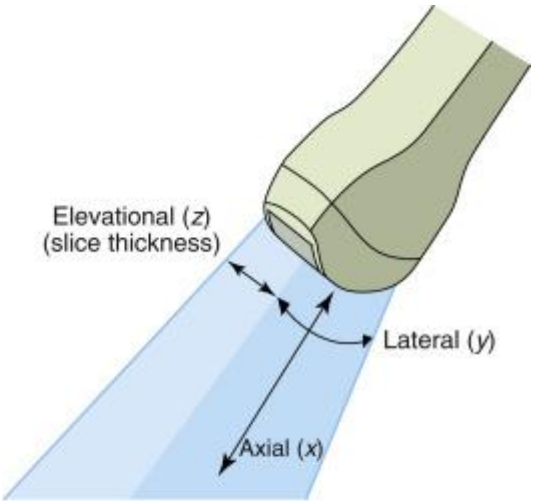
BASICS OF THREE-DIMENSIONAL ECHOCARDIOGRAPHY

WHAT IS 3D/4D ECHOCARDIOGRAPHY?

3D echo permits 3-dimensional analysis and display of ultrasound data. The term 4D echo is sometimes used to introduce time (moving 3D images) as the "fourth dimension".

3D ECHO PROBE

Data acquisition is achieved by imaging with 3D matrix array transducers.



2D vs. 3D matrix array transducers

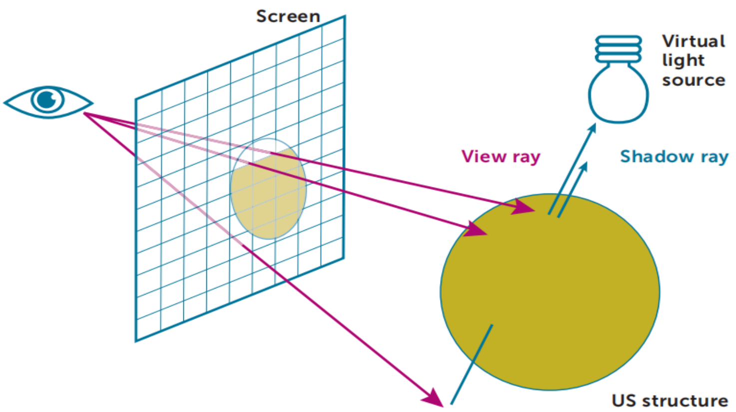
3D transducers acquire a pyramidal volume set (piezoelectric elements are arranged in a rectangular grid (matrix grid)) using more than 3000 independent piezoelectric elements. The beams are formed to a large extent within the transducer. The imaging frequency of transthoracic 3D transducers is between 2 and 4 MHz in contrast, 2D transducers only scan a two-dimensional sector, which composed of 128 piezoelectric elements each electrically isolated and placed in a single row.

FORMS OF 3D ECHOCARDIOGRAPHY

	Description	Advantage	Disadvantage
Real time (live) 3D (RT3D)	Structures are displayed in 3D format while imaging – live, dynamic 3D imaging. Acquisition of multiple pyramidal datasets per second	– Immediate results – Can be used for monitoring procedures, evaluating heart valves, ventricular function – Can be used when RR intervals vary (e.g., atrial fibrillation) – Live 3D color flow can be superimposed on a live 3D data set to visualize blood flow in real time.	– Small or narrow sector – 3D zoomed mode/view – Low spatial & temporal resolution (frame rate) – Orientation sometimes difficult
Triggered multi-beat (full volume) 3D acquisition	A complete dataset is required during several heartbeats	– Higher temporal & spatial (axial & lateral - elevational)) resolution – More possibilities of quantification, analysis & display – Used for detailed structural assessments and surgical planning	– Post-processing required – Time consuming & patients needs to be still in a position & breath holding (that is challenging) – Only works in sinus rhythm (ECG gated heart cycles from 2 to 6, that are subsequentially stitched together to create a single volumetric data set) – Stitching artifacts

3D IMAGE REPRESENTATION

Volume Rendering	Rendering algorithm that create the impression of three-dimensionality on a 2D screen (ray casting, shear warp etc.,)
Surface Rendering	Surfaces are displayed as solid structures or wire frames (i.e., cast of the ventricular cavity) **Or** This technique represents 3D objects by their surface boundaries. The data is converted into a mesh of polygons, typically triangles, which are then rendered to create a 3D image.
2D tomographic slices	3D dataset is sliced to reconstruct 2D cut planes (multiplane) **Or** Cross-sectional images of a 3D object or structure that are obtained using imaging techniques like CT (Computed Tomography), MRI (Magnetic Resonance Imaging), or ultrasound. These slices are essentially 2D representations of a thin section of the object, and when stacked together, they can reconstruct the entire 3D structure.

