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Incidence of intra and postoperative complications associated with transesophageal echocardiograms (TEE) in pediatric patients

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Thesis

INCIDENCE OF INTRA AND POSTOPERATIVE COMPLICATIONS ASSOCIATED WITH TRANSESOPHAGEAL ECHOCARDIOGRAMS (TEE) IN PEDIATRIC PATIENTS

by

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Second, I would like to thank my friends and family for their support throughout my education. They remain a driving motivation behind my continued passion for medicine and academics.

INCIDENCE OF INTRA AND POSTOPERATIVE COMPLICATIONS ASSOCIATED WITH TRANSESOPHAGEAL ECHOCARDIOGRAMS (TEE) IN PEDIATRIC PATIENTS

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ABSTRACT

The benefits of intraoperative transesophageal echocardiography (TEE) during cardiac surgery are well documented. Intraoperative TEE accurately confirms and in many cases refines delineation of congenital heart lesions, can be used as a means for establishing an intraoperative technical surgical score, and offers a low incidence of intraoperative complications. It seemed likely that the rate of perioperative complications in children would be congruent with the current available data in adults.

After Institutional Review Board approval, a retrospective chart review of patients at Boston Children's Hospital who underwent the TEE procedure between May 2012 and December 2014 was conducted. The final study sample consisted of 129 patient charts. Adverse events related to TEE were documented and defined as follows: 1) those potentially attributable to TEE and 2) those with a high likelihood of being related to TEE; defined as dysphagia, esophageal perforation, gastrointestinal bleeding, and throat discomfort/pain.

Of the 129 total cases, there was only one case reporting an intraoperative adverse event with a high likelihood of being related to TEE. This

incidence rate of 0.77% is consistent with the literature existing on adult and pediatric TEE safety studies. Literature on postoperative adverse events related to intraoperative TEE use in pediatric patients was limited to the incidence of dysphagia. The sample included no incidence of dysphagia and the review enumerated six postoperative adverse events (4.65%) of which had a high likelihood of being related to TEE. Three of these events were classified as major and three were classified as minor. Major postoperative events included blood draining from nasogastric/orogastric tubes and blood tinged secretions suctioned from the endotracheal tube. Minor events were patient reported as sore throat and voice hoarseness.

It was concluded that TEE use is not associated with an increased risk of adverse events in pediatric patients if performed according to institutional procedure and recommendations. Intraoperative TEE offers immediate assessment of the adequacy of surgical repair and presence of residual lesions. This information can be used to generate a surgical technical performance score. The ability to detect and correct residual lesions with information provided by intraoperative TEE allows the surgeon to improve technical performance thereby reducing postoperative morbidity.

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LIST OF ABBREVIATIONS

ASD……..atrial septal defect

ASE…….American Society of Echocardiography

AVSD……...atrioventricular septal defect

CCHD……critical congenital heart defect

CDC……Center for Disease Control

CHD……...congenital heart defect

CW……..…continuous wave

ECMO……..extracorporeal membrane oxygenation

HIPAA……Health Insurance Portability and Accountability Act

HLHS……...Hypoplastic Left Heart Syndrome

LVAD……left ventricular assist device

ICU……...intensive care unit

ME……mid-esophageal

NIH…….National Institute of Health

PAPVR…….partial anomalous pulmonary venous return

PVR……pulmonary valve replacement

PW……pulse wave

SCA…….Society of Cardiovascular Anesthesiologists

TAPVR……total anomalous pulmonary venous return

TEE……..Transesophageal Echocardiogram

TG……transgastric

TGA……...transposition of the great arteries

TTE……...Transthoracic Echocardiogram

VSD…….ventricular septal defect

INTRODUCTION

Echocardiography

Cardiac sonography was first described by Drs. Inge Edler and Carl Hertz in their paper, "The Use of Ultrasonic Reflectoscope for the Continuous Recording of the Movements of the Heart Walls," first published in 1954.[1] Since that time, such advancements have been made to allow for an ultrasound transducer probe to be placed within a patient's esophagus in a procedure known as a transesophageal echocardiogram (TEE).[2] TEE was first utilized in 1971 to record and measure blood flow through the aortic arch.[2,3] In comparison to the standard transthoracic echocardiogram (TTE), it is generally considered that TEE offers a preferable imaging capability.[4] TEE is typically done under general anesthesia with intubation as the probe must be placed into the patient's esophagus. Various probes exist with continuous wave Doppler, pulse wave Doppler, color Doppler, M-mode, 2-D, and 3-D echocardiography imaging capabilities. Probes may possess one or more of the listed capabilities (see **Table 1**).[4,5]

TEE Guidelines

In 1992, the American Society of Echocardiography (ASE) and the Society of Cardiovascular Anesthesiologists (SCA) established their initial guidelines and recommendations for performing intraoperative transesophageal

echocardiography examination.[6] In a 1999 follow-up report, a set of twenty views were defined in order to standardize the procedure. The views were universal between an adult and pediatric examination.[4,6] In 2013, the same organizations published updated guidelines and recommendations for TEE, which included an additional eight views.[7] In addressing the original report:

> "Although the comprehensive intraoperative views have been widely adopted, they have a number of limitations. … The 20 views do not address any specific diagnosis and do not include some views needed to adequately examine common cardiac disorders."[7]

The twenty-eight views are as described below in **Figures 1 - 28**. Letter designations with numerical subscript seen after "mitral valve" refer to specific leaflets of the valve. Images were adapted from Table 10 of Hahn et al., 2013 (see **Appendix**).[7]

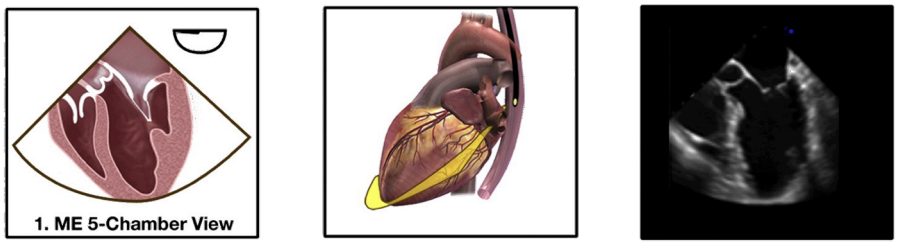


Figure 1: Five-Chamber View (ME)
(Adapted from Hahn et al., 2013, Table 10)

As seen from the mid-esophageal level, the five-chamber view allows for visualization of the left atrium, right atrium, left ventricle, right ventricle, tricuspid valve, aortic valve, mitral valve (A_2A_1-P_1), left ventricular outflow tract, and the interventricular septum.[7]

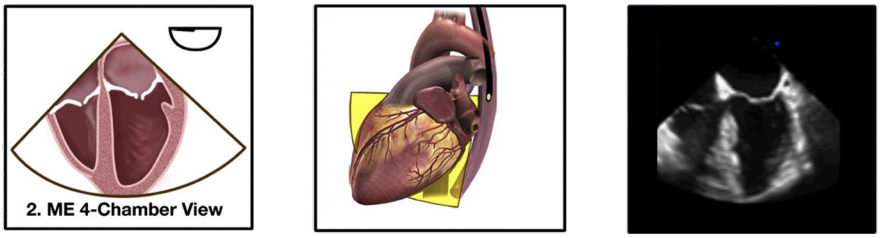


Figure 2: Four-Chamber View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the mid-esophageal level, the four-chamber view allows for visualization of the left atrium, right atrium, left ventricle, right ventricle, tricuspid valve, mitral valve (A_3A_2-P_2P_1), interventricular septum, and interatrial septum. Slight probe advancement allows for imaging of the coronary sinus.[7]

