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Chapter

Three-Dimensional Ultrasound Visualization of Peripheral Vessels

by

Einar Stranden, Carl-Erik Slagsvold, Brit Morken,
Hans J. Alker, Jon Bjørdal

Professor Einar Stranden, Ph.D.
Vascular Diagnostic and Research Laboratory
Aker Hospital, University of Oslo
0514 Oslo, Norway

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Ultrasound evaluation of the arterial system has a central role in noninvasive examination of patients with vascular diseases[1,2,3]. Structures are visualized by the reflection of ultrasound from the interfaces between tissues of different acoustic impedances, thereby depicting anatomic details. Compared to angiography, the ultrasound modality has the advantage of providing information on the vessel wall as well as the atherosclerotic plaque[4]. Furthermore, a three-dimensional (3D) impression of the vasculature is obtained by moving the ultrasound transducer back and forth. A dynamic impression of the vessel wall is also acquired. This information is lost when conveying the two-dimensional (2D) image printout. Readers not experienced with ultrasound examinations often find these 2D images difficult to interpret, because they are an abstract representation, often with little resemblance to the three-dimensional reality. Although desired for some time (Table 1), 3D information derived from ultrasound images has not been available until recently.

Vascular disorders are essentially three-dimensional and should logically be visualized that way, especially in regard to vascular malformations and the quantification of atherosclerotic plaques[5]. Current technology has been used for 3D rendering of larger organs like the heart and kidney, and volume estimation of abdominal organs[6]. In particular, 3D echocardiography has proved to render important clinical information[7]. Somehow, little attention has been paid to display 3D ultrasound data of peripheral blood vessels. This chapter is focusing on the acquisition and combination of ultrasound data to create 3D images for the assessment of vascular disorders, either from gray scale (B-mode) data or the power estimate of the received Doppler signal (ultrasound angio).

Table 1
Three-dimensional (3D) ultrasonic vascular reconstruction

Why 3D ultrasound?	Limitations
·Surgeons tend to create 3D impression by mental reconstruction of 2D infor- mation.	·Complex instrumentation, high costs
·Mentally reconstructed images are often erroneous as is often demonstrated during surgery.	·Long processing time, yet improving
·3D reconstructions may be used for both diagnostics and surgical planning.	·Unproven diagnostic capabilities
·Precise delineation and quantification of disease, e.g. atherosclerotic plaque, may be difficult using 2D images.	·No current standardization in views/-orientation
·Improves ultrasound scanning for educational purposes	

3D/4D representation
A 2D ultrasound image is composed of X x Y picture elements, or *pixels* (Fig. 1). This concept can be extended to the imaging of 3D objects. The depth, or Z dimension, can be modelled by stacking a series of 2D planes in depth. The 2D picture elements are then interpolated to become cubes. These cubes, which form the 3D image, are called volume elements or *voxels*. The volume representation is called a cuberille. When volumetric information is correlated with time to form the fourth dimension (4D), every voxel element has variations over time. Representation in 4D is particularly used when time dynamics plays an essential role, e.g. displaying the heart or cardiovascular structures over a cardiac cycle.

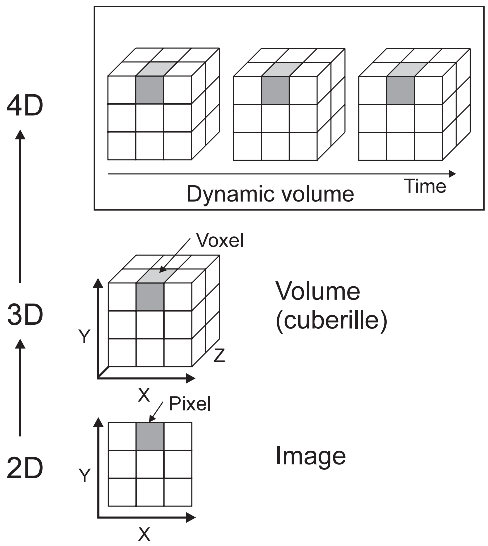

Fig. 1.
Schematic illustration of the elements constituting a two-dimensional (2D) ultrasound image, an image volume (3D) and a dynamic volume (4D) displaying volumetric information over time. The basic element in 2D is pixel; whereas voxel in 3D/4D.