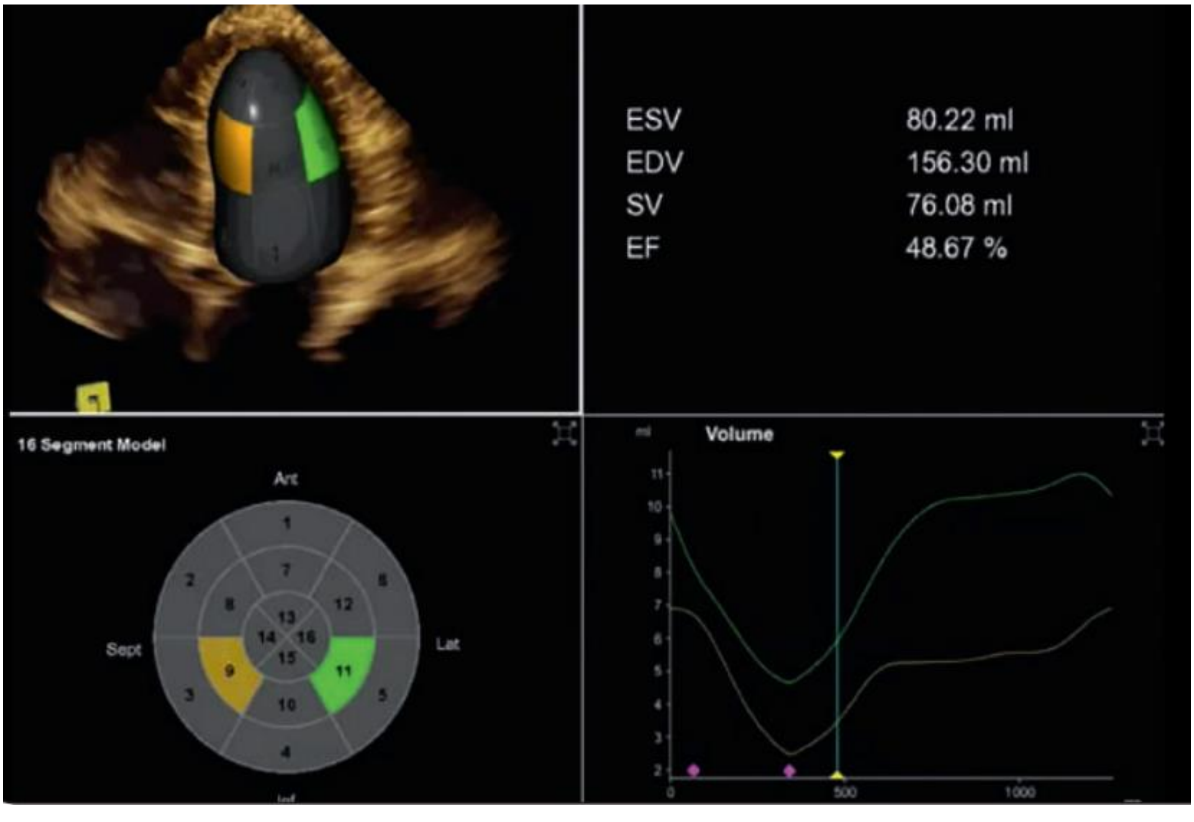


Principle of ray casting (volume rendering technique). Ray tracing is an algorithm that simulates the effects of light as it would be seen by the observer (eye) while it passes through a voxel space.

