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UNDERSTANDING THE DIMENSIONS IN ECHOCARDIOGRAPHY

George Thomas, MD
Fellow, Indian Academy of Echocardiography
Senior Consultant, Department of Cardiology
Indira Gandhi Co-operative Hospital, Kochi 682 020
E-mail: gthomas@doctor.com

INTRODUCTION

Echocardiography—or ultrasound cardiography (UCG)—has made tremendous progress since its inception. In 1950, WD Keidel was the first to use ultrasound to study the heart. Elder and Hertz pioneered the pulsed ultrasonic technique in the mid 1950s. These advances resulted in amazing developments in ultrasound imaging of the heart.

Ultrasound cardiography imaging has evolved from one-dimensional M-mode to two-dimensional (2-D) to present-day, three-dimensional (3-D) imaging. The advent of 3-D imaging has brought ultrasound imaging—in terms of *dimensions*—to completion. Three-dimensional imaging can be thought of as the final phase of UCG imaging technology. Now that all the dimensions in UCG are available, how can they be integrated them into clinical practice? This article attempts to shed some light on this issue.

THE DIMENSIONS

To understand and integrate the various dimensions of UCG, one needs to have a basic understanding of *dimensions* (Figure 1)—for the purposes of this discussion, *physical dimensions.* Dimension represents the number of degrees of freedom available for movement in a space.[1,2] For example, the space in which one lives is 3-D. One can move sideways (X axis), backward and forward (Y axis), or up and down (Z axis). Movement in any other direction can be expressed in terms of these three axes. Mathematically expressed, the dimensions of an object are the number of coordinates needed to specify an object. For example, a rectangle is 2-D (two coordinates—X and Y), whereas a cube is 3-D (three coordinates—X, Y, and Z). How do these dimensions relate to each other? By taking a lower dimension and moving it, one gets a higher dimension (see Figure 1). For example, moving a point (zero dimension) traces a line (one dimension); moving a line traces a plane (two dimensions); and a moving a plane traces a solid (three dimensions).

Mathematical dimensions are more complicated. They are ultimately based on the dimensional concept of Euclidean n-space (E^n). The point E^0 is zero-dimensional. The line E^1 is one-dimensional. The plane E^2 is 2-D. In general, E^n is n-dimensional.

Some theories predict that the space in which one lives actually has many more dimensions (frequently 10, 11, or 26), but the universe measured along these additional dimensions is subatomic in size. Time is incorrectly referred to as the "fourth dimension"; time is not the fourth dimension of space, but rather of spacetime. This does not have a Euclidean geometry, so temporal directions are not entirely equivalent to spatial dimensions.

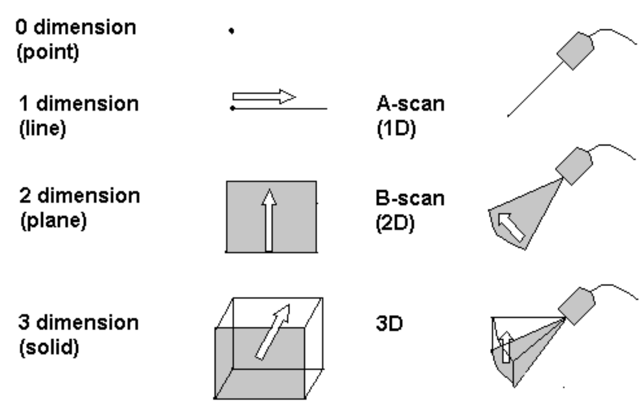

FIGURE 1. Diagram showing the different spatial dimensions and how they relate to each other (see text). The corresponding UCG dimensions are also shown.

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DIMENSIONS IN ULTRASOUND CARDIOLOGY

Ultrasound cardiography has made tremendous imaging developments in terms of dimensions (Figure 1). To understand these ultrasound dimensions better, one needs to be familiar with the various *scans* and *modes*. The three scans are A-scan, B-scan, and C-scan. These scans represent *data acquisition formats*. An A-scan is data acquisition along a single line of ultrasound beam. A B-scan is a plane consisting of multiple A-scans. A C-scan is also a plane, but it is parallel to the transducer face (i.e., the *C-plane*). In a C-scan, only echoes from a certain range within the object are displayed with the help of gating and can create an "en face" image.

