Three-Dimensional Doppler Ultrasound: A Tool for the 21'st Century

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Abstract: Three-dimensional (3D) ultrasound now offers a method to overcome former limitations of two-dimensional Doppler. Important 3D areas include the spatial delineation of the patency and pathways of blood vessels as well as the measurement of flow in them. In our laboratory, we have been investigating a variety of 3D uses: detection and mapping of arteries (3D power Doppler, in vitro), mitral valve regurgitation (3D color Doppler, in vitro and in vivo), gastric flow (3D color Doppler, in vivo) and methods of blood flow measurement. These are discussed with a few examples given.

INTRODUCTION

Blood vessels in the body are spatially three-dimensional (3D). They generally follow a tortuous pathway with considerable variation throughout the body in vessel distances from and orientations to the surface of the skin. These facts make it difficult to properly measure and describe blood velocity, flow, and vessel pathways using 2D Doppler ultrasound. New opportunities have emerged for more accurate and definitive description with the advent of 3D ultrasound. Three dimensional color Doppler, 3D power Doppler, and 3D pulsed Doppler are just three new Doppler areas which offer fresh opportunities for the 21'st Century.

Three-dimensional ultrasound imaging and interrogation are being achieved in a variety of ways. Currently, most methods involve 3D spatially tracking of a 2D imaging method or fixed scanning pattern of a 2D method. For example, a two dimensional B-mode imaging is scanned across an organ while the images and the 3D spatial position are recorded into a computer memory. A 3D reconstruction is then implemented off-line for viewing and studying the data. We have employed a magnetic based six dimensional tracking system (Bird™, Ascension Technology Inc, Burlington, VT) which keeps track of the 2D imaging probes 3D spatial position and 3D orientation(1). Another commonly employed method is to move the 2D imaging probe in equal and known steps acquiring images at each position. Equally stepped angles are used in a variety of cases including multilane transesophageal echocardiography (discussed later). For linear stepped scanning the 3D data collected with this method is easily spatially aligned in a computer like a “sliced bread loaf” for reconstruction. The additive feature for 3D Doppler, is the acquisition of Doppler information in the same way and in some cases at the same time as B-modes images are acquired. The only difference for 3D Doppler compared to B-mode imaging is a longer dwell time is needed at each location to acquire accurate Doppler information.

METHODS, EXAMPLE RESULTS, AND DISCUSSION

It was of interest to us to learn whether 3D power Doppler could be used to detect and map the pathways of the coronary arteries. We therefore conducted some preliminary studies with pig hearts obtained from a slaughterhouse fixed with vinegar to preserve them and their flexibility. Blood mimicking fluid (e.g. 3 g/1L cellulose particles - Sigma Chemical Co. St. Louis, MO) was pumped through the left coronary artery. An ATL (Bothell, WA) linear 10-5 MHz (L-10-5™) probe and HDI 3000™ imaging machine were used. The heart was submerged in a water tank and the probe was held fixed and scanned across the heart. Color power Doppler was used to image the blood vessels. The data was captured and transferred (1) to a Silicon Graphics Indigo® (Mountain View, CA ) where the color in the composite image was used to separate the color power Doppler from the gray scale image. The multiple "bread loaf slices" of the vessel were then reconstructed using the AVSTM visualization software from Advanced Visualization Systems (Waltham, MA). A reconstruction example is shown in Figure 1A. The image looks “bumpy" due to the limited resolution of the imaging probe for such small vessels (e.g. the left descending artery = 2.5 mm diameter). The methodology did demonstrate the feasibility in vitro of mapping the major vessels of the heart. If such mapping and study of patency could be achieved in vivo with non-invasive scanning this would be of immense value in diagnosing coronary artery disease - a challenge for the next century.

Transesophageal echocardiography is commonly used in the operating room to assess mitral valve function. (The probe is placed in the esophagus after the patient is asleep with the 2D sector scanning phased array located posterior to the heart). Multiplane probes allow mechanically rotating (in steps e.g. 2.5°) the array, in the plane of the array, around an axis that is perpendicular to it. We have captured B-mode and color Doppler images of the mitral valve region of patients in this way. Data was digitized from the video tape recordings off-line, processed to
separate out the Doppler information, and then reconstructed (Figure 2B). The time during the cardiac cycle at which data was taken and the reconstruction (Figure 2B) represents the early systole, when the pressure is high in the left ventricle. The blood flow has started to flow out of the aortic valve as indicated and considerable regurgitation is beginning back through the diseased mitral valve. In the cutaway view shown, the left atrium (only partially shown) facing up and the apex (not in the picture) facing down. Such information is valuable in assessing surgical repair of the mitral valve (before and after surgery).

A technique for measuring blood flow using 3D pulsed Doppler or high quality color Doppler is shown in Figure 2. The 3D scan allows a fixed radial distance (the edge of the sector in the example) to cut the vessel. The intersection of this radius along the sector and in the multiple planes sets up a surface that cuts through the vessel. The Doppler vectors normal to that surface will be measured with the Doppler system at each sector angle and in each multiple plane where this intersection occurs. Then each Doppler value when multiplied by each surface area component they represent (a sector width, beam thickness, and interpolated area on each side between planes) and then the product is summed over the entire inscribed surface it is equal to the flow through the vessel.

In conclusion, three methods of applying 3D Doppler have been presented with two examples given. We believe these illustrate some of the potential for 3D Doppler for the future - especially 2000 and beyond.

REFERENCES