Diagnosis of Congenital Heart Disease with Echocardiography (Echo)

Shivam Patel *,1

*Department of Biomedical Engineering, Illinois Institute of Technology, Chicago, IL 60616, USA

Introduction:

Approximately 40,000 newborns are diagnosed with congenital heart disease (CHD) every year, and 1 in 4 of those require surgery within their first year of life.[1] Current diagnostic modalities for CHD include electrocardiograms (ECG), chest X-rays, echocardiograms, cardiac CT, and cardiac MRI. Among the available diagnostic tests for CHD in fetal and pediatric patients, echocardiograms provide better spatial and temporal resolution, allowing doctors to differentiate between diseased and healthy structures of the heart. This paper covers a broad range of information about Echocardiography including the types of echocardiography, a discussion of the image quality (signal to noise ratio, temporal and spatial resolution, and imaging artifacts), and equations defining important relationships that affect echocardiography.

Methods:

Echocardiography is an imaging modality that uses ultrasound (high-frequency sound waves) to evaluate the pumping action of the heart in a cross-sectional 2D view.[2] With implementation of a doppler imaging mode, the hemodynamic assessment of the heart can also be incorporated.[3] The three types of echocardiograms include transthoracic echocardiograms (TTE), transesophageal echocardiograms (TEE), and exercise stress echocardiograms. The current clinical standard for diagnosing CHD in pediatric patients is TTE. During transthoracic echocardiograms, a sonographer first applies electrodes to the chest to continuously measure the sinus rhythm followed by application of an ultrasound transmission gel (USTG) to a patient's chest. Once the transducer probe is pressed firmly against the skin, it emits ultrasound waves to the heart, and the moving images are projected onto a digital screen as the ultrasound waves echo back to the transducer probe. A linear-array transducer contains piezoelectric crystals (elements) arranged in a square matrix configuration which emit ultrasound waves upon stimulation of an alternating electric current and vice versa. This allows for the crystals to act as both a transmitter and receiver. Phased-array transducers are a special type of transducer that have capability of representing the echoing ultrasound waves in a 3D representation. Currently, 2D TEE probes have 64 total elements while higher end, more expensive 3D TEE and 3D TTE probes have over 2500 and 3000 elements respectively. The diameter of the crystals determines the frequency of the transmitted ultrasound wave. For more detailed visualization of the heart compared to the transthoracic procedure, transesophageal echocardiograms may be implemented. In this method, an endoscope guides a small transducer into the esophagus which allows for a smaller distance between the transducer and heart, thereby improving the imaging resolution and detail. The exercise stress echocardiography procedure evaluates cardiac function during high stress by performing Echo before and after the heart is induced to be tachycardic through either exercise or pharmacologic agents. Exercise is typically performed on a treadmill or bicycle, and the pharmacologic agents used to increase heart rate are dobutamine and other vasodilators. Exercise stress Echo is a diagnostic procedure for only adults capable of exercise, excluding elderly patients, newborns, and certain pediatric patients.

Spatial resolution of an ultrasound beam is dependent on numerous factors, and the spatial resolution is depicted in terms of axial, elevational, and lateral planes. To improve resolution across all the planes, a higher frequency/lower wavelength may be used. Axial resolution and lateral resolution can both be improved with a wider bandwidth. A shorter pulse length and narrow aperture improve axial and lateral resolution, respectively. A significant factor to consider is the inverse relationship between spatial resolution and penetration. Deeper structures are observed better than superficial structures in low resolution/high penetration settings, and superficial structures exhibit enhanced detail with poor clarity of deeper structures at high resolution/low penetration settings. Medical ultrasound frequencies range from 1 to 20 MHz, and the frequency of each Echo system is dependent on its specific purpose, but most transducers for Echo range from 2 to 7 MHz.