Modes are *data display formats*. There are two types: A *or amplitude mode* and B or *brightness mode*. In A-mode, the amplitude of the returning signals is displayed graphically as spikes (Figure 2). In B-mode, the returning signals are displayed as dots of varying brightness. A-mode is only available in A-scans. In cardiology, A-mode and A-scan are not used for structural studies. However, spectral Doppler studies use similar-looking formats. B-mode is possible in all scans. M-mode—or *motion mode*—is also called *time motion* mode. M-mode actually represents A-scan data displayed in B-mode along a vertical-depth axis. These data are represented sequentially with respect to time. In other words, M-mode can be called real-time B-mode A-scan. Thus, we have the following dimensions in diagnostic ultrasound. A-scan is the first dimension. B- or C-scan is the second dimension. Multiple B- or C-scans, or a combination of B- and C-scans, represent the third dimension. This scan is usually done in a pyramidal-volume format. When a dimension is displayed in relation to time, it does not become a higher dimension. In such cases, the term "real time" should be used. For example, real-time 3-D is incorrectly called 4-D. But if this were true, then real-time 2-D would be 3-D!

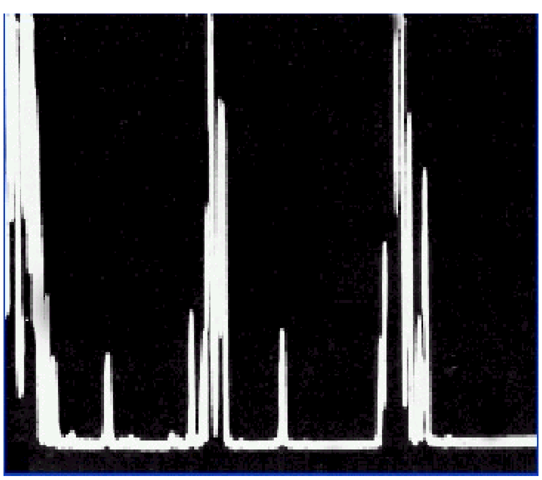

FIGURE 2. Display of A-mode sonogram. The spikes (i.e., amplitude) represent the reflected ultrasound.

QUANTITATIVE AND QUALITATIVE ASPECTS OF DIMENSIONS

By simple mathematical modeling, one sees that in higher dimensions, the amount of data acquired and displayed per unit of time is exponentially increased. At the same time, measurement becomes more complicated, and errors increase as higher dimensions are reached (Figure 3). Thus, the higher dimensions yield better qualitative perspective, and lower dimensions yield better quantitative perspective (Figure 4). For example, it would be difficult to appreciate valve morphology with M-mode imaging, whereas valve morphology is better detailed with 3-D imaging.

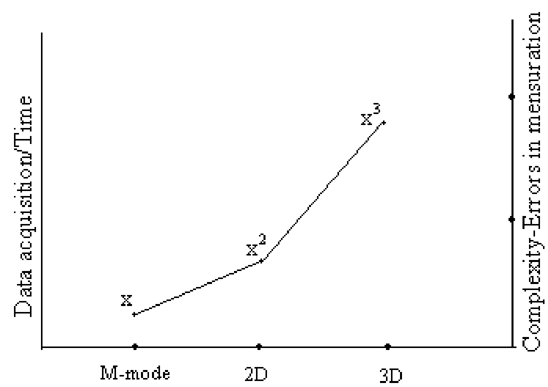

FIGURE 3. Simplistic graph showing the relationship of the various UCG dimensions regarding data acquisition and measurement parameters is shown.