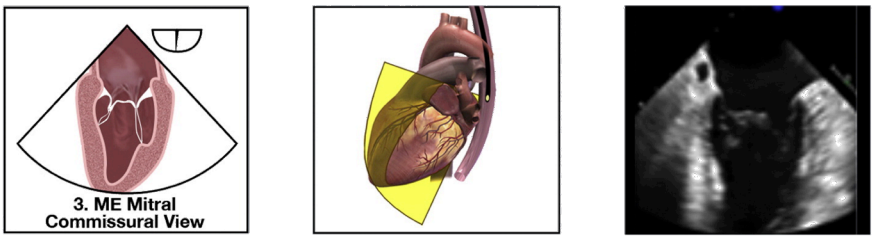


Figure 3: Mitral Commissural View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the mid-esophageal level, the mitral commissural view allows for visualization of the left atrium, left ventricle, mitral valve (P_3-$A_3A_2A_1$-P_1), coronary sinus, papillary muscles, and chordae tendinae.[7]

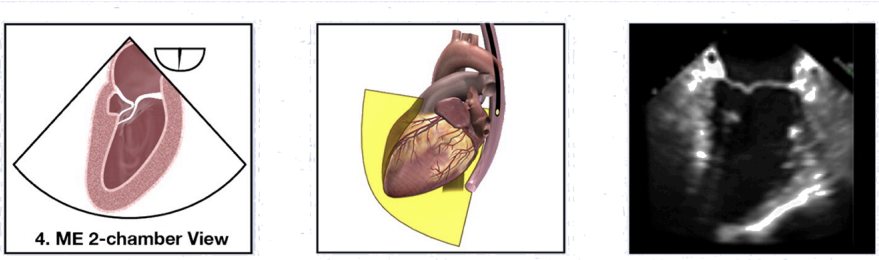


Figure 4: Two-Chamber View (ME)
(Adapted from Hahn et al., 2013, Table 10)

As seen from the mid-esophageal level, the two-chamber view allows for visualization of the left atrium, left ventricle, left atrial appendage, mitral valve (P_3-$A_3A_2A_1$), and coronary sinus.[7]

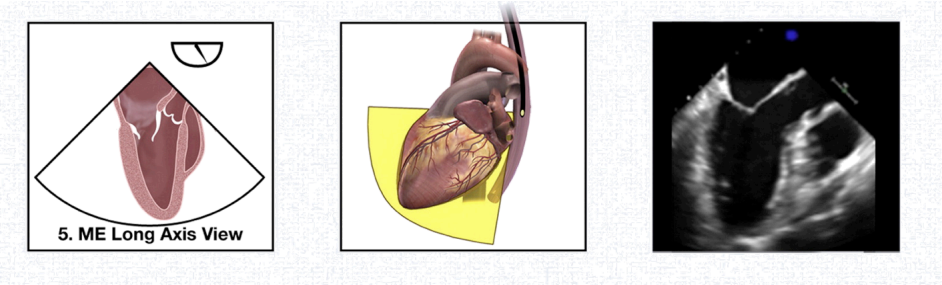


Figure 5: Long Axis View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the mid-esophageal level, the long axis view allows for visualization of the left atrium, left ventricle, aortic valve, mitral valve (P_2-A_2), left ventricular outflow tract, right ventricular outflow tract, coronary sinus, and the proximal ascending aorta.[7]

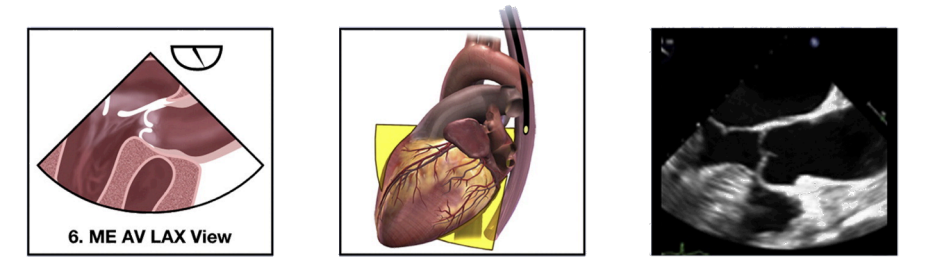


Figure 6: Aortic Valve – Long Axis View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the mid-esophageal level, the long axis view of the aortic valve allows for visualization of the left atrium, aortic valve, mitral valve (A_2-P_2), left ventricular outflow tract, right ventricular outflow tract, proximal ascending aorta,

sinuses of Valsalva, sinotubular junction, and a partial view of the ascending aorta.[7]

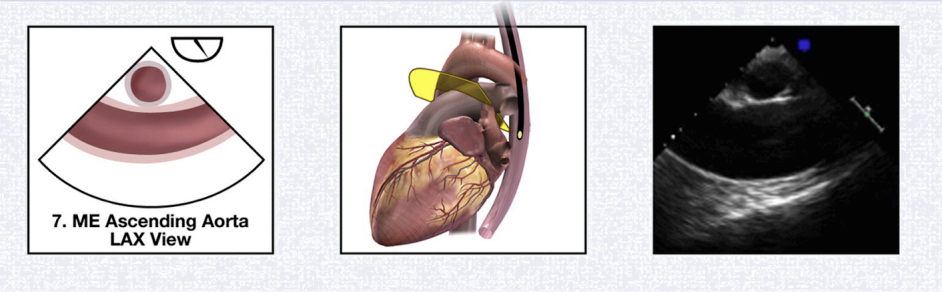


Figure 7: Ascending Aorta – Long Axis View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the mid-esophageal level, the long axis view of the ascending aorta allows for visualization of the proximal ascending aorta, mid-ascending aorta, right pulmonary artery, and pulmonary valve (with probe manipulation).[7]

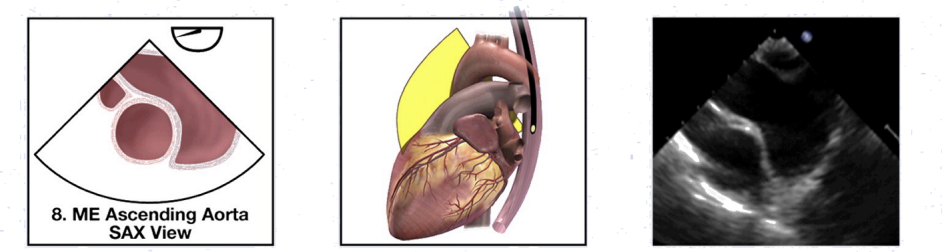


Figure 8: Ascending Aorta – Short Axis View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the mid-esophageal level, the short axis view of the ascending aorta allows for visualization of the mid-ascending aorta, superior vena cava,

main pulmonary artery, the pulmonary artery bifurcation, and the right pulmonary artery . The pulmonary valve can sometimes be seen with this view.[7]

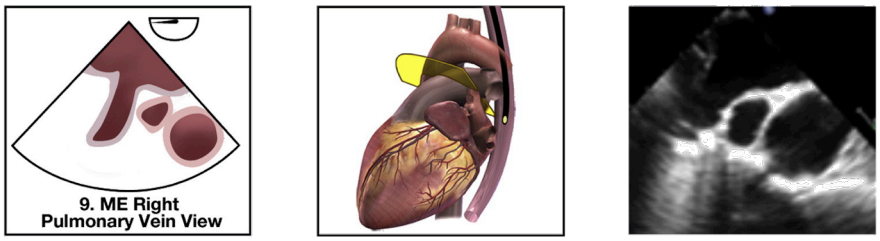


Figure 9: Right Pulmonary Vein View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the mid-esophageal level, the right pulmonary vein view allows for visualization of the mid-ascending aorta, superior vena cava, and the right pulmonary veins.[7]