METHODS
The 3D images were obtained by computer controlled acquisition using a TomTec Echo-Scan image processing work-station (TomTec Imaging Systems GMBH, Unterschliessheim, Germany), with or without respiration- and ECG-triggering to reduce movement artefacts. For acquiring 2D ultrasound images a Diasonics VST Master Series ultrasound scanner (Diasonics Ultrasound Inc., Milpitas, CA, USA) with 5 and 10 MHz linear transducers was used. An image volume was created by linear translation of the transducer. A motor-driven transducer carriage was used to provide stepwise (0.25 mm steps) movement along the blood vessel in transverse view orientation (Fig. 2).

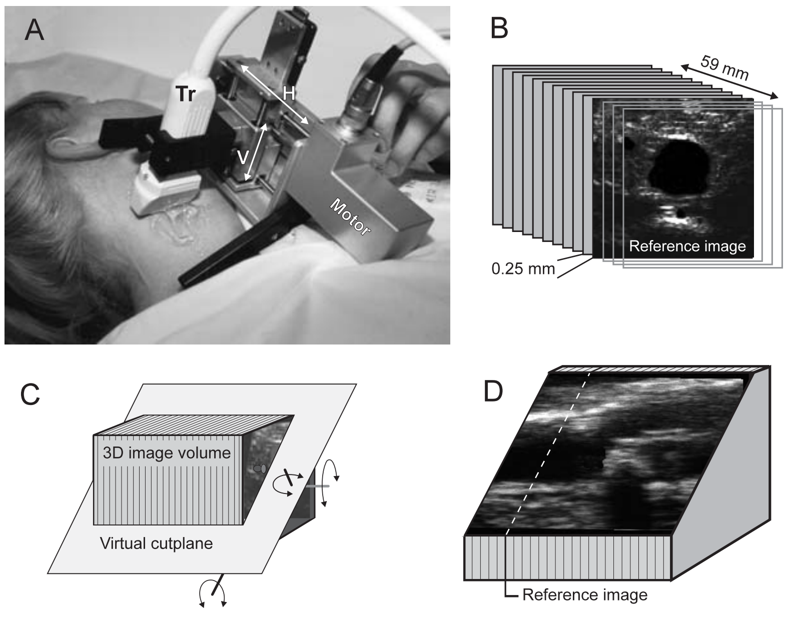

Fig. 2.
Ultrasonic 3D acquisition (A) and postprocessing (B-D). (A): A 3D image volume is created by stepwise linear translation (H) of the ultrasound transducer (Tr). At each step an image is acquired. Vertical passive sliding movement (V) ensures good skin contact. (B): A series of maximum 236 axial 2D sections (longitudinal scan length 59 mm) are placed one behind the other to form a rectangular image volume. A reference image is chosen within this series where important clinical information is displayed. (C-D): Visualization of the region of interest within the image volume is done with virtual cutplanes (viewing-planes) in any direction and location within the volume. These cutplanes may be freely moved and rotated at any angle (a, b or g). The cutplanes are slices in the image volume and visualized as gray scale images (D).

The movement of the motor driven transducer was performed untriggered or triggered by electrocardiography (ECG). Electrocardiography-triggered acquisition garantees that different stored sequences are time-synchronized within the cardiac cycle. A series of maximum 236 axial 2D sections (longitudinal scan length 59 mm) are placed one behind the other to form a rectangular image volume. Visualization of the image volume is done with virtual cutplanes (viewing-planes) in any direction and location (Figs. 2 and 3). These cutplanes may constitute orientations not obtainable in conventional ultrasound examinations, and may thus disclose new clinical information, as shown in 3D echocardiography[7]. Time to perform data acquisition varied between approximately 10 s for untriggered to 3-4 minutes for ECG-triggered investigation (Table 2).

