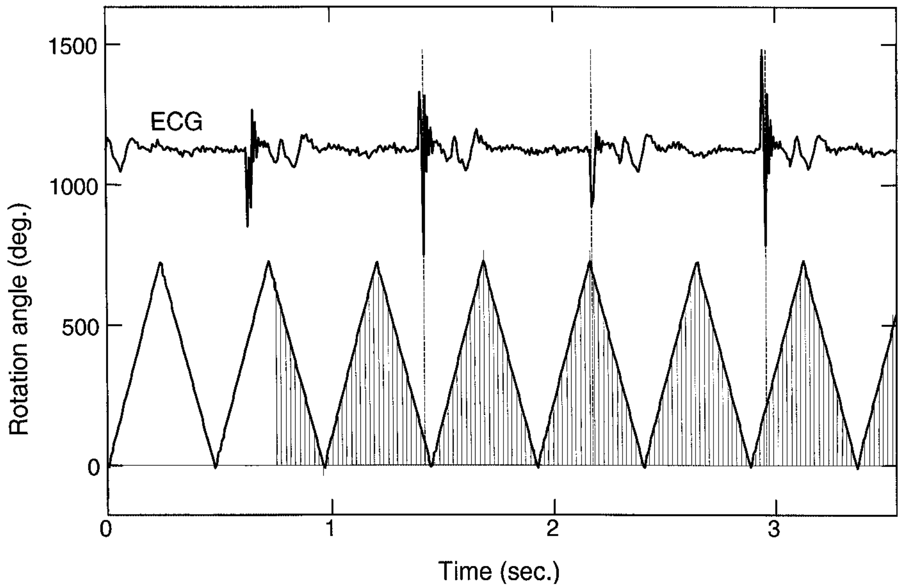

Figure 1 Electrocardiogram signal and probe rotation angle as function of time. Vertical plain lines indicate images. In this acquisition, available data are spread out through 2 complete cardiac cycles, although one 1 is needed for reconstruction.

minimize the arbitrary thoracic movement during breathing, recording must be performed at the end of expiration, defined by the modification of cardiac impedance measurement.[11] The classic 3D echocardiograph is therefore not adapted for fast change in systolic function, as in stress echocardiography. Similarly, it is not validated in the case of cardiac arrhythmia.

Real-time 3D echocardiography, which acquires a pyramid of data in real time, is very attractive. It requires a special 2D probe (matrix sensor) and is able to acquire the entire volume of the ventricle in a few milliseconds.[12] Echocardiographs equipped with such probes are now available because of electronic and software improvements. This technique has been tested in clinical studies[13-15] for several years, and correlation with other cardiac 3D imaging modalities (computed tomographic scan, scintigraphic imaging, magnetic resonance imaging) is good. However, it requires not only a specific probe but also a particular ultrasound system, which increases the cost dramatically. Moreover, because of low temporal and image resolutions and small pyramidal volume acquisition,[16] cardiac imaging is still suboptimal with this system compared with a state-of-the-art standard echocardiographer.

This article reports a study carried out by using a new technique called LV4D, for left ventricle in 4 dimensions (3D + time). LV4D uses an echocardiographic probe connected to a commercial echocardiograph. The innovative feature of the probe is the fast rotation of the phased-array sensor around the main axis of the scan head. Figure 1 shows electrocardiogram (ECG) signal and probe rotation angle as a function of time (ECG and probe rotations do not need to be synchronized for 4-dimensional [4D] reconstruction). The rotation is inverted each 720 degrees because of cable twisting. The probe produces successive images at different angles and short time intervals. After a manual drawing of the cardiac endomyocardium, a specific program based on spatiotemporal interpolations reconstructs the beats of the LV volume. The reconstructed volumes are displayed on a computer screen as a contractile mass, or in terms of numerical values. LV4D is a real 4D method because all data, acquired during a single cardiac cycle, are used to reconstruct each volume. Such intensive use of data means that acquisition time can be reduced to a single cardiac cycle,[17] which is a great benefit compared with methods that synchronize acquisition on the ECG. The aim of the study related here was to test the new LV4D method on a set of healthy subjects to verify its accuracy on cardiac volumes and ejection fraction, compared with classical echocardiographic imaging.