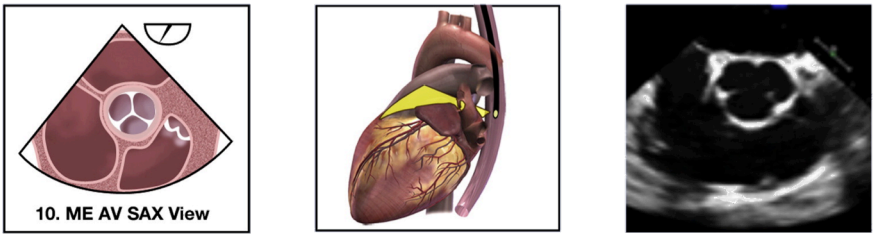


Figure 10: Aortic Valve – Short Axis View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the mid-esophageal level, the short axis view of the aortic valve allows for visualization of the left atrium, right atrium, aortic valve, pulmonary valve, superior interatrial septum, and the right ventricular outflow tract.[7]

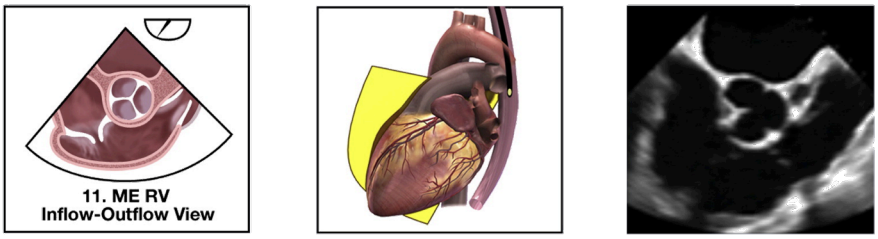


Figure 11: Right Ventricle Inflow-Outflow View (ME)
(Adapted from Hahn et al., 2013, Table 10)

As seen from the mid-esophageal level, the right ventricle inflow-outflow view allows for visualization of the left atrium, right atrium, aortic valve, tricuspid valve, pulmonary valve, superior interatrial septum, main pulmonary artery, and the right ventricular outflow tract.[7]

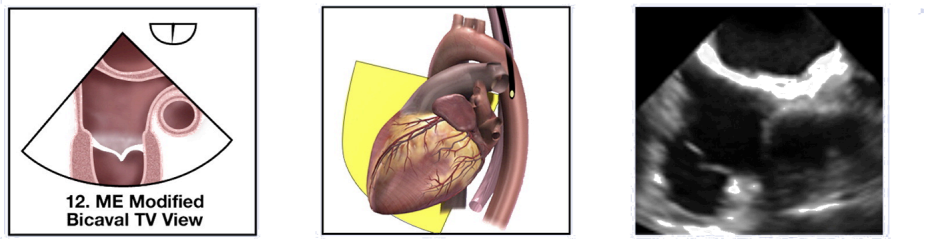


Figure 12: Modified Bicaval Tricuspid Valve View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the mid-esophageal level, the modified bicaval tricuspid valve view allows for visualization of the left atrium, right atrium, tricuspid valve, interatrial septum, superior vena cava, inferior vena cava, and the coronary sinus.[7]

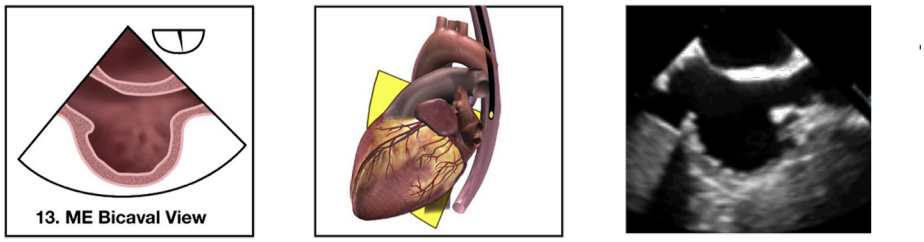


Figure 13: Bicaval View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the mid-esophageal level, the bicaval view allows for visualization of the left atrium, right atrium, right atrial appendage, superior vena cava, inferior vena cava, and the interatrial septum.[7]

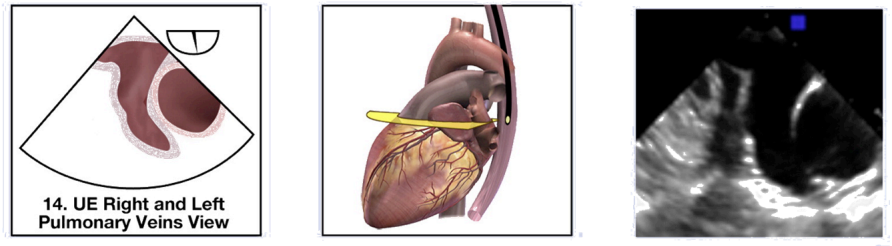


Figure 14: Right and Left Pulmonary Vein View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the mid-esophageal level, the right and left pulmonary vein view allows for visualization of the pulmonary veins and the pulmonary artery.[7]

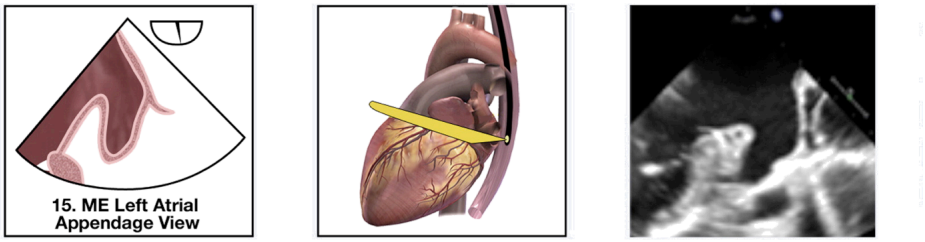


Figure 15: Left Atrial Appendage View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the mid-esophageal level, the left atrial appendage view allows for visualization of the left atrial appendage and the left superior pulmonary vein (often).[7]

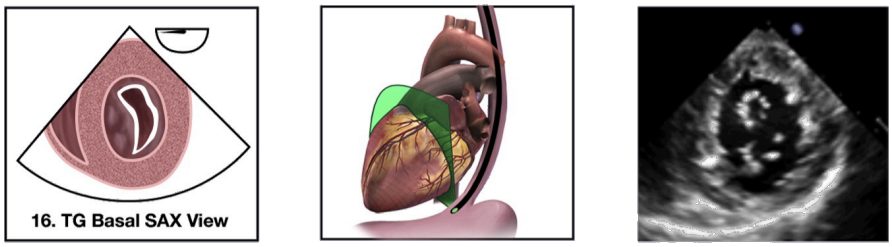


Figure 16: Basal – Short Axis View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the transgastric level, the short axis view of the basal portion of the heart allows for visualization of the left ventricle, right ventricle, and the mitral valve.[7]