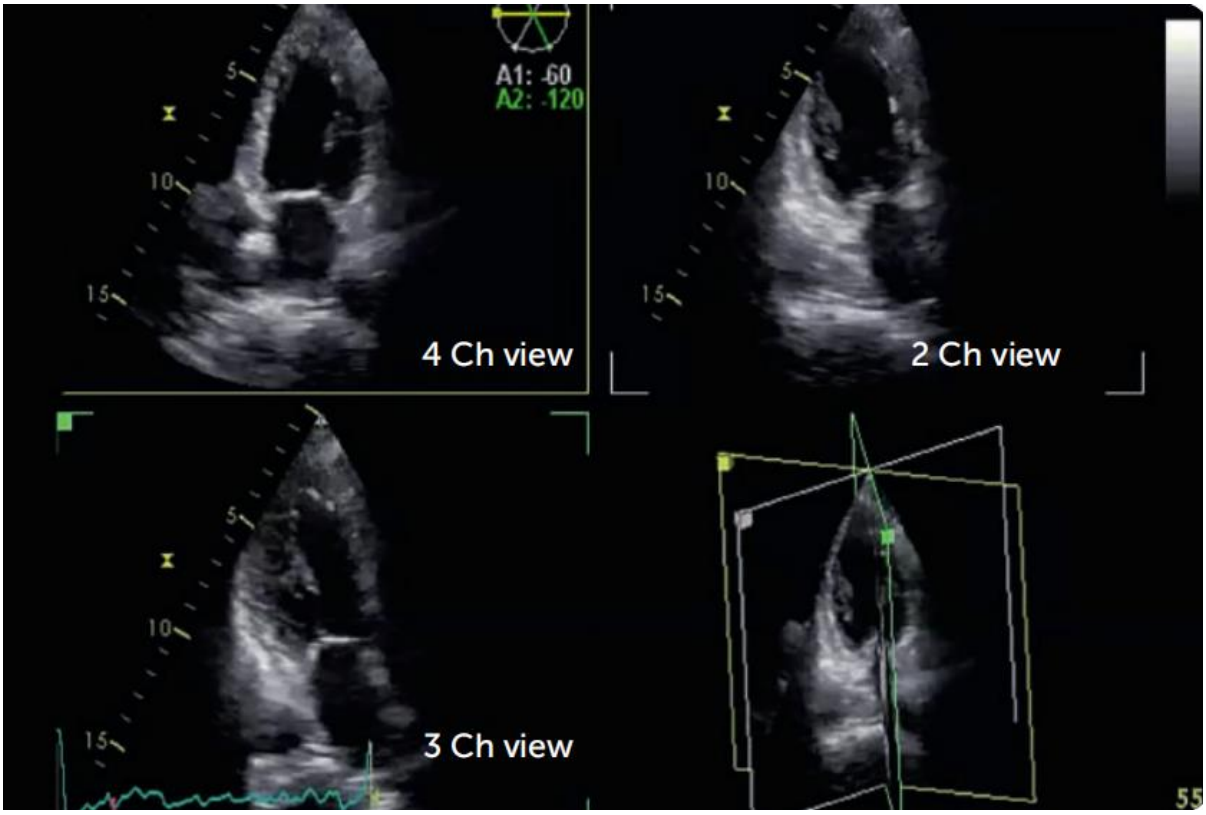
Note: 3D-dimensional image “pixels” are known as voxels.

3D rendering algorithms “recode” the original ultrasound pixels/voxels to create a sense of depth (distance shading, grey-level gradient coding etc.). Therefore, we lose information concerning the density of tissue and tissue characteristics. In other words, we cannot distinguish fibrosis or calcification from other less echogenic tissue.

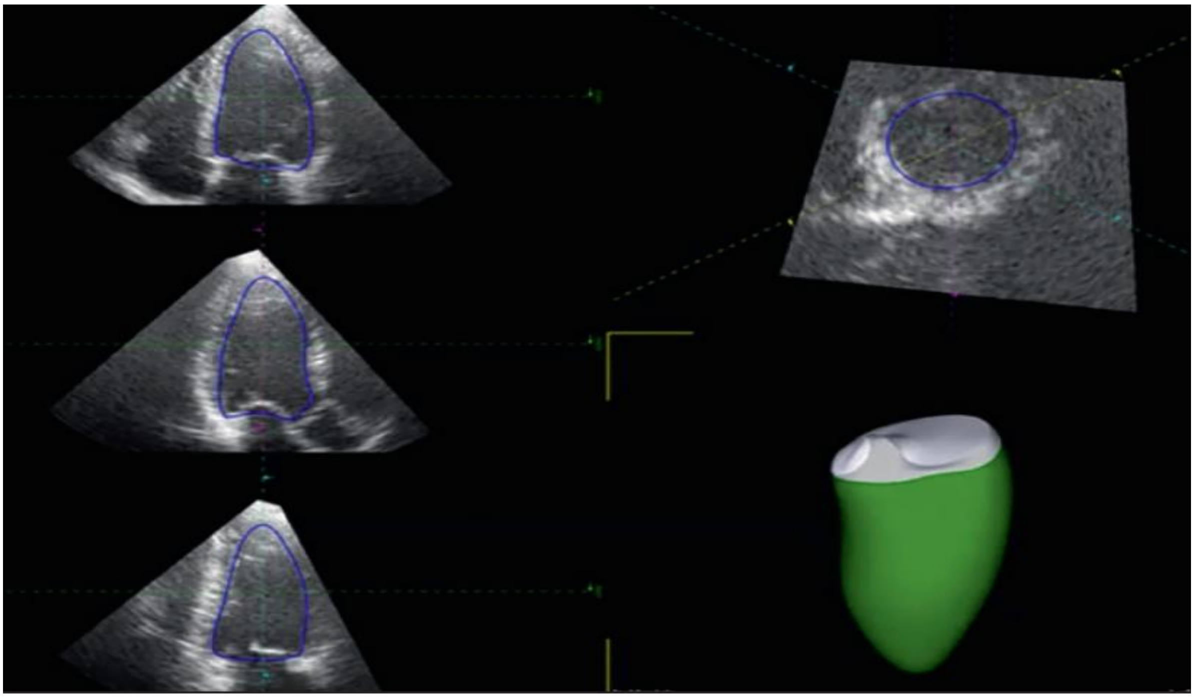
SURFACE AND VOLUME RENDERING – apical four-chamber view/3D Combination of left ventricular surface and volume rendering with segmental analysis (comparison of two regional volumes). The curves in the right lower quadrant represent the regional volume curves during the cardiac cycle. The bull’s eye shows the selected segments (mid lateral segment= 11, mid septal segment= 9) in the left lower quadrant.