METHOD

Materials

A complete description of the experimental 4D echocardiographic imaging system is detailed.[18] It is composed of the following 4 main parts: (1) A 3.5-MHz 64-element phased-array sensor equipped with a continuous rotating motor, included in a new echocardiographic probe manufactured by Vermon (Vermon, Tours, France); (2) a commercial 2D AU4 echocardiographer from ESAOTE-SPA (Esaote Biomedica, Untrasound, Genoa, Italy); (3) a control electronic board plugged into a PC that drives the probe motor (start and stop, spinning speed control, accurate measurement of the probe angle relative to an arbitrary origin); and (4) software based on Fourier-Shannon interpolation[19] on a classical PC computer (Pentium Pro 200 MHz), in charge of both the interactive segmentation of images and LV volume reconstruction and visualization.

Examination

Healthy volunteers were recruited at the institution after informed consent. To be part of the test, subjects had to satisfy 4 inclusion criteria:

- No history of cardiac disease, including arrhythmia
- Normal standard echocardiographic examination, including a normal ejection fraction
- Good echogenicity on a standard echocardiographic examination
- Whole left ventricle visualized in a less than 90-degree sector acquisition

Two examinations were performed successively, a standard and a 4D echocardiographic examination.

Standard echocardiography. Subjects are in the left lateral recumbent position. Apical 4-chamber loops are acquired at end-tidal breath hold. Left ventricular tele-diastolic and tele-systolic volumes are computed according to the Simpson algorithm.[20] Ejection fraction is then calculated. Systolic time is determined by the duration between the beginning of the R-wave on the ECG (defining the tele-diastole time) and the minimal ventricular diameter in parasternal time movement (TM) incidence.

4D echocardiography. In apical 4-chamber position on a motionless subject and at end-tidal breath hold, the acquisition sector is reduced as far as possible (from 90 to 60 degrees) and depth is minimized to visualize the entire left ventricle. In these conditions, the frame rate varies between 48.33 and 53.62 images per second. The echocardiographic probe is then rotated up to 8.4 rotations per second. Speed stability is reached in less than 3 seconds, and image acquisition starts only after this step. The memory of the ultrasound system allows cineloops composed of about 150 pictures to be recorded, which correspond to 2 to 3 cardiac cycles; data acquisition does not last more than 3 or 4 seconds. All the digital images of a selected cardiac cycle (ie, the cycle with the highest quality imaging out of the 2 or 3 acquired) are then transferred to a PC to be processed by the 4D reconstruction software previously described.[21,22] Endocardial limits are manually traced by the operator on 3 consecutive images corresponding to tele-diastole, then to tele-systole (these instants are defined in the ECG as in standard echocardiography). The reconstruction software interpolates all the outlines in the other images of the cardiac cycle in less than 3 minutes. If required, automatic contours may be validated or corrected individually by the operator. All these data are computed to make a 3D representation of a contractile left ventricle, as shown in Figure 2. The evolution of the LV volume is represented as a function of time, as shown in Figure 3. Tele-diastolic volume, tele-systolic volume, and ejection fraction are then calculated from this curve.

Statistical Analysis

For each examination, the estimations of the tele-diastolic and tele-systolic volumes of the left ventricle obtained from the standard Simpson and LV4D methods are compared.

RESULTS

Eleven volunteers, mean age 24 years, were examined. Table 1 shows age, weight, and height of subjects in columns 2, 3, and 4. During the classical 2-dimensional examination, monoplane Simpson volumes were determined to estimate the ejection fraction. Columns 5, 6, and 7 of Table 1 represent tele-diastolic volume, tele-systolic volume and ejection fraction estimations, respectively. These estimations should be compared with those in columns 8, 9, and 10, which represent the values obtained with the LV4D examination.