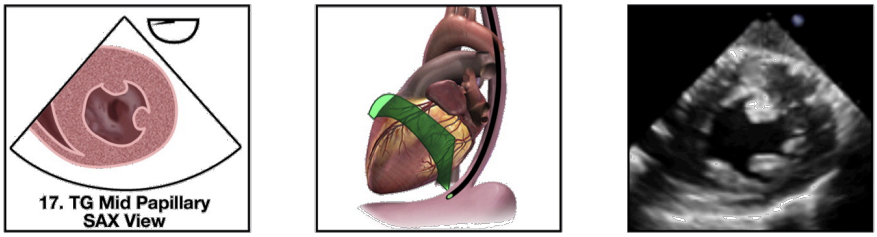


Figure 17: Mid-Papillary – Short Axis View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the transgastric level, the short axis view of the mid-papillary region allows for visualization of the left ventricle, right ventricle, and papillary muscles. Myocardium supplied by the left anterior descending coronary artery, circumflex coronary artery, and the right coronary artery are viewed simultaneously.[7]

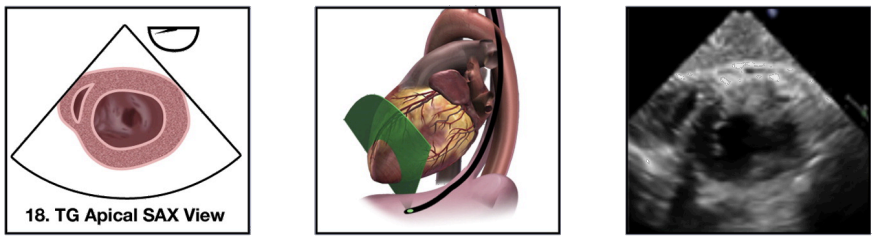


Figure 18: Apical – Short Axis View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the transgastric level, the short axis view of the apex allows for visualization of the apexes of the left ventricle and right ventricle.[7]

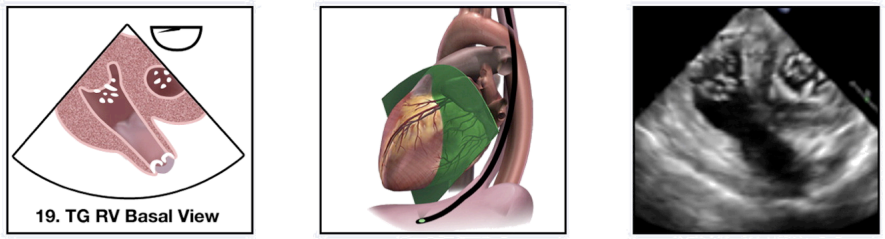


Figure 19: Right Ventricle – Basal View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the transgastric level, the view of the right ventricle allows for visualization of the left ventricle, right ventricle, tricuspid valve, pulmonary valve, and the right ventricular outflow tract.[7]

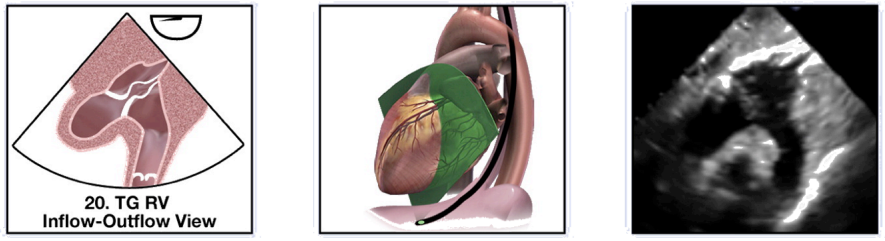


Figure 20: Right Ventricle Inflow-Outflow View (TG)
(Adapted from Hahn et al., 2013, Table 10)

As seen from the transgastric level, the right ventricle inflow-outflow view allows for visualization of the right atrium, right ventricle, tricuspid valve, pulmonary valve, and the right ventricular outflow tract.[7]

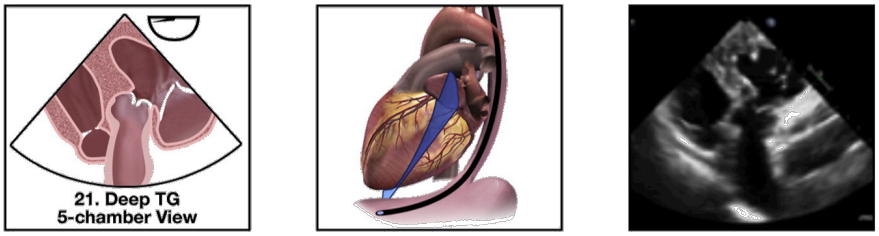


Figure 21: Five-Chamber View (TG)
(Adapted from Hahn et al., 2013, Table 10)

As seen from the deep transgastric level, the five-chamber view allows for visualization of the left ventricle, right ventricle, aortic valve, mitral valve, left ventricular outflow tract, and the aortic root.[7]

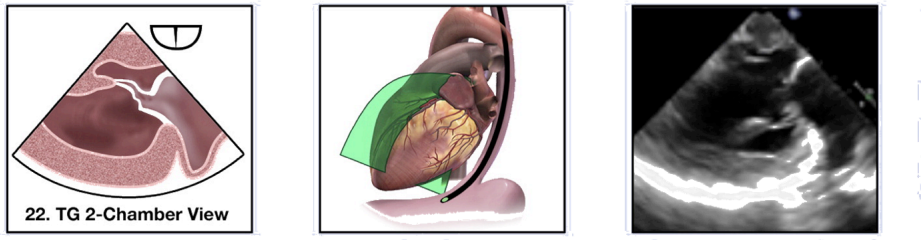


Figure 22: Two-Chamber View (TG)
(Adapted from Hahn et al., 2013, Table 10)

As seen from the transgastric level, the two-chamber view allows for visualization of the left atrium (often), left ventricle, mitral valve, left atrial appendage (often), papillary muscles, and the chordae tendinae.[7]

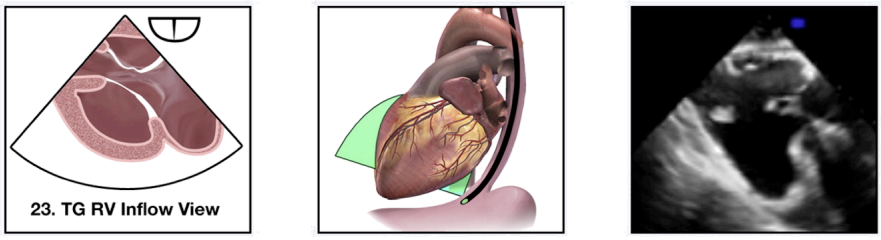


Figure 23: Right Ventricular Inflow View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the transgastric level, the right ventricular inflow view allows for visualization of the right atrium, right ventricle, tricuspid valve, pulmonary valve (with probe manipulation), right ventricular outflow tract (often), papillary muscles, and the chordae tendinae.[7]

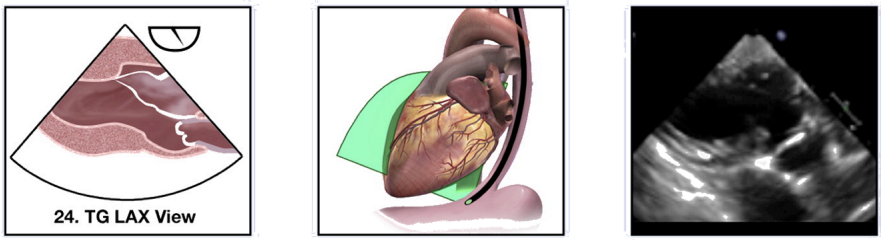


Figure 24: Long Axis View (TG)
(Adapted from Hahn et al., 2013, Table 10)

As seen from the transgastric level, the long axis view allows for visualization of the left ventricle, right ventricle, aortic valve, mitral valve, left ventricular outflow tract, and the aortic root.[7]