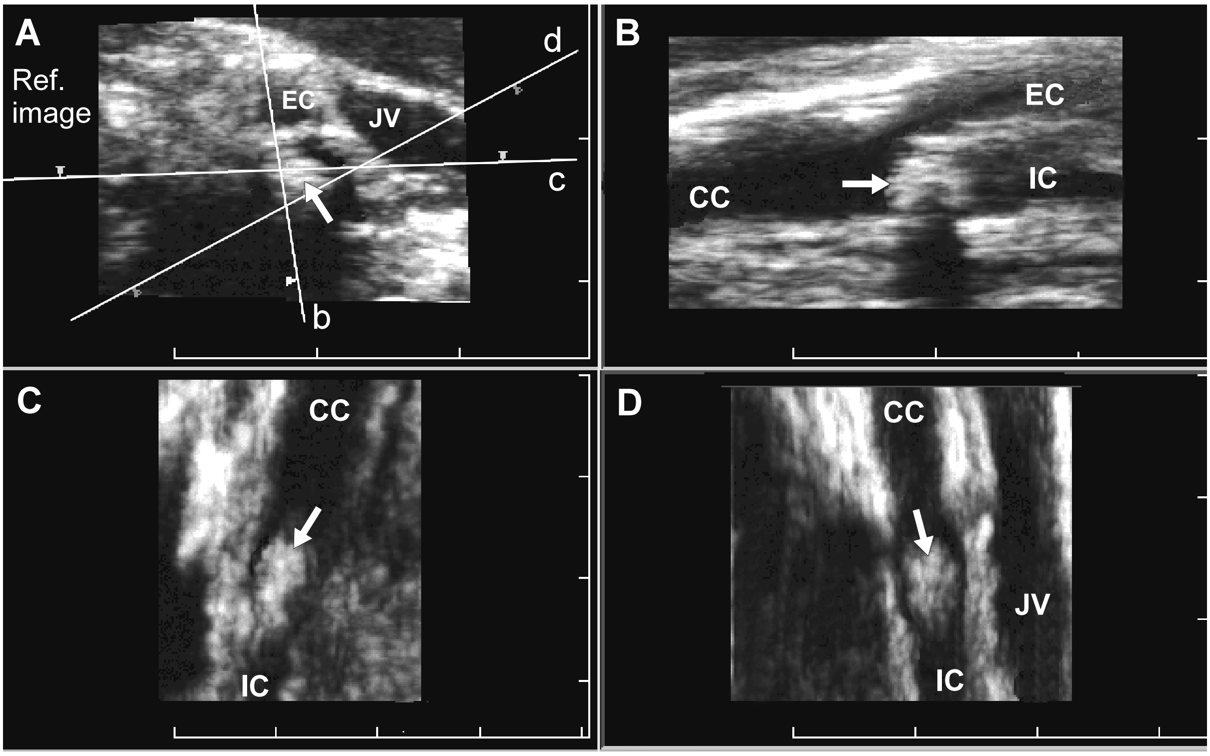

Fig. 3.
One to eight viewing windows may be chosen for displaying the data. In the current 4-window presentation (A) is the reference image view containing three cutplanes. The cutplanes b, c and d are represented by the 2D "slices" of the image volume in quadrant (B), (C) and (D), respectively. A calcified, atherosclerotic plaque is indicated with an arrow. (B) is the traditional longitudinal section through common carotid (CC), internal carotid (IC) and external carotid (EC) arteries, showing the plaque at the proximal part of the internal carotid artery. Quadrants (C) and (D) are sections through the plaque at a smaller angle to the transducer contact skin surface, not easily obtained at conventional examination.

Table 2
Typical acquisition/processing times for 3D and 4D ultrasound imaging

	Untriggered (min.)	ECG-triggered (min.)
3D volume acquisition	0.15	3-4
Cuberille generation	1	5
3D orientation of viewing plane	10	10
3D/4D image generation	3	15

Image transformation and filtering
During 3D data acquisition and image processing, the data undergo several transformation- and filtering operations. The process starts with the acquire-mode where ultrasound information is video-captured in real-time at a fixed framerate. The first postprocessing step is to transform the 2D videograbbed data into a cubic representation of the image volume. The volume representation is always 128-by-128-by-128 voxels; each voxel is the result from the 3D interpolation selecting neighbouring pixels in the 2D video-capture. When data is ECG-triggered, a set of cuberilles are generated over the heart cycle, making the data representation four-dimensional.

The next postprocessing step applies to the interactive process of reviewing the data when "viewing"-windows are opened for examination of the volume. This viewing function is the essential tool for the positioning of viewing-planes (up to eight) in relation to objects or structures which are of clinical interest (e.g. figure 3).