For the 11 examinations carried out, mean cardiac frequency is 65.6 bpm ($\pm$5.5 bpm). Mean tele-diastolic volume, calculated by the Simpson monoplane method, is 71.6 cm^3 ($\pm$9.2 cm^3), which is fairly close to the volume calculated with the LV4D: 67.2 cm^3 ($\pm$6.1 cm^3). Mean tele-systolic volume by the Simpson method is 28.7 cm^3 ($\pm$4.0 cm^3), which is also close to LV4D 25.4 cm^3 ($\pm$4.0 cm^3). Similarly, mean ejection fraction by the standard method is 60% ($\pm$2%) and 62% ($\pm$3%) by LV4D. All these results show that the differences are not statistically significant. The volumes determined by both methods are strongly correlated (correlation coefficient greater than 0.98), as indicated in Figure 4. This result is confirmed by the Bland and Altman plot of Figure 5, which shows the difference between the LV4D measurements and the average volume measurements.

To reduce artifacts, the manual endocardial delineation needed for the reconstruction was repeated 3 times for each cycle to give mean results. Similarly,

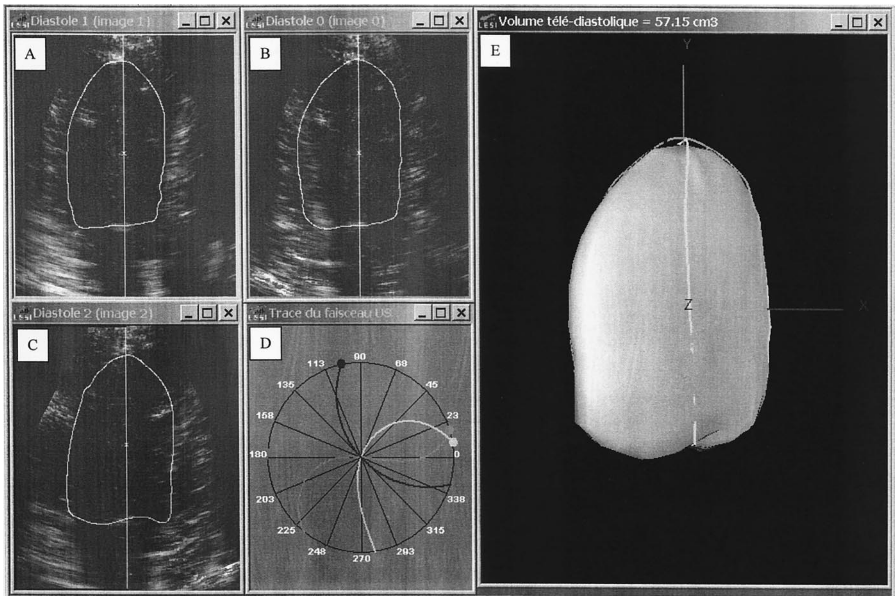

Figure 2 **A**, **B**, and **C** correspond to 3 successive images at tele-diastolic time, with manual endocardial contour tracing showed, each one corresponding to cross section that has rotated for about 60 degrees from previous one. These 3 cross sections are shown on **D** (apical view). Acquisition planes are curvilinear because of continuous fast-rotating speed of transmitting-receiving ultrasound probe. "S-shape" of one of the curves indicates quick inversion of probe rotation. **E** shows 3-dimensional image calculated with data extracted from **A**, **B**, and **C**. Endocardial borders are also traced on 3 successive images at tele-systolic time. Next, all contours are interpolated by software, corrected if necessary by operator, and then inserted in algorithm to make a 4-dimensional reconstruction.