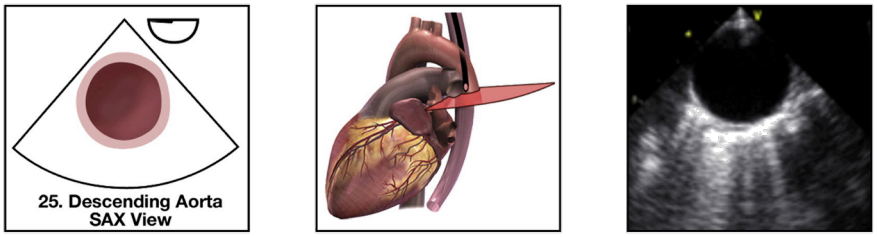


Figure 25: Descending Aorta – Short Axis View
(Adapted from Hahn et al., 2013, Table 10)

Best seen from the level of the diaphragm and superior to the mid-esophageal level, the short axis view of the descending aorta allows for visualization of the descending aorta, hemiazygous vein, azygous vein, and intercostal arteries. If the view is attempted at the transgastric level, the celiac artery may be visualized.[7]

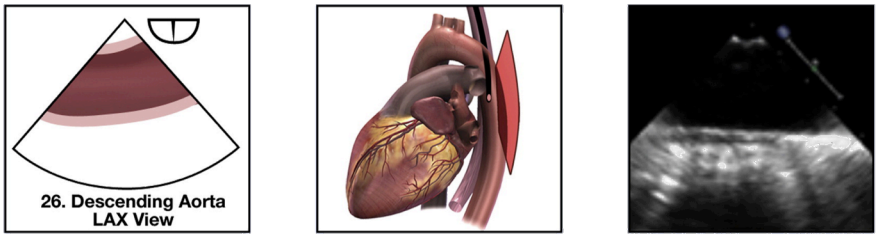


Figure 26: Descending Aorta – Long Axis View
(Adapted from Hahn et al., 2013, Table 10)

Like the short axis view of the descending aorta, this view is best seen from the level of the diaphragm and superior to the mid-esophageal level with visualization of the descending aorta, hemiazygous vein, azygous vein, and intercostal arteries.[7]

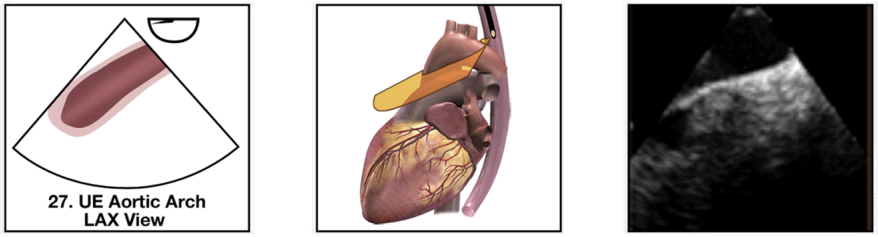


Figure 27: Aortic Arch – Long Axis View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the upper esophageal level, the long axis view of the aortic arch allows for visualization of the aortic arch, left subclavian artery, innominate vein, and mediastinal tissue.[7]

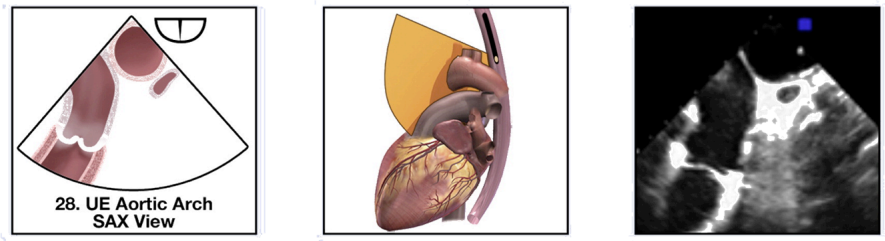


Figure 28: Aortic Arch – Short Axis View
(Adapted from Hahn et al., 2013, Table 10)

As seen from the upper esophageal level, the short axis view of the aortic arch allows for visualization of the aortic arch, pulmonary valve, pulmonary artery, innominate vein, right brachiocephalic artery, left common carotid artery, and mediastinal tissue.[7]

TABLE 1 Types of Echocardiography[4,5]	
M-mode echocardiography	M-mode echocardiography produces a one dimensional view of the structure in question displayed over a time axis. M-mode is most useful in measuring the size of the various heart structures.
Doppler echocardiography	Doppler echocardiography is used to measure blood flow through individual structures of the heart. This technique is useful in evaluating valvular insufficiency, shunts, stenosis, and other flow related defects.
Pulse Wave Doppler	Pulse wave (PW) Doppler utilizes bursts of ultrasound to a specific distance from the transducer. PW Doppler allows for measurement of flow within a specific structure, but is limited in its ability to measure flow velocity by the rate of ultrasonic pulses.
Continuous Wave Doppler	Continuous wave (CW) Doppler utilizes a continuous transmission and reception of ultrasound. CW Doppler allows for unlimited measurement of flow velocity, but is limited in its ability to pinpoint a specific observation area.
Color Doppler echocardiography	Color Doppler is an enhanced form of PW Doppler. Color Doppler displays different colors to designate direction of flow (typically red represents flow towards the probe and blue represents flow way from the probe).
Two-dimensional echocardiography	2-D echocardiography enables two dimensions of the heart to be visualized simultaneously (as opposed to one dimension in M-mode). This technique enables observation of the relative positioning between heart structures and the motion of heart structures.
Three-dimensional echocardiography	3-D echocardiography provides enhanced anatomically realistic images of the heart structures over the 2-D echocardiogram. The third dimension allows for greater accuracy and assessment by the physician.

Congenital Heart Defects

In the normal adult, whole body circulation is achieved through the series, biventricular pumping of the heart to the pulmonary and systemic circulations. Systemically, oxygen deplete blood enters the right atrium from the inferior and superior vena cavas. From the right atrium, blood passes through the tricuspid valve into the right ventricle. The right ventricle pumps the deoxygenated blood into pulmonary circulation through the pulmonary valve into the pulmonary artery and onwards towards the lungs. From the lungs, oxygen replete blood enters into the left atrium. From the left atrium, the blood passes through the mitral valve into the left ventricle. Finally, from the left ventricle the blood is pumped into systemic circulation through the aortic valve into the aorta.[8]

Fetal heart development is a dynamic process and development continues until just shortly after birth. Noteworthy differences in neonatal heart anatomy include the existence of a hole between the right and left atria, known as a foramen ovale. Additionally, there is the existence of a connection between the great arteries (aorta and pulmonary artery), known as the ductus arteriosus.[8]

Congenital heart defects (CHDs) are defects in the heart that can alter normal blood circulation. Manifested during fetal development, CHDs are present at birth and are the cause of congenital heart disease.[8,9] According to the National Institute of Health (NIH) and the Center for Disease Control (CDC), CHDs are the most common type of birth defect affecting 8 per 1,000 births and approximately 40,000 births per year.[8,9,10] Treatment of patients affected by CHD

varies according to severity and include medications, device insertion, surgical changes to anatomy, and/or heart transplant; the most severe of defects being classified as critical congenital heart defects (CCHDs). Some CHD patients do not require treatment. The more common defects are outlined below and in **Table 2**.[8]

Atrial Septal Defect

An atrial septal defect (ASD) is a defect, or hole, in the wall of tissue separating the two atria of the heart. This wall of tissue is known as the atrial septum. As the child grows, this hole may begin to close on it's own, but more severe defects require surgical intervention. It is estimated that there are approximately 2,000 births per year in the United States with an ASD. There are many potential complications associated with this defect and include: mixing of arterial and venous blood resulting in decreased oxygen saturation, pulmonary hypertension, heart failure, increased risk of stroke, lung infections, difficulty breathing, shortness of breath, peripheral edema, and pulmonary edema.[8]