The final phase of postprocessing is the computation of 3D/4D images containing information of tissue surfaces, their orientation and distance from the viewing-plane. The user may select between different approaches like distance-, texture- and gradient-shading for surface rendering or volume visualization, with maximum- or minimum value-projection (Fig. 4). In distance shading the distance from the observer to the surface of the object is converted into a grey value. Surface points which are more distant from the observer will become darker than points which are close to the observer. Our studies on vascular 3D processing indicate that gradient-shading is an applicable and robust technique. In gradient-shading, the orientation of surface (aspect angle) together with distance determine the grey value, providing images with visual appearance correlating well with normal photographical techniques. Figure 5 depicts the proximal anastomosis of a patient with a reversed vein femoropopliteal bypass applying the 3D gradient-shading technique.

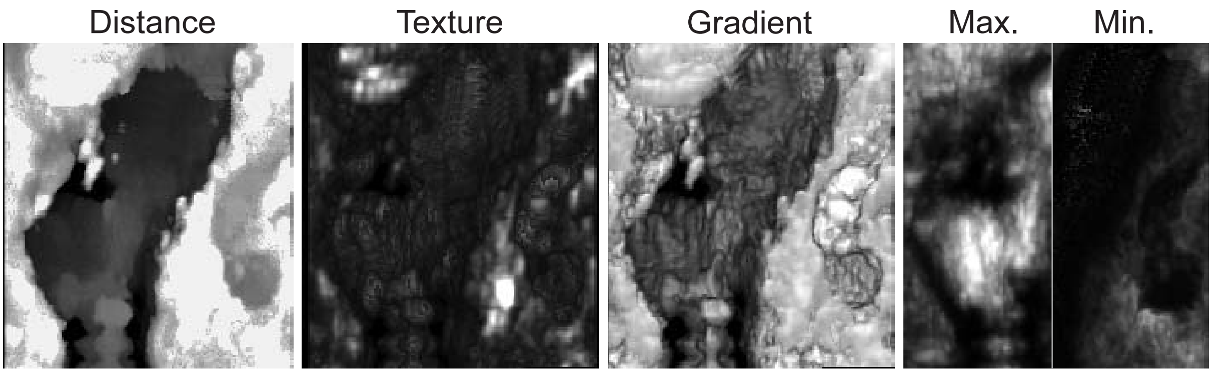

Fig. 4.
In the process of generating 3D images, distance-, texture- or gradient algorithms and maximum/minimum value-projection, may be applied to render "realistic" appearances. For 3D vascular studies gradient-shading is an applicable and robust technique. All images depict a small section of a common femoral artery (as indicated at the darker part of the distance- and gradient-filter images) containing moderate atherosclerotic plaques.

3D image generated from blood flow information
Colour Doppler velocity data has been used to isolate vascular structures from gray scale tissue images, thereby obtaining clearer vessel anatomy[8]. The use of velocity data has a two-fold advantage over gray scale generated images. Firstly, a major difficulty with volume data visualization is that the majority of volume elements do not contain clinically relevant data. Extraction of clinically useful information may therefore be difficult other than displaying a 2D slice. Using velocity information reduces this problem. Secondly, eliminating gray scale and instead using velocity data for surface rendering also improves visualization of vascular structures. This is especially important when understanding complex spatial relationships.

In the current study ultrasound angio was applied as the source for velocity data. This technique utilizes the power estimate (amplitude information) of the received Doppler signal, not the frequency shift as in colour Doppler flow imaging. The amplitude modality has an advantage over frequency shift modality being three times more sensitive, hence more suited for detecting low blood velocities. Figures 6, 7 and 8 depict 3D/4D rendering of arteries and veins based on ultrasound angio. In figure 6 a carotid bifurcation area (same patient as in figure 3) is rendered from an untriggered acquisition as viewed from three different cutplanes. The pronounced stenotic plaque of the proximal internal carotid artery is barely obtained in this mode, because the artery oscillates during the cardiac cycle and its image is regenerated by averaging, thus smoothening the surface model. However, when the same region is acquired with ECG-triggering, much higher precision is obtained (Fig. 7). In this view, the stenosis is depicted as a lack of flow information as indicated by the arrow. The irregularities in the generated surface points to the potential pitfall using blood flow information for rendering a 3D structure, due to the non-uniformity of fluid dynamic as well as technical aspects, as discussed below.