Temporal resolution for Echo is dependent on the mode of its data acquisition and representation. In a 2D imaging mode, Echo has a temporal resolution of 30 frames per second over 128 scan lines. In contrast, the M-mode scans over a single line, providing a superior temporal resolution of 2,000 frames per second in combination with a high spatial resolution. These factors allow for timing of subtle cardiac events in rapid moving structures like valves in addition to precise size measurements of observed structures. Although the M-mode provides such high temporal and spatial resolution, the entirety of the beating heart may only be seen in the 2D and 3D imaging modes of Echo. Signal to noise ratio (SNR) is another important technical consideration. SNR increases for Echo when the transducer is closest to the heart. As a result, TEE automatically has better SNR compared to TTE. Furthermore, obese patients can result in a lower SNR because the ultrasound waves attenuate from surrounding tissues.

Discussion:

Typically, the M-mode and 2D mode scans are seen on digital screens in grayscale. Larger differences in acoustic impedances causes large amounts of ultrasound reflection. Lower amounts of reflection produce darker spots, whereas higher amounts of reflection produce brighter spots. In doppler mode, a color-based display shows a red color for blood moving towards the transducer and blue color for blood moving away from the transducer. This color representation is the degree of doppler shift on a predetermined color spectrum with corresponding doppler shift values. The doppler shift can be mathematically represented with Equation 1:

$$F_d = \frac{2F_t V \cos\theta}{c}$$

where F_d is the doppler shifted signal; F_t is the transmitted doppler frequency; c is the propagation speed of ultrasound in soft tissue (1540 m/s); V is the velocity of the moving blood; and θ is the angle between the Doppler ultrasound beam and direction of blood flow.[5] The Physicians observe the Echo scans and the measurements of the heart structures and blood ejection fractions. For congenital heart disease, abnormal scans or measurements signify particular defects.

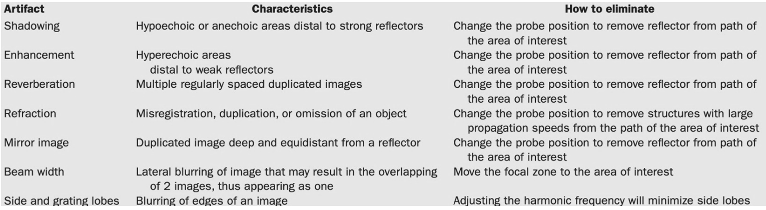
The technical specifications for successful Echo procedures are complicated, especially because of the interaction of ultrasound with tissues and presence of imaging artifacts. An important consideration is that active piezoelectrical crystals generate heat. This may burn the patient, thereby reducing the amount of time the Echo procedure can be switched to a 3D or doppler mode. The thermal effects of ultrasound can be characterized with Equation 2:

$$\frac{dT}{dC} = \frac{2\alpha I}{p} * C_m$$

where dT/dC is the rate of increase in temperature of the tissues; α is the tissue coefficient at the probe's frequency; I is the ultrasound intensity; p is the tissue density; and C_m is the specific heat of the tissue.[4] Furthermore, when an ultrasound beam penetrates a medium, attenuation occurs due to reflection, refraction, and absorption. Attenuation is an important factor to consider. For instance, USTG is used in transthoracic Echo to minimize the amount of air present between the patient and the transducer probe, because air's low acoustic impedance causes 99% of ultrasound waves to reflect. If a sonographer does not apply sufficient USTG or does not firmly press the transducer onto the skin, inaccurate results may occur. Another consideration is that ultrasound has a cavitation effect; small gas filled bubbles are created upon interaction with tissue. The relationship between the size of the bubble (R_o) and resonance frequency (F_o) is represented by Equation 3:

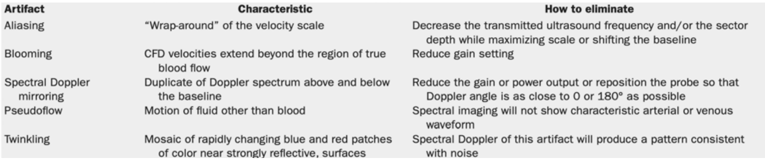
$$F_o = \frac{3260}{R_o} .$$

Although cavitation can be significant for other regions of the body, the clinical impact of cavitation in cardiac tissue during Echo is insignificant because the viscosity of blood dramatically lessens its effect.[4] The complexity of imaging artifacts in Echo has been widely discussed in the medical community with conversations focusing immensely on how much training should actually be required for an individual to properly interpret Echo scan results. One study demonstrated that artifacts were present for 46% of patients in the ascending aorta during a TEE procedure for suspected aortic dissections.[6] A review of imaging artifacts in Echo provided great detail about 2D grayscale ultrasound artifacts, 3D artifacts, and spectral and color flow doppler artifacts.[6] Figures 1, 2, and 3 give lists of the imaging artifacts, their characteristics, and how to eliminate them.



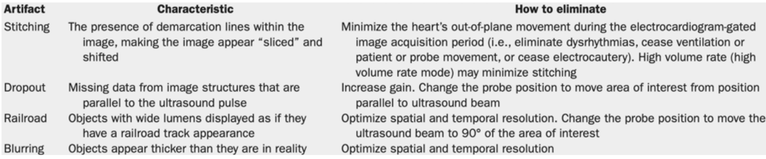
Artifact	Characteristics	How to eliminate
Shadowing	Hypoechoic or anechoic areas distal to strong reflectors	Change the probe position to remove reflector from path of the area of interest
Enhancement	Hyperechoic areas distal to weak reflectors	Change the probe position to remove reflector from path of the area of interest
Reverberation	Multiple regularly spaced duplicated images	Change the probe position to remove reflector from path of the area of interest
Refraction	Misregistration, duplication, or omission of an object	Change the probe position to remove structures with large propagation speeds from the path of the area of interest
Mirror image	Duplicated image deep and equidistant from a reflector	Change the probe position to remove reflector from path of the area of interest
Beam width	Lateral blurring of image that may result in the overlapping of 2 images, thus appearing as one	Move the focal zone to the area of interest
Side and grating lobes	Blurring of edges of an image	Adjusting the harmonic frequency will minimize side lobes

Figure 1: *Two-Dimensional Grayscale Ultrasound Artifacts, Reprinted from Le, H. T., Hangiandreou, N., Timmerman, R., Rice, M. J., Smith, W. B., Deitte, L., & Janelle, G. M. (2016). Imaging Artifacts in Echocardiography. Anesthesia and analgesia, 122(3), 633–646.*



Artifact	Characteristic	How to eliminate
Aliasing	"Wrap-around" of the velocity scale	Decrease the transmitted ultrasound frequency and/or the sector depth while maximizing scale or shifting the baseline
Blooming	CFD velocities extend beyond the region of true blood flow	Reduce gain setting
Spectral Doppler mirroring	Duplicate of Doppler spectrum above and below the baseline	Reduce the gain or power output or reposition the probe so that Doppler angle is as close to 0 or 180° as possible
Pseudoflow	Motion of fluid other than blood	Spectral imaging will not show characteristic arterial or venous waveform
Twinkling	Mosaic of rapidly changing blue and red patches of color near strongly reflective, surfaces	Spectral Doppler of this artifact will produce a pattern consistent with noise

Figure 2: *Spectral and Color Flow Doppler Artifacts, Reprinted from Le, H. T., Hangiandreou, N., Timmerman, R., Rice, M. J., Smith, W. B., Deitte, L., & Janelle, G. M. (2016). Imaging Artifacts in Echocardiography. Anesthesia and analgesia, 122(3), 633–646.*