Atrioventricular Septal Defect

Similar to the ASD, the atrioventricular septal defect (AVSD) is characterized by a hole separating two or more of the heart chambers and can be classified as either a complete AVSD or a partial AVSD. A complete AVSD exists when there is a large hole in the center of the heart where the atrial

septum and ventricular septum would ordinarily meet. A complete AVSD also affects the normal flow of blood through the heart. Due to the size of this defect instead of the typical anatomy of two internal heart valves, there exists one common valve in the center of the heart.[8]

A partial, or incomplete, AVSD is less severe compared to the complete AVSD. The partial AVSD is characterized by a hole in the atrial septum with a small hole in the ventricular septum near where the two septa join. Additionally, the partial AVSD heart typically will have the typical two valves between the respective atria and ventricles.[8]

As with the ASD, the complete and partial AVSDs have many of the same potential complications. Of note, the degree to which there is arterial and venous blood mixing will generally be greater than with the ASD and will vary according to severity of the defect. It is estimated that there are approximately 2,000 births per year in the United States with an AVSD.[8]

Coarctation of the Aorta

Coarctation of the aorta is characterized by a narrowing of a part of the aorta.[8,11] The defect typically occurs in proximal descending aorta near the ductus arteriosus, in the descending aorta.[11] Like a stenotic aorta valve in the heart of an older individual, this narrowing increases the resistance of flow through the aorta. This increased resistance to flow can cause an increase in the workload of the left ventricle.[8,11] The result of this increased workload, if left

untreated, can cause thickening of the ventricular muscle and further cascade into heart failure resulting with its associated signs and symptoms. Depending on the patient's age upon presentation, clinical findings can range from heart failure to systemic hypertension in the upper extremities with diminished pulses in the lower extremities. It is estimated that there are approximately 1,500 births per year in the United States with coarctation of the aorta.[8]

Transposition of the Great Arteries

Transposition of the great arteries (TGA) can refer to either dextro-Transposition of the Great Arteries (d-TGA) or levo-Transposition of the Great Arteries (l-TGA). TGA is strictly a switching of the position of the pulmonary artery and the aorta; the aorta connects the right ventricle and the pulmonary artery connects to the left ventricle. Blood flow through a heart with d-TGA results in returning venous blood to the right atrium being immediately pumped systemically, bypassing the lungs. Similarly, pulmonary venous return is immediately pumped back into pulmonary circulation.[8]

This condition is not always fatal because it is almost always accompanied by a patent ductus arteriosus and either an ASD or ventricular septal defect (VSD), both of which allow for mixing of oxygenated and deoxygenated blood. Severity of symptoms is directly related to the degree of oxygenated and deoxygenated blood mixing. It is estimated that there are approximately 1,250 births per year in the United States with d-TGA and all require surgical

intervention. The most common of surgical procedures to correct this defect is the arterial switch procedure. As suggested by its name, this procedure relocates the transposed arteries to their normal anatomical locations.[8]

L-TGA, also referred to as corrected TGA, is the condition in which, in addition to the transposition of the great arteries, the ventricles have also transposed; that is there is both ventriculoarterial and atrioventricular discordance. In l-TGA, the right ventricle receives oxygenated blood from the left atria and pumps it systemically through the aorta. Conversely, the left ventricle receives deoxygenated blood from the right atria and pumps it through the pulmonary artery. This condition is extremely rare and is usually associated with the presence of a VSD, pulmonary stenosis and an abnormal tricuspid valve.[8]

Hypoplastic Left Heart Syndrome

Hypoplastic Left Heart Syndrome (HLHS) is a CHD in which the left side of the heart does not develop properly. Normal heart structures found in the left heart are either underdeveloped or nonexistent. Anatomy of infants born with this syndrome is complex and so too are the procedures to correct the birth anatomy. Generally, HLHS is characterized by an underdeveloped, nonfunctioning left ventricle. Systemic circulation at birth is achieved as follows: oxygen rich blood returning to the left atria enters into the right atria via an ASD (or patent foramen ovale); mixed oxygenated and deoxygenated blood is then pumped to the pulmonary artery where it can be shunted to the aorta via the

patent ductus arteriosus.[8] This single ventricle circulation is unsustainable and must begin to be addressed, almost immediately after birth, in a three-staged surgical palliation culminating in what is known as a Fontan circulation.[8,12]

It is estimated that there are approximately 960 births per year in the United States with HLHS.[8]

Pulmonary Atresia

Pulmonary atresia is a condition in which no pulmonary valve forms. As such, blood entering the right ventricle cannot pass into the pulmonary artery for transport through the pulmonary circulation. This condition can present with or without a ventricular septal defect. Any blood entering the right ventricle either regurgitates back into the right atria and then through a patent foramen ovale into the left atria; or, in the presence of a VSD, blood can additionally pass from the right ventricle into the left. Blood in the left heart is pumped through the aorta with pulmonary circulation achieved through a patent ductus arteriosus.[8]

Treatment of pulmonary atresia varies according to severity of symptoms and size of the right ventricle. Typically, treatment consists of surgery to open the tissue where the pulmonary valve should exist and implant a replacement valve.[8] If the right ventricle is significantly underdeveloped, staged surgical palliation similar to the treatment of HLHS is performed.[8,12] It is estimated that there are approximately 400 births per year in the United States with pulmonary atresia.[8]

Tetralogy of Fallot

Tetralogy of Fallot is a CHD and term that describes a defined group of heart defects occurring within the same patient. The component defects are a VSD, positioning of the aorta over the VSD (over-riding aorta), right ventricular outflow tract obstruction due to a combination of pulmonary valve stenosis, pulmonary artery stenosis, and infundibular obstruction (subpulmonic stenosis). Right ventricular hypertrophy develops as a consequence of chronic right ventricular outflow tract obstruction. Like with most CHDs, these patients present clinically with decreased oxygen saturation and cyanosis. Arterial and venous blood mixes at the site of the VSD and is circulated systemically through the aorta.[8]

Surgical closure of the VSD and widening of the pulmonary valve and artery achieves sustainable heart function. It may be necessary to repair or replace the pulmonary valve in a subsequent procedure for some patients. It is estimated that there are approximately 1,700 births per year in the United States with Tetralogy of Fallot.[8]

Anomalous Pulmonary Venous Return

Anomalous pulmonary venous return can be classified as either partial (PAPVR) or total (TAPVR). In a normal heart, the pulmonary veins return oxygenated blood from the pulmonary circulation to the left atrium for continued

circulation systemically. In PAPVR and TAPVR, all or some of the pulmonary veins return oxygenated blood back to the right atrium. There are generally three subtypes of TAPVR: supracardiac, cardiac, and infracardiac; and are defined based upon the location of where the pulmonary veins connect. In supracardiac TAPVR, the confluence of pulmonary veins drain via a vertical connecting vein to the superior vena cava and subsequently the right atrium. In cardiac TAPVR, the confluence of pulmonary veins drain directly into the right atria usually via the coronary sinus. In infracardiac TAPVR, the confluence of pulmonary veins drain via a connecting vein to a venous structure below the diaphragm (usually a hepatic vein or the inferior vena cava which then returns to the right atria. It is estimated that there are approximately 400 combined births per year in the United States with PAPVR or TAPVR.[8]