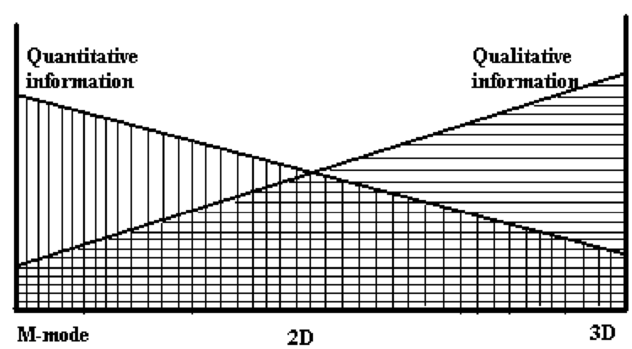

FIGURE 4. Graphic representation showing the relationship of the UCG dimensions to the amount of qualitative information and the ease and accuracy of obtaining quantitative information. Note that qualitative information is best with 3-D imaging, and the ease of obtaining quantitative information and its accuracy is better in M-mode.

Measurements increase in complexity at higher dimensions. It is simpler to measure the length of a line than the volume of a cube. This scenario becomes more complicated if the object is of irregular shape (e.g., the heart). That is why measurements are easier and more accurate with M-mode than 3-D. This comparison is exemplified by the fact that 3-D volume measurements require elaborate software[3] and involve much drudgery in tracing the 2-D areas. These problems can, to a certain extent, be overcome by automatic edge detection.[4] However, the accuracy of automatic edge detection is ultimately dependent on image quality. Thus, it would be unreasonable to visualize the morphology of a structure with M-mode imaging, and it would be difficult to make volume measurements with 3-D imaging.

STRENGTHS AND WEAKNESSES OF ULTRASOUND CARDIOGRAPHY DIMENSIONS

Having discussed the basic issues regarding dimensions, one can now examine the strengths and weaknesses of the different UCG imaging modalities. This examination will allow one to optimally use these modalities in a complementary fashion for the clinical setting.

M-MODE

The M-mode UCG (Figure 5) yields a one-dimensional ("ice-pick") view of cardiac structures moving over time. The echoes from various tissue interfaces along the axis of the beam are swept across in time, thus providing the dimension of time. Hence, movement is recorded in a graphic manner. The lines on the recordings correspond to the position of the imaged structures in relation to the transducer and other cardiac structures at any instance in time. The echoes are plotted on a scrolling screen. With this technique, stationary structures appear as straight lines across the screen, whereas moving structures appear as undulating lines. The 2-D real-time image is often required as a guide to place the M-mode cursor accurately within the heart. The M-mode echocardiogram uses a high sampling rate and can yield cleaner images of cardiac borders, thus allowing the sonographer to obtain more accurate measurements of cardiac dimensions and to more critically evaluate cardiac motion. Carefully placing the M-mode beam at the appropriate locations within the heart as well as obtaining clean echoes of endocardial surfaces are critical tasks for achieving accurate measurements and for making the calculations performed from these measurements meaningful.

Because M-mode imaging is one-dimensional, it is best suited for linear measurements. Also, M-mode has the best frame rate and temporal resolution. Thus, M-mode is useful in recording fast movements (like the systolic anterior motion of the mitral valve) or subtle movements (like the "b-bump" of left ventricular systolic dysfunction). M-mode imaging can also record motion in a graphic way. This technique is a useful tool in documenting cardiac arrhythmias and bundle-branch blocks. It also provides excellent graphic display of wall-motion abnormalities. M-mode is also suitable for pattern recognition by waveform analysis. The limitation is that because this mode provides information available only in the line of the ultrasound beam, a sampling problem exists. Also, it may not be possible to access all of the areas of the heart with this mode. Omni plane M-mode (or anatomic M-mode)[5] has, to a certain extent, overcome this problem.

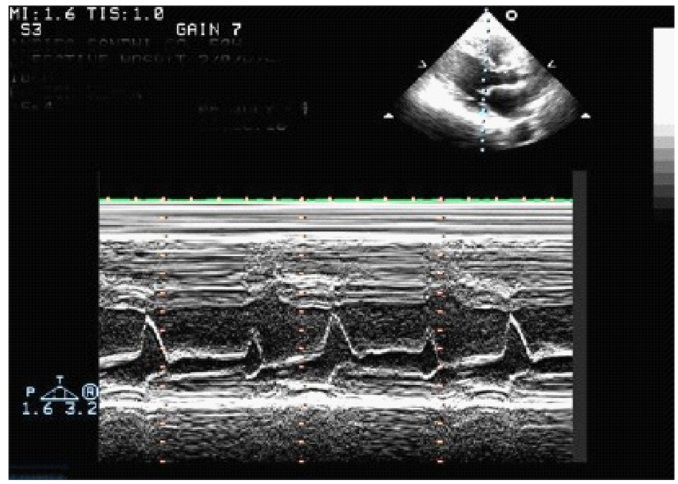

FIGURE 5. M-mode view of mitral valve. Note the minimal structural details but best measurement possibilities.