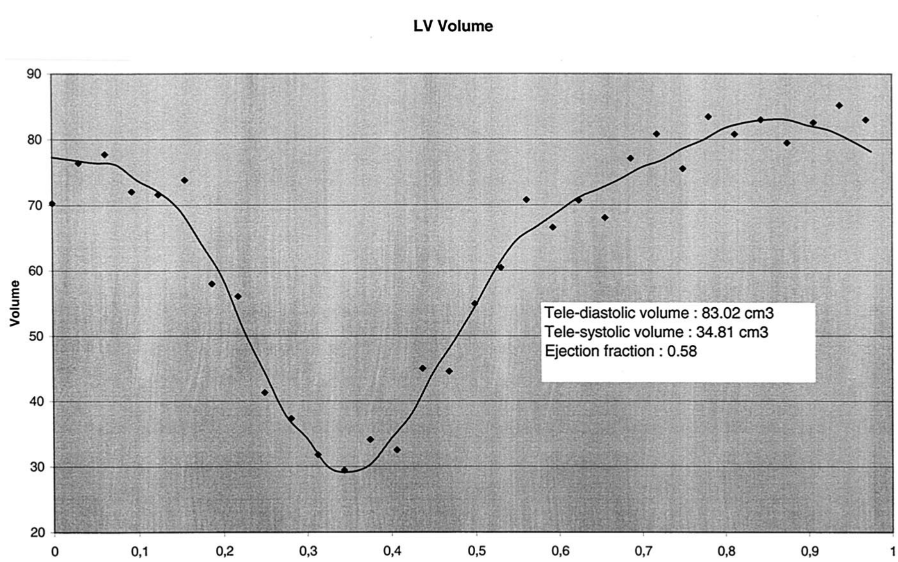

Figure 3 Volume evolution is represented either by 3-dimensional visualization or by volume-time curve. Each dot shows computed volume of each reconstructed volume. Plain curve is computed regression curve. Ejection fraction is deduced from this curve.

intraoperator variability of the 4D method was studied by repeating the manual contour tracing on the same images several weeks later by the same investigator. This second endocardial delineation showed a variation less than 3%.

DISCUSSION

The reconstruction of the myocardial contraction using data acquired during a single cardiac cycle needs images acquired in very rapid succession, but

Table 1 Classification data for volunteers

No.	Age	Weight	Height	$DVol_{Simp}$	$SVol_{Simp}$	EF_{Simp}	$DVol_{LV4D}$	$SVol_{LV4D}$	EF_{LV4D}
1	40	74	166	57.15	23.71	**0.59**	59.33	20.61	**0.65**
2	23	75	190	65.51	27.28	**0.58**	60.76	22.28	**0.63**
3	28	68	167	70.53	28.82	**0.59**	71.48	25.39	**0.64**
4	21	66	180	80.38	31.05	**0.61**	69.40	24.17	**0.65**
5	23	75	183	84.64	33.5	**0.60**	77.87	33.84	**0.57**
6	23	73	182	79.93	31.38	**0.61**	70.75	30.30	**0.57**
7	21	85	175	81.53	34.57	**0.58**	72.56	27.58	**0.62**
8	22	70	181	72.71	30.82	**0.58**	65.44	25.71	**0.61**
9	23	58	173	59.2	22.75	**0.62**	60.00	24.41	**0.59**
10	22	74	185	69.15	24.15	**0.65**	61.70	20.54	**0.67**
11	20	65	165	67.19	27.93	**0.58**	70.02	24.61	**0.65**
Mean	24.18	71.18	177.06	71.63	28.72	**0.60**	67.21	25.40	**0.62**
SD	5.64	7.00	8.39	9.18	3.98	**0.02**	6.12	3.99	**0.03**

$DVol_{Simp}$, Simpson tele-diastolic volume; $SVol_{Simp}$, Simpson tele-systolic volume; EF_{Simp}, ejection fraction determined by the Simpson's method; $DVol_{LV4D}$, left ventricular 4-dimensions tele-diastolic volume; $SVol_{LV4D}$, left ventricular 4-dimensions tele-systolic volume; EF_{LV4D}, ejection fraction determined by left ventricular 4-dimensions.

with angles uniformly distributed in space, to get a correct interpolation. The fast and continuously rotating sensor used here meets these requirements. This is not the case for the step-by-step rotating devices used in classical 3D imaging, which cannot reach high speeds without introducing disturbing oscillations during image acquisition. Conversely, continuous rotation entails specific problems such as image quality (ultrasound diffusion) and unusual incidence (images acquired along conic sections, Figure 6). Nevertheless, this preliminary study shows in practice that imaging carried out with such a device remains widely exploitable for 4D reconstruction.