MULTIPLANAR REPRESENTATION – apical views/3D Simultaneous display of four- (upper right), two- (upper left), and three-chamber views (lower left). The right lower corner shows the corresponding cut planes.



ENDOCARDIAL SURFACE RENDERING – apical full volume acquisition/3D Surface rendering is performed in accordance with semi-automated endocardial tracing on apical and short-axis views. The resulting volume (bag) is seen in the right lower corner.



3D IMAGE ACQUISITION

- Make sure you have a good ECG signal (R-wave).
- Aim for best possible 2D image quality (trash in, trash out).
- Try to limit the number of beats in order to reduce stitching artifacts.
- Check for stitching artifacts by viewing a cut plane perpendicular to the sweep plane.
- Acquire images during breath hold to reduce motion and stitching artifacts.
- Select an adequate gain (mid-range) threshold to discern true structures from noise.
- Choose the smallest necessary sector width to achieve the highest possible frame rate.
- Use 2D images as a reference.
- For better orientation on the 3D image, recapitulate cardiac anatomy and topography

Cropping techniques (software algorithms) allow the operator to "Cut away" structures that obscure one's view of the structure of interest (i.e. cut away parts of the left ventricle to view the mitral valve or the septum). You can reconstruct in 3D only those structures that can also be visualized in 2D.

CLINICAL APPLICATIONS OF 3D ECHOCARDIOGRAPHY

Calculation of true volumes (heart chambers)

Calculation of Ejection Fraction and Volumes of the Left Ventricle

- 3D volumes do not require geometric assumptions and are superior to all other echocardiographic methods
- 3D volume assessment can be combined with contrast to enhance endocardial border delineation
- 3D volume computation also allows computation of "regional" ejection fractions
- Semi-automated edge detection algorithms are usually employed to define endocardial borders. While the accuracy of semiautomated endocardial border detection algorithms has been greatly improved, it is often still necessary to manually correct the contours
- Foreshortening of the left ventricle affects volume computations
- Exclude trabeculations when tracing the LV cavity

Monitor interventional procedures on live 3D

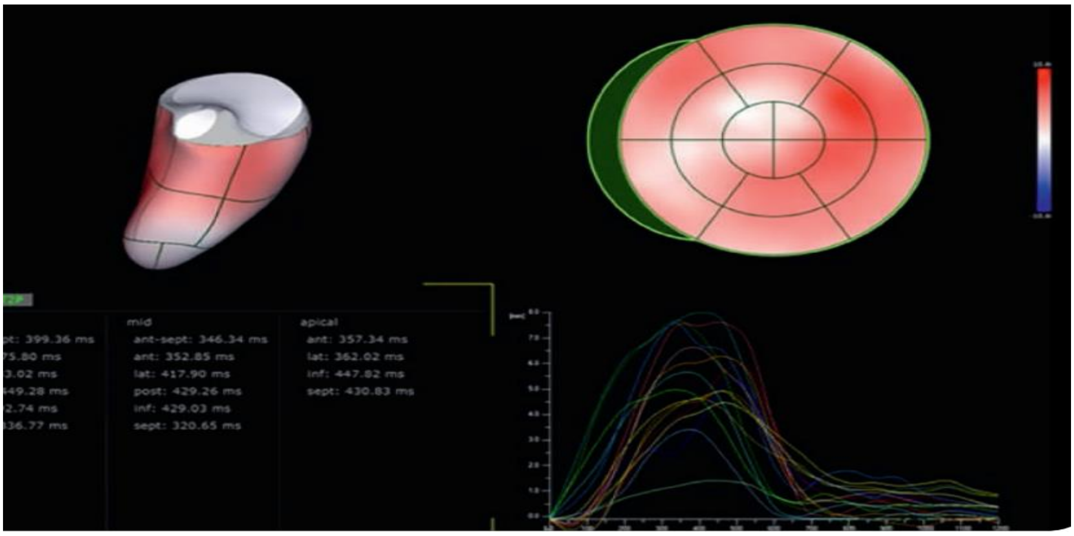
- Live 3D – TEE imaging employs higher frequencies (5- 7 MHz) and has better spatial resolution than transthoracic 3D echo. It is the method of choice to monitor interventional procedures (e.g. MitraClip, ASD closure, left atrial appendage occlusion).