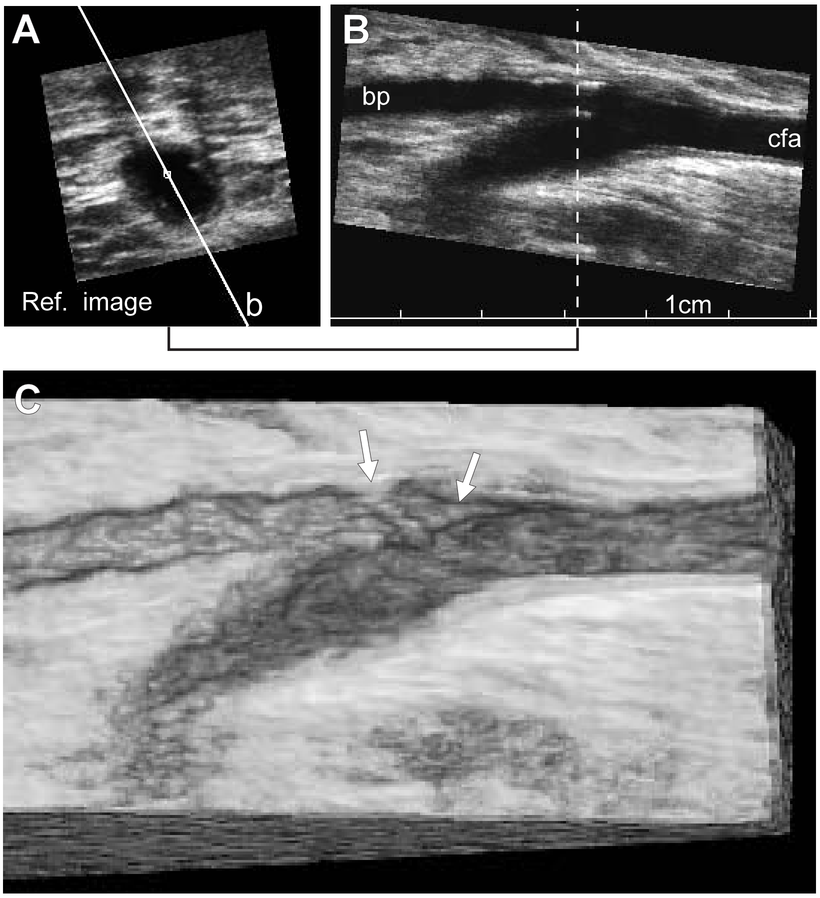

Fig. 5.
Views of the proximal anastomosis of a patient with a reversed vein femoropopliteal bypass (BP) to the common femoral artery (cfa), applying the 3D gradient-shading technique. The reference image A is a cross section through the anastomosis, indicated in the longitudinal view B as the interrupted line. The 3D image (C) is generated from the longitudinal section (B) and subsequently underlying parallel planes (in depth). The arrow to the right points to the anastomosis suture line, the other points to what is supposed to be a wall stricture.

Figure 8 depicts investigation of a patient with a cystic wall tumor in right iliac external vein. The tumor was discovered by clinical signs of venous outflow obstruction and recording of venous emptying rate by plethysmography. The content was nonechoic and the single layer outlining barely visible at careful gray scale scanning. Ultrasound angio immediately revealed the tumor as an area containing no flow components, indicated with an arrow. Three-dimensional rendering furthermore enhanced the perception of this tumor.

DISCUSSION

Three-dimensional imaging is a novel discipline in medicine[9]. Significant advances in 3D visualization have been achieved over the last decade matching closely advances in medical imaging and medical technology, by applications of techniques such as computed tomography (helical scan CT)[10], magnetic tomography imaging (3D MRI)[11] and nuclear medicine (3D emission tomography)[12]. Three-dimensional reconstructions are used in a variety of medical applications, in for example planning of craniofacial surgery[13,14], neurosurgery[15] and orthopedics[16,17].

Three dimensional representation of the vasculature may become a valuable adjunct to conventional 2D imaging. An advantage of 3D representation lies in the fact that orientations are preserved, enabling descriptive data, not definable by 2D formats or a verbal report, to be conveyed rapidly and effectively to the clinician. This may allow physicians with less experience to interpret complex images and making diagnostic decisions that currently require specialists in sonography. The effectiveness of this transfer of information, however, depends on how realistic the 3D images appear.