The spinning speed of the scan head was adjusted here to ensure that each image is slightly less than 60 degrees (about 55 degrees) angularly distant from the previous one. Thus, a complete "static volume description" is obtained within 3 images, without angular position periodicity that could induce data accumulation at specific angles. With the frame rate value set to 53 images per second during examinations, about 17 volumes are reconstructed within the cardiac cycle. The rotation speed (RS, rotations per second), given by the formula:

$$RS = \frac{\Delta\alpha \times FR}{360} \quad (1)$$

where $\Delta\alpha$ and FR are respectively the angle (degrees) between 2 successive images and the frame rate (images per second) during acquisition, is thus 8.1 rotations per second. In fact, doing such rough calculus does not make sense: with the 4D method used to reconstruct the volumes, the whole set of data (images) acquired during the cardiac cycle is used to obtain a single volume. The only precaution to take is verifying that data are uniformly distributed in time and space, without specific periodicity (no angle of strictly 60 degrees between 2 successive images), to guarantee a correct multidimensional interpolation. Such conditions can be checked a posteriori, using the representation of Figure 6, where axes x and y depict time and angle, respectively, passed during acquisition of images, whose middle (corresponding to the probe axis) is plotted in black squares (lines "localize" the LV contour within each image).

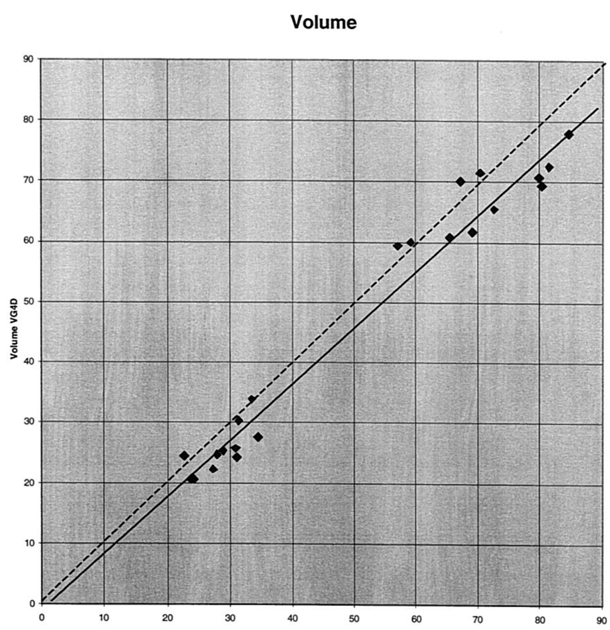

Figure 4 Comparison of measurements of tele-diastolic and tele-systolic volumes obtained by classical 2-dimensional Simpson and new left ventricular 4-dimensional (LV4D) methods. Equation of regression line (plain) is y = 0.94x − 1.16. Correlation coefficient is $r = 0.98$. *Dashed line* y = x indicates theoretical line of equality of methods.

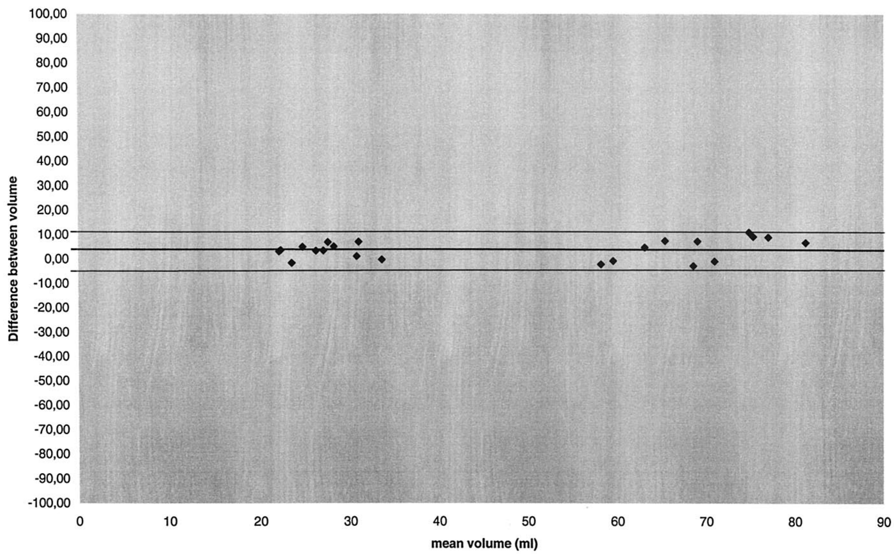

Figure 5 Bland and Altman plot of difference between left ventricular 4-dimensional (LV4D) measurements as function of average measurements. Three lines indicate mean and ± 2 SD of difference.