Artifact	Characteristic	How to eliminate
Stitching	The presence of demarcation lines within the image, making the image appear "sliced" and shifted	Minimize the heart's out-of-plane movement during the electrocardiogram-gated image acquisition period (i.e., eliminate dysrhythmias, cease ventilation or patient or probe movement, or cease electrocautery). High volume rate (high volume rate mode) may minimize stitching
Dropout	Missing data from image structures that are parallel to the ultrasound pulse	Increase gain. Change the probe position to move area of interest from position parallel to ultrasound beam
Railroad	Objects with wide lumens displayed as if they have a railroad track appearance	Optimize spatial and temporal resolution. Change the probe position to move the ultrasound beam to 90° of the area of interest
Blurring	Objects appear thicker than they are in reality	Optimize spatial and temporal resolution

Figure 3: *Three-Dimensional Artifacts, Reprinted from Le, H. T., Hangiandreou, N., Timmerman, R., Rice, M. J., Smith, W. B., Deitte, L., & Janelle, G. M. (2016). Imaging Artifacts in Echocardiography. Anesthesia and analgesia, 122(3), 633–646.*

Echo scan results have been shown to be accurate, precise, and reproducible. In a prospective study with 80 cases of confirmed congenital heart defects at 3 pediatric cardiology outpatient clinics in Khartoum, Sudan, the mean sensitivity and specificity were 90.2% and 99.3% respectively.[7] These high values demonstrate that Echo scans have high accuracy for diagnosis of congenital heart disease. In terms of precision, Echo's doppler mode with color-based display is less precise than the desired precision for diagnosis of CHD in vasculature. An ultrasound contrast reagent can be administered to the patient intravenously to opacify the left ventricular chamber and improve the delineation of the endocardial borders, or cardiac catheterization can be applied to further visualize the vasculature. Although multiple Echo scans can be taken to get different views of the heart, the reproducibility of the test is highly dependent on the sonographer and instantaneous changes in the heart's condition. Although standard methods for imaging exists, images taken by different sonographers can still be slightly differently, causing different interpretations by physicians.

Conclusion:

Echo is an effective way of diagnosing CHD. Studies show that the advent of multiple, improved Echo techniques has dramatically improved acquisition of high-resolution moving images of the heart and has assisted in the diagnosis of CHD with higher sensitivity. While imaging artifacts might interfere with Echo scan results, Echo is a highly effective diagnostic procedure due to its high spatial and temporal resolution, allowing for quick and accurate visualization of the heart's structures.

References:

1. Centers for Disease Control and Prevention. (2022, January 24). Data and statistics on congenital heart defects. Centers for Disease Control and Prevention. Retrieved September 14, 2022, from https://www.cdc.gov/ncbddd/heartdefects/data.html
2. *Echocardiogram: Types and what they show*. Cleveland Clinic. (2022, May 9). Retrieved from https://my.clevelandclinic.org/health/diagnostics/16947-echocardiogram
3. U.S. National Library of Medicine. (n.d.). Doppler ultrasound: Medlineplus medical test. MedlinePlus. Retrieved from https://medlineplus.gov/lab-tests/doppler-ultrasound/
4. University of Nebraska Medical Center. (n.d.). *Expert Transesohageal Echocardiography*. e-Echocardiography. Retrieved from https://e-echocardiography.com/page/page.php?UID=1429454151
5. The standard transthoracic echo study. Thoracic Key. (2016, June 5). Retrieved from https://thoracickey.com/the-standard-transthoracic-echo-study/
6. Le, H. T., Hangiandreou, N., Timmerman, R., Rice, M. J., Smith, W. B., Deitte, L., & Janelle, G. M. (2016). Imaging Artifacts in Echocardiography. *Anesthesia and analgesia*, *122*(3), 633–646. https://doi.org/10.1213/ANE.0000000000001085
7. Ali, S., & Bushari, T. (2018). Validation of the accuracy of handheld echocardiography for diagnosis of congenital heart disease. *Annals of pediatric cardiology*, *11*(3), 250–254. https://doi.org/10.4103/apc.APC_159_17