Because it is one-dimensional, M-mode is not suited for area and volume measurements. Thus, the extrapolated volume index of the ejection fraction is no longer relevant. This factor was relevant in the early days of UCG when 2-D and 3-D were not available. Today, M-mode–derived fractional shortening (linear measurement) would be appropriate and scientifically correct. Even though M-mode represents the oldest form of this imaging modality, it will continue to have an important role to play in the assessment of cardiac disorders, due to its great ability to readily and repeatedly quantify intracardiac linear dimensions.

TWO-DIMENSIONAL ULTRASOUND CARDIOGRAPHY

Two-dimensional UCG (Figure 6) allows a plane of tissue (both depth and width) to be imaged in real time. Thus, the anatomic relationships between various structures are easier to appreciate than with M-mode images. An infinite number of imaging planes through the heart are possible; however, standard views are used to evaluate the intracardiac and extracardiac structures. Two-dimensional echocardiography has better spatial resolution that yields better structural details. However, it can overestimate or underestimate the shape and size of irregular and skewed objects, depending on the "cut" (Figure 7). Two-dimensional UCG is best suited for area measurement. However, it can also be used for linear measurements. Two-dimensional UCG can provide diagrammatic representations on plane surfaces (e.g., paper).

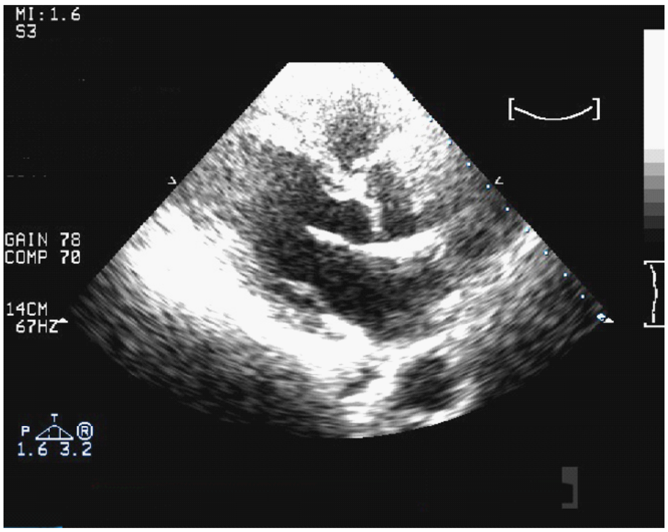

FIGURE 6. Two-dimensional view of mitral valve. Note the better structural details. Measurements are possible.

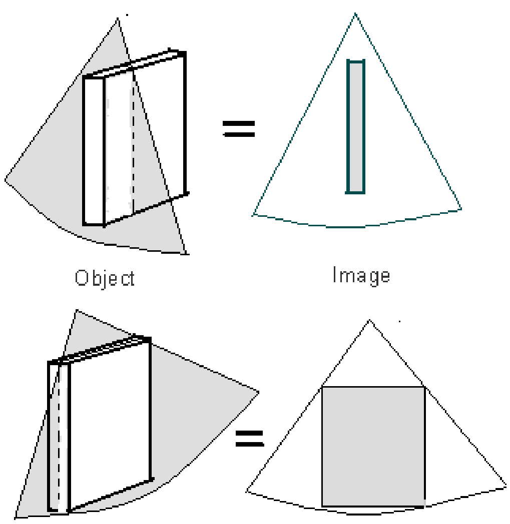

FIGURE 7. Schematic diagram showing how 2-D imaging can underestimate or overestimate an object size.