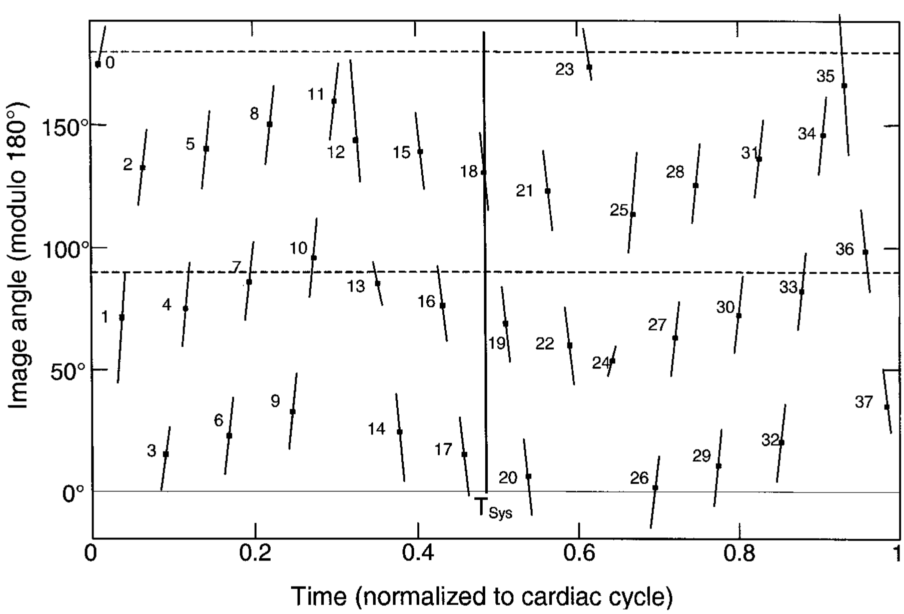

Figure 6 Angular and temporal distribution of images in cardiac cycle. *Black squares* indicate middle of images (corresponding to probe axis). *Plain lines* simulate extent of left ventricular contour in each image.

For 3 reasons, increasing the rotation speed of the scan head is not a crucial point. First, a faster speed would not improve the reconstruction accuracy at equal frame rate (same image number to process), because the only objective is to distribute images uniformly within the time-angle plane. Second, because of the significant curvature of the image, a faster speed would introduce imaging complications, such as major diffusion of ultrasound beams, to be characterized, or image distortion, making it more difficult to define the endocardium. Finally, mechanical factors confine spinning to about 10 rotations per second: Because of the wires connecting the sensor to the probe, the rotation must be inverted every 2 rotations. Very high speeds of rotation would increase the time required to decelerate then accelerate the sensor, which could not be neglected anymore. To avoid this drawback, a sensor mounted on rotating contacts was developed by Roelandt et al.[23] Even though preliminary results are encouraging, especially in 3D ultrasound image reconstruction, the noise introduced in images by contract friction seems to be prohibitive.

Increasing the image acquisition frequency is not essential. To keep a correct angular and temporal distribution of images, increasing the frame rate leads to increasing the spinning speed, which could be difficult to reach with current rotating technology limitations. A frame rate of about 50 images per second is adequate for regular patient rates (50-70 bpm) as shown in Figure 1. In the case of tachycardia, a slightly higher cadence is required to process a sufficient number of images per cardiac cycle.