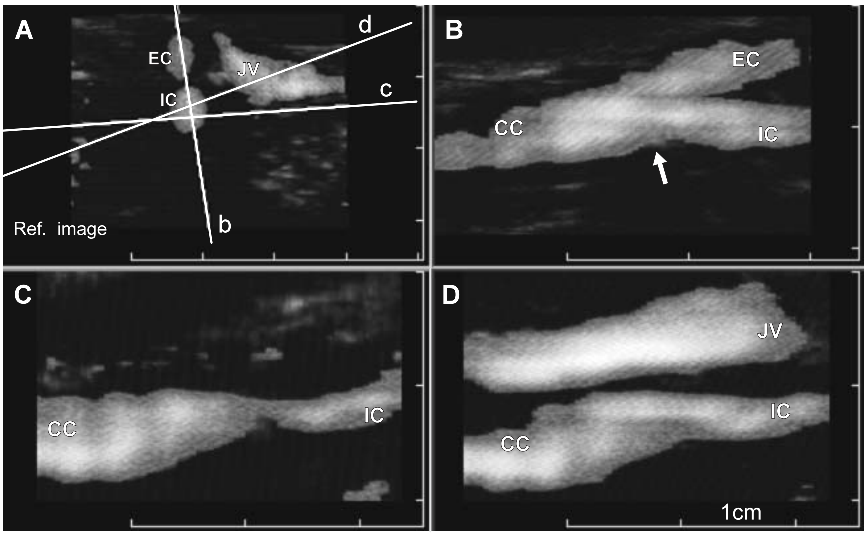

Fig. 6.
Visualization of carotid artery and jugular vein (JV) at the carotid bifurcation area of the same patient as in figure 3, based on untriggered ultrasound angio flow imaging. Annotations are as in figure 3. Cutplanes have similar orientation as in figure 3, although rotated 90° for (C) and (D). The pronounced stenotic plaque of the proximal internal carotid artery is barely obtained in this mode (arrow).

A limitation using flow information when representing 3D vascular structures lies in the application of high-pass filters and the stationary echo cancellers of the ultrasound scanner. These are likely to determine the displayed three-dimensional shape, rather than the vessel wall. It is the vessel wall structure and not the flow which ideally should be displayed. This is shown in figure 7 where the rendering of the external carotid artery is incomplete during diastole. This is the consequence of cessation in blood flow during diastole due to the high resistance in the vascular bed distal to the external carotid artery. This is a normal finding in spectral Doppler investigations. The vascular resistance of the internal carotid artery is low, causing blood to flow in forward direction during the complete cardiac cycle.