THREE-DIMENSIONAL UCG

Present-day 3-D UCG (Figure 8) can be called *real-time dynamic volumetric* 3-D. The term *real-time* applies because the image movements occur as and when the structure moves. The term *dynamic* is used because when the transducer is placed on a patient's chest, you instantly see 3-D images. If the transducer is taken away, the image disappears immediately. There is no need for respiratory or ECG gating (except for full-volume data acquisition). The operator can manipulate the image to see cardiac anatomy from several perspectives. This is regarded as volumetric because the data acquisition is in a pyramidal-volume format. This format is possible due to a *matrix array* as opposed to a linear array in two dimensions. Two-dimensional linear array imaging produces sector B-scan. This is a long axis sector perpendicular to the scan head. The matrix array can also produce *frontal short-axis* cuts parallel to the scan head (C-scan). Image display is composed of simultaneous steerable, intersecting B-scan sector arcs with multiple C-scan planes. These C-scan planes are adjustable in depth anywhere in range within the scan volume in real time or in playback with no image degradation.

On cursory examination, the advantages of 3-D may appear vague because 3-D "states the obvious." That is, there will be nothing to extrapolate. The lower dimension has a greater role in analysis and extrapolation.[6] For many in the field, this role makes the lower dimension more exciting and erudite. For comparison, if one looks at M-mode, there are many calculations and assumptions to be made. This process makes M-mode imaging a complicated and "highbrow" form of investigation.

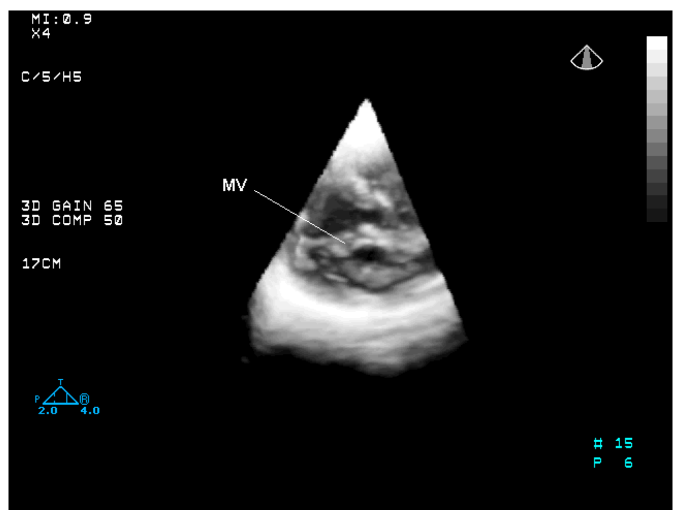

FIGURE 8. Three-dimensional image of mitral valve (MV). Note the structural details. The anterior leaflet appears like a ledge, and the surface is clearly visible. Volume measurements are very difficult with 3-D imaging.

In 3-D UCG, the computer performs all the calculations and presents the heart structure in an "as-is" condition. Three-dimensional UCG involves looking at the heart as if one is holding it in one's hands, with the additional ability to turn and slice it any way one wants. This quality makes interpretation of images easy for the uninitiated sonographer. It offers volumes per second rather than frames per second; therefore, one gets more information in less time (i.e., the entire array of apical views in the same amount of time that it takes to obtain the apical four-chamber view). This benefit will resolve issues more rapidly and thus allow better productivity. Therefore, although the benefits of 3-D UCG may not be explicitly obvious, there are many situations for which this modality will be advantageous.

Three-dimensional UCG yields the best spatial orientation and structural details. Another advantage is the concept of *virtual specimens* by full-volume data acquisition. Relatively inexperienced sonographers can perform this technique; and later these specimens can be cut, cropped, and analyzed as specified by the cardiologist. M-mode and 2-D images study only a limited region, so image acquisition requires diagnostic logic for optimum results. An untrained hand may miss important views while recording images. Similarly, the virtual specimens can be transmitted electronically to distant specialists (telemedicine)[7] for skilled analysis. Specific areas for which 3-D UCG has an edge are described next.