In this preliminary study, the classical Simpson method is used on a group of volunteers to evaluate the LV ejection fraction by a validated technique.[1] Correlation between bidimensional measurements and the LV4D method is fairly good, and can be related to other studies that compare 2D and 3D methods.[4,5] The LV4D method has not yet been tested on larger LV volumes (here, all volumes are < 100 cm^3). Nevertheless, Figure 5 shows that agreement does not depend on cardiac volumes. The only problem that may arise could come from the need for a larger conic image or a deeper depth during acquisition to contain the whole ventricle, which could induce a slower frame rate acquisition. Even if LV4D still has to be tested under these conditions, the high frame rates available on every up-to-date ultrasound system should ensure correct acquisition. Similarly, this study concerns only hearts with no cardiac geometric irregularity, and must therefore now be validated on pathologic hearts. The problem is that the classical 2D Simpson method can no longer be used for the validation, because of the numerous simplifications it implies. Thus, a larger validation on real patients is in progress to compare the LV4D results with those obtained in nuclear medicine (cavity tomography or sestamibi synchronized tomoscintigraphy). The first results obtained show the superiority of LV4D compared with other standard methods. Furthermore, there is no theoretical constraint on using LV4D with all the modalities of cardiac imaging exploited in echocardiography: second harmonic imaging, contrast imaging, tissue Doppler imaging.[24] Initial tests carried out are very promising.

CONCLUSION

Although widely used by cardiologists, 2D echocardiographyhas well-known limits in the quantitative evaluation of systolic function, especially in the case of abnormal hearts. Classical 3D echocardiography is a first answer to these restrictions, but it requires acquisition over several cardiac cycles, which prevents its use when fast variation of systolic function occurs, typically in stress echocardiography. The new LV4D technique is very innovative and attractive because of the simplicity of the technical requirements (a fast rotating sensor and a computer), the ease of use (studies on difficult subjects, such as children or elderly people, are possible) and its potential use in the case of fast change in the systolic function (stress echocardiography, arrhythmia and pharmacologic studies). Obtaining complete cardiac measurements in less than 5 minutes (single cardiac cycle acquisition included) is a great advantage compared with other standard methods. Initial results conducted on a set of healthy subjects have shown a good correlation with classical 2D measurements.

We thank the ANVAR (Agence Nationale de Valorisation de la Recherche), the Région Centre, and the French Ministry of Research and Technology for their involvement or financial support in this research project.

REFERENCES

1. Force TL, Folland ED, Aebischer N, Sharma S, Parisi AF. Echocardiography assessment of ventricular function. In: Marcus ML, Schelbert RH, Skorton DJ, Wolf GL, editors. Cardiac imaging. Philadelphia: WB Saunders; 1991. p. 374-401.
2. Roelandt J, Salustri A, Mumm B, Vletter W. Precordial three-dimensional echocardiography with a rotational imaging probe: methods and initial clinical experience. Echocardiography 1995;12:243-52.
3. Chuange ML, Parker RA, Riley MF, Reilly MA. Three-dimensional echocardiography improves accuracy and compensates for sonographer inexperience in assessment of left ventricular ejection fraction. J Am Soc Echocardiogr 1999;12:290-9.
4. Schroder KM, Sapin PM, King DL, Smith MD, DeMaria AN. Three-dimensional echocardiographic volume computation: in vitro comparison to standard two-dimensional echocardiography. J Am Soc Echocardiogr 1993;6:467-75.
5. Gopal AS, Shen Z, Sapin PM, Keller AM, Schnellbaecher MJ, Leibowitz DW, et al. Assessment of cardiac function by three-dimensional echocardiography compared with conventional noninvasive methods. Circulation 1995;92:842-53.
6. Nosir YF, Salustri A, Kasprzak JD, Breburda CS, Ten Cate FJ, Roelandt JR. Left ventricular ejection fraction in patients with normal and distorted left ventricular shape by three-dimensional echocardiographic methods: a comparison with radionuclide angiography. J Am Soc Echocardiogr 1998;11:620-30.
7. Heusch A, Koch JA, Krogmann ON, Korbmacher B, Bourgeois M. Volumetric analysis of the right and left ventricle in a porcine heart model: comparison of three-dimensional echocardiography, magnetic resonance imaging and angiocardiography. Eur J Ultrasound 1999;9:245-55.
8. Gopal AS, Schnellbaecher MJ, Shen Z, Boxt LM, Katz J, King