Assessment of Dyssynchrony

- Regional volume curves are plotted against time. These plots are used to determine the time difference between the individual segments to minimal volumes (end-systole). The degree of dispersion of timing correlates with the degree of dyssynchrony
- The systolic dyssynchrony index is a measure of dyssynchrony. It is calculated as the standard deviation of regional ejection times (time to minimal regional volume).
- Dyssynchrony can also be visualized by dynamic tracking of regional contraction on a bull's eye display.

Note: There is currently no recommendation to select patients for cardiac resynchronization therapy based on 3D analysis of dyssynchrony

TIMING OF CONTRACTION – apical full-volume acquisition/3D All segments reach their lowest volume (end systole) at (almost) the same time.



3D Stress Echocardiography

- Facilitates image acquisition by multiplane imaging
- Better visualization of the apex

- Is limited by its low frame rate: Currently this is the major limitation of 3D in stress echo
- Can be combined with contrast

Assessment of Right Ventricular Function

- 3D volume computation of the right ventricle is superior to 2D methods (Complex morphology of the right ventricle).
- Semi-automated edge detection algorithms are applied to detect the endocardial border.
- Right ventricular volume and function computations with 3D have clinical impact (diagnosis and prognostic information) in many diseases (e.g. cardiomyopathy, atrial septal defect, tetralogy of Fallot, pulmonic regurgitation).

Display structures (e.g. valves) in a more realistic format (volume rendering)

Mitral Valve Morphology in 3D Echocardiography

- 3D valve assessment can be performed with 3D- TTE and 3D-TEE
- 3D TEE is superior to 3D TTE
- Allows detection of structural defects and lesions (prolapse, flail, restriction, vegetations), Can define the exact location (leaflet scallop) of the defect
- May be useful in patients who have undergone mitral valve replacement and repair (e.g. detection of paravalvular leaks)
- Is used to select patients for the MitraClip procedure and monitor them during the procedure
- Allows the investigator to study the motion and geometry of the mitral valve apparatus
- May be combined with 3D color Doppler

Note: The mitral valve is best studied from a surgical view (en face view from the left atrium). While 3D imaging of the aortic, tricuspid, and pulmonic valves is feasible and may sometimes provide relevant information, the 3D image quality of these valves is usually inferior to that of the mitral valve

3D display of color jets (quantification of regurgitant lesions)

- Possible with live 3D and multi-beat full volume acquisition
- Still has limited spatial and temporal resolution

- 3D color Doppler with TEE is given preference over TTE
- Permits better appreciation of flow convergence, vena contracta, and jet geometry
- Color jets can also be displayed through reconstructed multi-slice cut planes

Further Clinical Applications of 3D Volume Rendering of Structures

- Endocarditic vegetations and complications
- Pacemaker lead interference with tricuspid valve closure
- Atrial septal defects – quantification of defect size
- Complex congenital abnormities
- Intra-cardiac masses
- Measurement of the aortic root/annulus (e.g. TAVR evaluation)
- Calculation of myocardial mass
- Reconstruction of imaging planes that cannot be displayed with conventional 2D echocardiography
- 3D deformation imaging (strain, strain rate)

ADVANCED QUANTIFICATION TOOLS

3D Speckle Tracking	Calculation and visualization of 3D deformations
Heart Chamber segmentation algorithms	Semi-automated methods for endocardial border detection (ventricles, atria)
Regional wall motion analysis	Allows calculation of regional ejection fraction & regional timing of contraction
Parametric display	Color-coded display of various parameters, such as wall motion, contraction timing, strain, etc.,

FUTURE PERSPECTIVES

- Improvements in temporal and spatial resolution
- Smaller transducers/footprint
- Refined analysis tools
- Fusion imaging: CT and 3D echocardiography
- 3D strain