CARDIAC MASSES

A distinctive use of 3-D UCG is the study of intracardiac masses, including thrombi and vegetations. As previously mentioned, 2-D imaging can overestimate or underestimate the size and extent of intracardiac masses (Figure 7). On the other hand, 3-D UCG can more accurately assess the real extent of such masses. Three-dimensional UCG also offers better resolution due to increased scan lines and multiple angles for interrogation (as opposed to the lesser number of scan lines with 2-D UCG), thus making imaging of cardiac masses easier.[8]

CONGENITAL HEART DISEASE

Three-dimensional UCG performs well in the evaluation of congenital heart disease. Also, complex anatomic relationships and connections are easier to understand with 3-D UCG. This makes the task of diagnosing congenital heart disease easy, even for a novice. Three-dimensional UCG also improves the ability to locate abnormalities for interventional planning.[9] This new technology provides important information regarding surgical outcomes.[10]

ANEURYSMS AND DISSECTIONS

Another area for which 3-D UCG has a distinct advantage is the study of aneurysms and pseudo-aneurysms.[11] This modality is also useful in the study of aortic dissections.[12] The extent of such lesions can be easily delineated.

PERICARDIAL EFFUSIONS

The extent of pericardial effusions can be easily evaluated by 3-D UCG, especially in the case of localized effusions. Also, this modality can help guide treatment.

VENTRICULAR VOLUMES AND DERIVATIONS

This is another area for which 3-D UCG is found to be useful. Until now, ventricular volumes were estimated using geometric assumptions. Several studies have shown that 3-D UCG is superior to 2-D UCG for estimating both left and right ventricular volumes.[13] The advent of real-time volumetric scanning has certainly improved 3-D volume computation.[14] Better calculation of left ventricular mass would also become a reality.[15] However, there are limitations in volume computation (vide infra).

PACEMAKER LEAD PLACEMENT AND ENDOMYOCARDIAL BIOPSY

Three-dimensional UCG allows more precise pacemaker lead placement[16] and makes endomyocardial biopsy possible. Real-time 3-D UCG has been used to assist placement of biventricular pacemakers, especially via the coronary sinus and when placement is difficult due to right ventricular volume overload or increased tricuspid regurgitation. This modality is also used to document the fact that biventricular resynchronization improves overall cardiac function.[17] Similarly, 3-D UCG is extremely accurate and time-efficient in bioptome placement for endomyocardial biopsy.[18]

STRESS ULTRASOUND CARDIOGRAPHY

Three-dimensional UCG is also useful for cardiac stress testing. The advantage in this area is that simultaneous instantaneous views of the heart from different views can be obtained. Simultaneous confirmation of wall-motion abnormalities in different views is possible. Real-time 3-D is more efficient at acquiring the information in less time without creating respiratory artifacts. With this modality, more cardiac segments can be analyzed during the same cardiac cycle.[19]

IMPROVEMENT IN THE STUDY OF VALVULAR REGURGITATION

Valvular regurgitation is often a diagnostic dilemma. The cause of mitral regurgitation often eludes the investigator. In such cases, 3-D UCG is useful. It can identify partial prolapse, valve fenestrations, and other defects. Distinguishing between dilated cardiomyopathic and ischemic cardiomyopathic mitral regurgitation can aid in the differential diagnosis.[20] Also, quantification of regurgitant jets will become more accurate with 3-D UCG.[21]

MYOCARDIAL INFARCTION

Three-dimensional UCG makes it possible to quantify infarcted tissue with greater precision.[22] That is, the extent of infarcted myocardium in terms of area and volume could be more accurately assessed.

LIMITATIONS

Three-dimensional imaging can only visualize what is seen on the 2-D image. Thus, 3-D UCG is also susceptible to problems of sub-optimal image acquisition. Three-dimensional image quality greatly depends on the quality of the 2-D image and the ability to obtain a motion- and artifact-free 3-D data set. There are reports that measurements performed from B-scan views may be closer to the actual values than those from C-scan views, presumably because they are less highly influenced by distortions related to lateral resolution.[26] Three-dimensional imaging only creates a "virtual sense of depth" on a flat (2-D) screen and will require a sufficient learning curve for confident interpretation. In fact, experienced hands may have to unlearn many techniques learned during the M-mode and 2-D period, to obtain optimum advantage of the new modality. The display of the entire 3-D volume set still needs to be perfected. Although the matrix transducer is somewhat larger than a standard 2-D probe, the ergonomics are quite similar. At present, the equipment is quite costly. All these limitations will certainly be overcome with the development of newer techniques and growing experience with 3-D UCG.