DL. Freehand three-dimensional echocardiography for determination of left ventricular volume and mass in patients with abnormal ventricles: comparison with magnetic resonance imaging. J Am Soc Echocardiogr 1997;10:853-61.
9. Kupferwasser I, Mohr-Kahaly S, Stahr P, Rupprecht HJ, Nixdorff U, Fenster M, et al. Transthoracic three-dimensional echocardiographic volumetry of distorted left ventricles using rotational scanning. J Am Soc Echocardiogr 1997;10:840-52.
10. Munt BI, Leotta DF, Bolson EL, Coady K, Martin RW, Otto CM, et al. Left ventricular shape analysis from three-dimensional echocardiograms. J Am Soc Echocardiogr 1998;11: 761-9.
11. Roelandt JR, Yao J, Kasprzak JD. Three-dimensional echocardiography. Curr Opin Cardiol 1998;13:386-96.
12. Schmidt MA, Ohazama CJ, Agyeman KO, Freidlin RZ, Jones M, Laurienzo JM, et al. Real-time three-dimensional echocardiography for measurement of left ventricular volumes. Am J Cardiol 1999;84:1434-9.
13. Collins M, Hsieh AL, Ohazama CJ, Ota T, Stetten G, Donovan C, et al. Assessment of regional wall motion abnormalities with real-time 3-dimensional echocardiography. J am Soc Echocardiogr 1999;12:7-14.
14. Zwas DR, Takuma S, Mullis-Jansson S, Fard A, Chaudhry H, Wu H, et al. Feasibility of real-time 3-dimensional treadmill stress echocardiography. J Am So Echocardiogr 1999;12: 285-9.
15. Shiota T, McCarthy PM, White RD, Qin JX, Greenberg NL, Flamm SD, et al. Initial clinical experience of real-time three-dimensional echocardiography in patients with ischemic and idiopathic dilated cardiomyopathy. Am J Cardiol 1999;84: 1068-73.
16. Takuma S, Zwas DR, Fard A, Wu H, Chaudhry H, Di Tullio MR, et al. Real-time, 3-dimensional echocardiography acquires all standard 2-dimensional images from 2 volume sets: a clinical demonstration in 45 patients. J Am Soc Echocardiogr 1999;12:1-6.
17. Nguyen LD, Leger C. Visualization of the left ventricle volume deformation using ultrasound images acquired during a single cardiac cycle. Thirteenth Rotterdam Symposium on Echocardiography, June 23-25, 1999.
18. Canals R, Lamarque G, Chatain P. Volumetric ultrasound system for left ventricle motion imaging. IEEE Trans Ultrasonics, Ferroelectrics, Frequency Control 1999;46:1527-38.
19. Shannon CE. A mathematical theory of communication. Bell Systems Tech J 1948;27:379-623.
20. Folland ED, Parisi AF, Moynihan PF, Jones DR, Feldman CL, Tow DE. Assessment of left ventricular ejection fraction and volumes by real-time, two-dimensional echocardiography: a comparison of cineangiographic and radionuclide techniques. Circulation 1979;60:760-6.
21. Bonciu CI, Weber R, Nguyen LD. 4-D Reconstruction of the left ventricle from a single cycle ultrasound acquisition. Signal Processing IX, Theories and Applications. Vol 2. Proc of EUSIPCO-98, September 1998. p. 677-80.
22. Ledee R, Leger C, Thiel J, Fantini J, Lamarque G, Bonciu CI, et al. Restitution volumique du VG par sonde échographique 2D tournante. ITBM (Innovation and Technology in Biology and Medicine) 1994;15:403-18.
23. Lancee CT, de Jong N, van Egmond FC, Bom N, Roelandt JRTC. Three-dimensional echo acquisition by a fast rotating phased array probe. 13 Rotterdam Symposium on Echocardiography, June 23-25, 1999.
24. Fedele F, Trambaiolo P, Magni G, De Castro S, Cacciotti L. New modalities of regional and global left ventricular function analysis: state of the art. Am J Cardiol 1998;81:49G-57G.