Tricuspid Atresia

In the normal heart, blood from the right atrium passes through the tricuspid valve as it enters into the right ventricle. With tricuspid atresia the TV does not form at all. Infants with tricuspid atresia always have other defects such as, an ASD, VSD, patent foramen ovale, and/or patent ductus arteriosus. These defects will allow for mixing of oxygenated and deoxygenated blood and delivery of blood to the pulmonary circulation.[8] Treatment for tricuspid atresia includes staged surgical procedures to establish a Fontan circulation. In the initial period following birth use of medication to maintain ductal patency may be necessary to

to allow for oxygenated and deoxygenated blood mixing, interim to surgical interventions.[8,12] It is estimated that there are approximately 400 births per year in the United States with tricuspid atresia.[8]

Ventricular Septal Defect

A ventricular septal defect (VSD) is hole that exists in the tissue separating the two ventricles. The structure of the septum varies significantly and defects in different regions of the septum have specific names. A VSD allows for mixing of oxygenated and deoxygenated blood within the heart. Typically, blood from the left ventricle will flow into the right ventricle. This flow across the ventricles will cause increased blood volume to the lungs resulting in pulmonary hypertension, impaired gas exchange across the pulmonary capillary bed, and increased work of breathing, among other complications. As the child grows, the defect may begin to close on it's own, but more severe defects require surgical intervention. It is estimated that there are approximately 16,500 births per year in the United States with a VSD.[8]

TABLE 2 Types of Congenital Heart Defects[8,9]

Atrial Septal Defect (ASD)	A hole in the septum dividing the atria
Atrioventricular Septal Defect (AVSD)	A large hole in the center of the heart where the atrial septum and ventricular septum would normally meet
Coarctication of the Aorta	A narrowing of the aorta near the ductus arteriosus
Transposition of the Great Arteries (TGA)	A switching of the positions of the pulmonary artery and aorta
Hypoplastic Left Heart Syndrome (HLHS)	The left atrium and ventricle is underdeveloped and generally nonfunctioning
Pulmonary Atresia	No formation of the pulmonary valve
Tetralogy of Fallot	A stenotic pulmonary valve and artery, an enlarged aorta, VSD, and right ventricular hypertrophy
Anomalous Pulmonary Venous Return	All or some of the pulmonary veins return blood to the right atrium
Tricuspid Atresia	No formation of the tricuspid valve
Ventricular Septal Defect (VSD)	A hole in the septum dividing the ventricles

Clinical Review

Prior to echocardiography, the primary method for diagnosis of simple and complex congenital heart defects was cardiac catheterization.[13] After the introduction of echocardiography, it was commonly accepted as a first-line imagining modality, but controversy existed in the field over the necessity of cardiac catheterization to confirm diagnosis. In 1998, Tworetzky et al, sought to resolve this controversy undertaking a retrospective study to "determine the diagnostic accuracy of echocardiography alone."[13] Their results suggested that "echocardiography alone is an accurate tool for the preoperative diagnosis of major congenital heart defects in most children undergoing primary complete repair, and may obviate the need for routine diagnostic catheterization."[13]

At Boston Children's Hospital in 2006, Larrazabal et al were able to utilize a host of echocardiographic data to establish a means to technically assess and score surgical performance across a diverse array of congenital heart defect procedures.[14]

Again at Boston Children's Hospital, in 2011, Nathan et al demonstrated that the previously created technical performance score was indeed an accurate predictor of patient outcomes and postoperative morbidity.[10,15] Furthermore, it was shown that postoperative morbidity was not affected by intraoperative surgical revision.[16] There was no significant difference in patient outcomes between cases where no reintervention was required and those cases that underwent immediate intraoperative reintervention, provided that the technical scores at the end of the case were satisfactory.[16,17] Comparatively, those patients who underwent postoperative surgical or catheter reintervention had significantly longer ICU lengths of stay over both the no reintervention required and the intraoperative reintervention groups ($p < 0.0001$ and $p < 0.005$, respectively).[16] These findings have been supported in subsequent studies.[17,18]

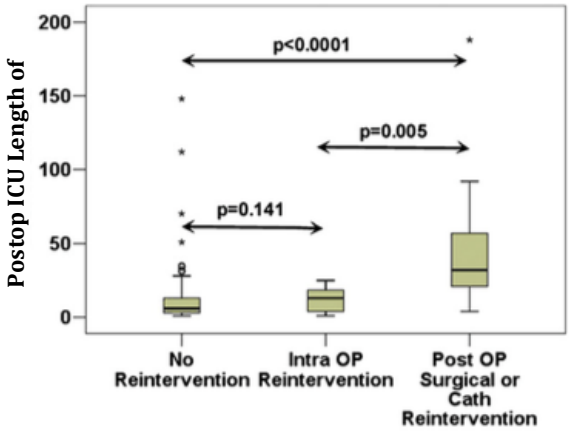


Figure 29: Length of Stay Analysis
(Adapted from Nathan et al., 2011.)

Subgroup analysis of intensive care unit length of stay in patients requiring no reintervention compared to intraoperative reintervention; no reintervention to postoperative reintervention; and intraoperative reintervention to postoperative reintervention.[16]

It can be inferred from **Figure 29**, and subsequently confirmed by a follow-up study by Nathan et al in 2014, that achieving an optimal surgical repair, without need for postoperative reintervention, results in shorter postoperative length of stay and a lower likelihood of postoperative adverse events in patients following congenital heart surgery. In the same study, it was additionally determined that in order to reduce the need for postoperative reintervention, the identification of residual lesions intraoperatively is critical.[16,17]

The benefits of intraoperative transesophageal echocardiography (TEE) during cardiac surgery are well documented.[2,4,16,17,19,20,21] Intraoperative TEE

accurately confirms and in many cases refines delineation of congenital heart lesions,[13] can be used as a means for establishing an intraoperative technical surgical score,[14,16] and offers a low incidence of intraoperative complications.[21] It was hypothesized that the rate of perioperative complications in children would be congruent with the current available data in adults. As a secondary aim the study sought to assess the overall compliance with established practices for probe size selection and placement at Boston Children's Hospital.

Intraoperative transesophageal echocardiograms offer an immediate feedback and technical performance score to the surgeon.[4] Having the ability to improve technical performance scores intraoperatively definitively offers the opportunity for lower postoperative morbidity.[16]

METHODS

After Institutional Review Board submission and approval, a retrospective chart review of patients at Boston Children's Hospital who underwent the TEE procedure between May 2012 and December 2014 was conducted. Exclusion criteria included age greater than 18 years at the time of procedure and TEE examinations associated with complex operative procedures, following which elective tracheal extubation within 24 hours after completion of surgery was not anticipated. This criterion was set as a benchmark in order to reduce confounding variables in our determination of the likelihood that an adverse event was truly a result of TEE. As a result, the majority of patients who were included in the study had undergone either a pulmonary valve replacement (PVR) or atrial septal defect (ASD) closure. PVR and ASD cases with additional procedures performed at time of the TEE procedure were evaluated on their study eligibility on an individual basis. The final study sample consisted of 129 patient charts. Adverse events related to TEE were documented and defined as follows: 1) those potentially attributable to TEE and 2) those with a high likelihood of being related to TEE; defined as dysphagia, esophageal perforation, gastrointestinal bleeding, and throat discomfort/pain.[22,23] Incidence rates were calculated at the aforementioned incidence levels of adverse events and compared against previous study data as population comparison.[20,21,22]

Patient charts were reviewed from the day of surgery through their time in the intensive care unit (ICU); exception protocol to be outlined. For purposes of recording a patient transferred from the ICU to the ward on the day of surgery was documented as spending 0 days in the unit. If the same patient was transferred from the ICU to the ward at 00:00 (postop day 1), they would be documented as spending 1 day in the unit.