Theoretically, 3-D UCG is best suited for volume measurements. The authors of many published papers extol the utility of 3-D imaging in volume measurement.[27] However, as mentioned earlier, this task can be an arduous proposition in clinical practice. This scenario can be understood if we consider the volume measurement of an irregular container—either by pouring in liquid from a measuring device or pouring out the contained liquid into a measuring device. Other more indirect methods use the lower dimensions of length or area and calculate the volume using formulas and extrapolations. In the case of 3-D UCG in its present format, direct measurements are impossible because the image is virtual and displayed on a 2-D screen. However, it is possible to measure the lower dimensions in various inaccessible regions by M-mode and 2-D imaging. Exact volume measurements may be possible with stereolithography,[28] wherein physical models are created from 3-D imaging and volumes can be determined by physically pouring in liquid.

Although quantitative aspects of UCG are important, qualitative information is no less important. Volume quantification by 3-D imaging would come as a disappointment in routine clinical practice. If one could give up the obsession of seeking volume data, then 3-D imaging would find its rightful place in routine clinical practice.

Another drawback is in the evaluation of wall-motion abnormalities. This is because wall motion involves myocardial thickening or thinning, so the only way to assess is to "cut" through (2-D) or "pierce" through (M-mode) the myocardium. These 2-D and M-mode renditions are possible with 3-D imaging; however, due to the lower frame rate, the images would not be satisfactory. Similar problems exist for cardiac hypertrophy. Also, the additional information (e.g., the inner surface of the ventricle) in 3-D confounds the evaluation of myocardial thickness by blurring the edges. Sophisticated tools are now available for wall-thickness measurements.[29] However, these tools are still relegated to the realm of research.

THE FUTURE

Improvements in 3-D software will lead to enhanced image quality. Novel ways of image representation such as stereoscopy, holography, or the generation of physical 3-D models (stereolithography) could enhance the perception of cardiac structures. As in dentistry, pre- and post-procedural physical models of valves will improve patient confidence in the procedure. Automated endocardial mapping will make functional assessment easier.[23] Further, real-time color Doppler will generate 3-D flow mapping. Also, real-time 3-D intracardiac UCG is being developed.[24,25] This technique would be useful in interventional electrophysiology. Three-dimensional UCG could enhance contrast myocardial perfusion studies and aid in novel drug delivery methods. Ultrasound contrast angiography may be just around the corner. Three-dimensional UCG could also be of use in guiding intravascular ultrasound and angioscopy. The possibilities are many and exciting.

CONCLUSION

Will the increased used of 3-D UCG mark the end of M-mode and 2-D? Not really. All these modalities will be complementary. Besides, 3-D images on a plane surface (monitor or paper) are, at best, 2-D virtual illusions; 2-D cuts in 3-D are essential aspects of the modality, so 2-D cannot be given up. In fact, 3-D could be used as a tool to teach M-mode and 2-D in a better way. By understanding dimensionality and applying those principles to diagnostic UCG, one can get maximum information by applying the right dimensional tool for the right purpose. A combination of the three dimensions can answer most of the daunting problems faced in clinical practice.