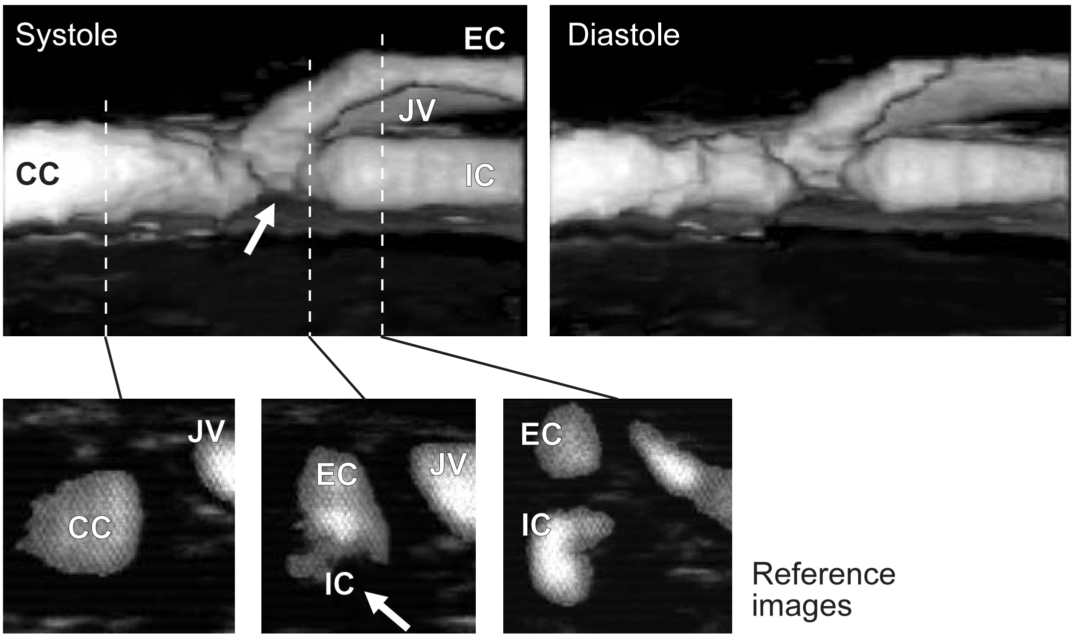

Fig. 7.
ECG-triggered ultrasound angio increases spatial and temporal resolution significantly compared to untriggered acquisition. This carotid bifurcation is the same as in figure 6. A stenosis is depicted as a lack of flow information as indicated by the arrow. Annotations are as in figure 3. Note that the flow contour not necessarily represents the vessel wall, as clearly shown in the external carotid artery during diastole, where blood flow may approach zero, giving an erroneous impression of an occluded external artery.

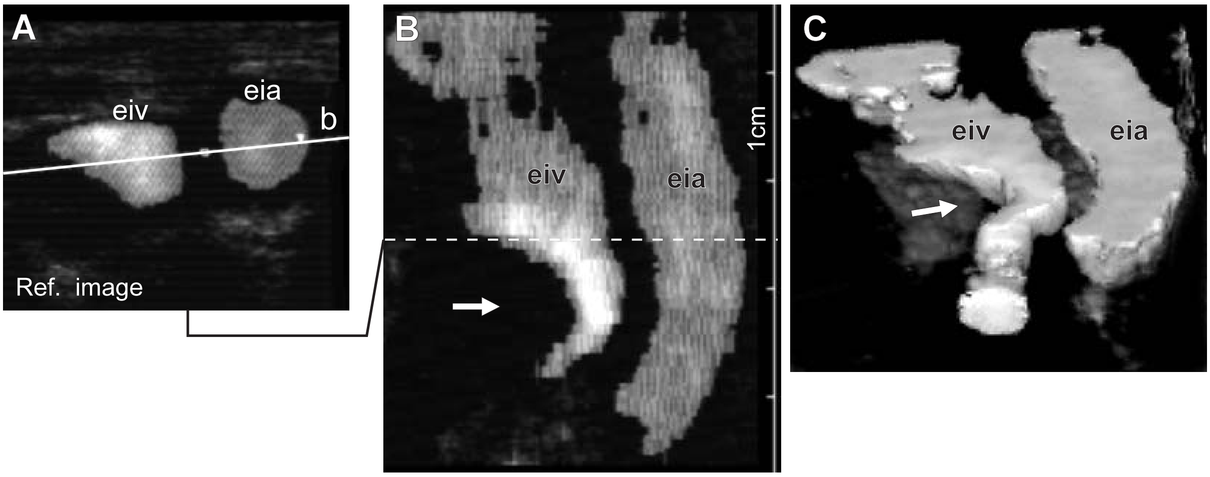

Fig. 8.
Investigation of a patient with a cystic wall tumor in right iliac external vein (arrow). Ultrasound angio depicts the tumor as an area containing no flow components (B). The content was nonechoic and the single layer outlining barely visible at careful B-mode scanning. Three-dimensional rendering furthermore enhanced the perception of this tumor (C).

Four-dimensional flow presentation is a fascinating display of flow contour during a cardiac cycle. Furthermore, 4D flow also indicates vessel wall movements, making comparisons of vessel wall compliance between prosthetic graft and artery readily visible.

Our experience shows that 3D/4D ultrasound is superior to 2D in communicating volumetric information, and the use of ultrasound angio may overcome problems related to poor B-mode visualization. Clinically, 3D imaging may become important in relation to arterial reconstructions performed without angiography, e.g. carotid endarterectomies. This study demonstrates that ECG-triggered 3D ultrasound intensity mode significantly improves the perception of the vascular structure as compared to conventional ultrasound techniques.

Future

What can be expected in the future? Available studies indicate that 3D/4D possess a capability to improve clinical information from ultrasound images, as is documented in echocardiology[7]. As the ultrasound scanner- and computer technology is being refined, development is going in the direction of real-time 3D/4D units imbedded into conventional scanners. Special 3D ultrasound transducers ensure more practical one-person operation. On-line guidance of the transducer and computer-assisted diagnosis (automatic area/volume calculations) is a natural next step. Furthermore, evolution of the software should provide accurate display of clinical relevant data, for instance by freely moving about in the image volume, by holographic presentation, or tracking to velocity vectors to obtain guided motion through the vascular sections.