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UNDERSTANDING THE DIMENSIONS OF ECHOCARDIOGRAPHY POST TEST

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1. **Who was the first researcher to use ultrasound to study the heart?**
   a. Godfrey Hounsfield
   b. WD Keidel
   c. Paul C Lauterbur
   d. Katherine Austin Lathrop
2. **One definition of dimension is**
   a. a sample meant to be representative of a whole population.
   b. a section formed by a plane cutting through an object, usually at right angles to an axis.
   c. the number of degrees of freedom available for movement in space.
   d. a number assigned to a quantity so that it can be compared to other quantities.
3. **Along what axis is side-to-side (or right-to-left) movement?**
   a. Tangential axis
   b. X axis
   c. Y axis
   d. Z axis
4. **Along what axis is front-to-back movement?**
   a. Tangential axis
   b. X axis
   c. Y axis
   d. Z axis
5. **Along what axis is up-and-down (head-to-toe) movement?**
   a. Tangential axis
   b. X axis
   c. Y axis
   d. Z axis
6. **Which of the following sets represents data acquisition formats?**
   a. A-, B-, and C-scans
   b. X, Y, and Z axes
   c. A- and B-modes
   d. Spacetime dimensions
7. **Which of the following sets represents data display formats?**
   a. A-, B-, and C-scans
   b. X, Y, and Z axes
   c. A- and B-modes
   d. Spacetime dimensions
8. **In B-mode, the returning signals are displayed as**
   a. spikes.
   b. dots of varying brightness.
   c. vertical streaks.
   d. horizontal, shaded bars.
9. **Comparing dimensions, which of the following is a TRUE statement?**
   a. The higher the dimension, the less data that are acquired and displayed per unit of time.
   b. The higher the dimension, the lower the chance of errors in measurement.
   c. Higher dimensions yield better qualitative perspective, and lower dimensions yield better quantitative perspective.
   d. Higher dimensions are superior from both a qualitative and quantitative perspective.
10. **An M-mode echocardiogram yields a**
    a. one-dimensional view of cardiac structures moving over time.
    b. 2-D real-time image.
    c. plane of tissue (both depth and width) to be imaged.
    d. real-time volumetric image.
11. **M-mode echocardiography is best suited for ____ measurements.**
    a. linear
    b. area
    c. volume
    d. real-time
12. **Two-dimensional echocardiography is best suited for _______ measurements.**
    a. linear
    b. area
    c. volume
    d. real-time
13. **A matrix array is used with _______ techniques.**
    a. M-mode echocardiography
    b. omni plane echocardiography
    c. 2-D echocardiography
    d. 3-D echocardiography
14. **Two-dimensional linear array imaging produces a sector _______ scan.**
    a. A-
    b. B-
    c. C-
    d. M-mode
15. **A C-scan image produces a/an _______ view.**
    a. angle-down
    b. parasternal
    c. long-axis
    d. frontal short-axis
16. **What drawback is associated with the use of 2-D imaging to evaluate intracardiac masses?**
    a. Two-dimensional imaging time is much longer than that of 3-D imaging time.
    b. Two-dimensional imaging time is a more invasive method; hence patient compliance is lower.
    c. Two-dimensional imaging studies are significantly more expensive than 3-D imaging studies.
    d. Two-dimensional imaging studies can overestimate or underestimate the size and extent of the mass.

17. The ability of 3-D echocardiography to illustrate complex anatomic relationships and connections is critical in
  a. graphing the echoes of cardiac structures moving over time.
  b. placing the M-mode cursor accurately within the heart.
  c. evaluating congenital heart disease or locating abnormalities for interventional planning.
  d. obtaining accurate linear measurements.

18. The generation of physical, 3-D models is also known as
  a. stereolithography.
  b. spacetime manipulation.
  c. tesseract.
  d. Lebesgue-covering dimension.

19. Compared to other methods, real-time 3-D imaging is more efficient at acquiring information in less time without respiratory artifact. This characteristic allows more cardiac segment to be analyzed during the same cardiac cycle. This is particularly valuable when
  a. creating a graph of the movement of cardiac structures.
  b. visualizing wall-motion abnormalities.
  c. performing stress UCG.
  d. the 2-D imaging information is inadequate.

20. Three-dimensional imaging techniques are NOT well-suited to the evaluation of
  a. aneurysms and dissections.
  b. wall-motion abnormalities.
  c. valvular regurgitation.
  d. cardiac masses.

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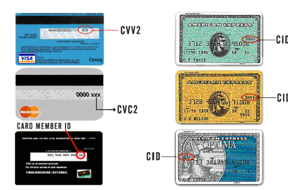

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