Much of the development in biomedical instrumentation, especially in ultrasound techniques, has been engineer-driven, with the medical profession following and adapting to the ideas put up by the technologists. The development in medical technology should to a larger extent be medical profession driven. We should be encouraged to define our needs regardless of the techniques being available at present. Then maybe our expectations could be met in the future.

REFERENCES

1. Ricotta JJ. Plaque charactenzation by B-mode scan. Surg Clin North Am, 70; 191-199: 1990
2. Comerota AJ, Ganley JJ, Karz ML, et al. Real-time B-mode carotid imaging. J Vasc Surg, 1; 84-95: 1984
3. Quill DS, Colgan MP, Sumner DS. Ultrasound screening for the detection of abdominal aortic aneurysms. Surg Clin North Am, 69; 713-20: 1989
4. Rubin JR, Bondi JA, Rhodes RS. Duplex scanning versus conventional arteriography for the evaluation of carotid plaque morphology. Surgery, 102; 749-55: 1987
5. Delcker A, Diener HC. Quantification of atherosclerotic plaques in carotid arteries by three-dimensional ultrasound. Br J Radiol, 67; 672-678: 1994.
6. Gilja OH, Thune N, Matre K, Hausken T, et al. In vitro evaluation of three-dimensional ultrasonography in volume estimation of abdominal organs. Ultrasound Med Biol, 20; 157-165: 1994
7. Pandian NG, Roelandt J, Nanda NC, et al. Dynamic three-dimensional echocardiography: Methods and clinical potential. Echocardiography, 11; 237-259: 1994
8. Pretorius DH, Nelson TR, Jaffe JS. 3-Dimensional sonographic analysis based on color flow Doppler and gray scale image data: A prelimenary report. J Ultrasound Med, 11; 225-232: 1992.
9. Barillot C, Gibaud B, Lis O, et al. Computer-graphics in medicine -- a survey. Crit Rev Biomed Eng, 15; 269-307: 1988.
10. Fishman EK, Drebin B, Magid D, et al. Volumetric rendering techniques: Application for three-dimensional imaging of the hip. Radiology, 163; 737-738: 1987.
11. Axel L, Herman GT, Udupa JK, et al. Three-dimensional display of nuclear magnetic resonance (NMR) cardiovascular images. J Comput Assist Tomogr, 7; 172-174: 1982.
12. Wallis JW, Miller TR, Lemer CA, et al. Three-dimensional display in nuclear medicine. IEEE Trans Med Imaging, 8; 297-303: 1989.
13. Koltai PJ, Wood GW. Three-dimensional CT reconstruction for the evaluation and surgical planning of facial fractures. Otolaryngol Head Neck Surg, 95; 10-15: 1986.
14. Vannier MW, Marsh JL, Warren JO. Three-dimensional CT reconstruction images for craniofacial surgical planning and evaluation. Radiology, 150; 179-184: 1984.
15. Virapongse C, Shapiro M, Gmitro A, Sarwar M. Three-dimensional computed tomographic reformation of the spine, skull, and brain from axial images. Neurosurgery, 18; 53-58.1986;
16. Totty WG, Vannier MW. Complex musculoskeletal anatomy: analysis using three dimensional surface reconstruction. Radiology, 150; 173-177: 1984.
17. Grasso G, Andreoni A, Romeo N, Cipriano R, Uzzielli G. Recent developments in imaging diagnosis in fractures of the acetabulum: rhe role of CAT and tridimensional reconstruction. Ital J Orthop Traumatol, 16; 79-91: 1990.

Title sheet

Einar Stranden, Ph.D.
Professor
Vascular Diagnostic and Research Laboratory
Department of Surgery
Aker University Hospital,
Oslo, Norway

Carl-Erik Slagsvold, M.D., Ph.D.
Consultant
Vascular Diagnostic and Research Laboratory
Department of Surgery
Aker University Hospital,
Oslo, Norway

Brit Morken, M.Sc.
Vascular Diagnostic and Research Laboratory
Department of Surgery
Aker University Hospital,
Oslo, Norway

Hans Jørgen Alker, Ph.D.
Vingmed Sound A/S
PO Box 141
3191 Horten, Norway

Jon Bjørdal
Vingmed A/S
PO Box 8
1324 Lysaker, Norway