At the onset of the study, the investigation team did not identify or foresee any potential health risks or discomforts to our patients, as the study was to be a retrospective chart review. Patients did not experience additional procedures beyond what was required for clinical care purposes. All electronic health data was and is stored in a password protected study folder accessible only to the investigatory team. Remote access to data was achieved through established institutional encryption requirements. All of the study personnel were and are familiar with HIPAA guidelines prior to accessing patient data. The data collected that is protected by HIPAA was the minimum required for finding potential subjects for this study. No additional protected health information was collected. Once a patient was determined to be eligible for full study investigation, the additional data collected was strictly related to diagnosis information and perioperative findings. Furthermore, the identities of patients in the study were only seen by the data collectors and by no other person.

Perioperative findings were investigated and documented from onset of anesthetic induction to transfer from intensive care unit to the general ward; or

according to the exception protocol. By formally analyzing the incidence of adverse events associated with TEE and compliance with Boston Children's Hospital internally developed TEE procedure form completion, we may be able to improve health outcomes of patients requiring TEE.

Exception Protocol

Exceptions to the above protocol of reviewing patient charts through the duration of intensive care unit stay were made for those patients who were admitted directly from the operating room to the general ward. For these patients, charts were reviewed from onset of anesthetic induction to their discharge from the hospital. These patients were included in this study as they were considered among the least complex of surgical cases and were not expected to add any confounding to our observations of adverse events. There were 13 patient charts out of the 129 that were reviewed in this fashion. This protocol does not apply to those patients designated as spending 0 days in the ICU.

RESULTS

For the patients that spent time in the ICU, the mean number of days until transfer to the ward was 1.43. This number included one outlier patient that spent 27 days in the ICU. Without this outlier, the mean time spent in the ICU dropped to 1.21 days. There was one patient that expired in the ICU and was not included in this mean calculation. The mean number of days until discharge for the 13 patients reviewed under the exception protocol was 1.23.

The age distribution of the study sample is shown below in **Figure 30.** As expected, the distribution is not normal. The age of patients who undergo surgical repair of CHDs and follow-up palliation is greatly influenced by a vast continuum of factors.

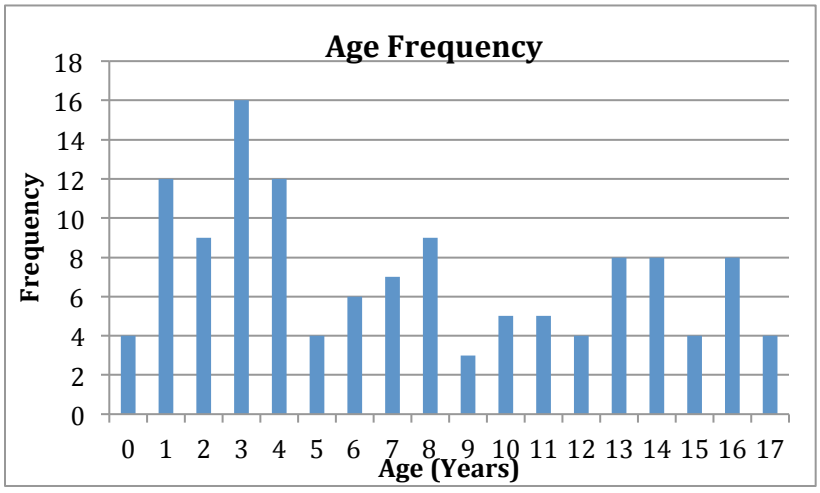


Figure 30: Age distribution of included patients. Mean: 7.93 years.

Types of Adverse Events

Upon completion of analysis of patient charts, the adverse events noted were sorted into categories as seen in Figures 31 and 32. Airway events were defined as complications occurring in the oral cavity, nasopharynx, and the oropharynx extending inferiorly to the larynx. Specific types of events included and noted to have occurred were stridor, upper airway congestion, upper airway obstruction, secretions, and sore throat. In intubated patients, endotracheal secretions were also included as an airway event. Respiratory events were defined as complications occurring mainly within the lungs. Specific events included occurrences of pneumothorax, pulmonary edema, desaturation, and lung collapse. Cardiac events were defined as noted arrhythmias. Thoracic events were defined by events such as chest pain, without any notation regarding arrhythmia. Gastrointestinal events were adverse events occurring between the esophagus and the bowels. These events included any noted bleeding or discomfort. Nausea and emesis were never marked as adverse events as these are known complications associated with anesthesia. There was one neurological event that consisted of seizure activity. All of the adverse events are seen below in **Figure 31**.

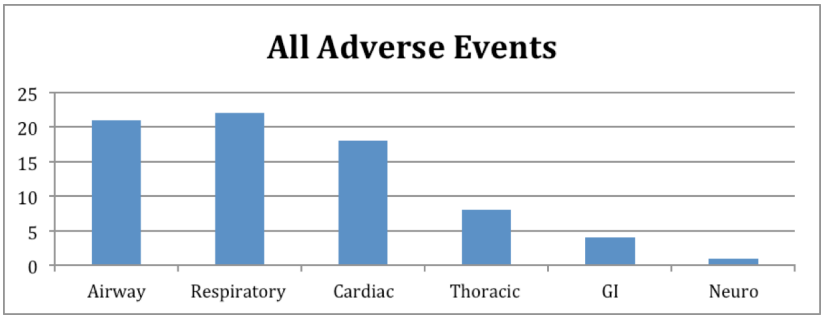


Figure 31: All adverse events categorized by type.

After further analysis of adverse events, we were able to rule out some events based on their likelihood of being attributable to other variables, such as arrhythmias and complications that could be attributed to comorbidities. For example, individuals with Trisomy 21 (Down Syndrome), Noonan Syndrome, and VACTERL Syndrome are all predisposed to having airway obstructions and were therefore counted as confounding variables.[24] The neurological event was considered to potentially be related to TEE because we were unable to specifically attribute it to any other cause. The cardiac event was documented as an arrhythmia intraoperatively and was considered attributable to TEE because it was specifically noted to have occurred during the TEE procedure. Other arrhythmias were attributed to the nature of the patient population and are to be expected, especially following heart surgery. Thoracic events such as chest pain were attributed to incision pain following surgery. **Figure 32** displays the results.

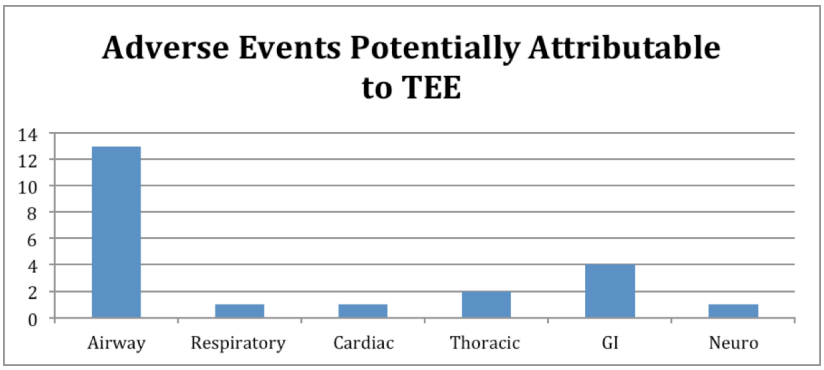


Figure 32: Adverse events potentially attributable to TEE. 19 cases with 22 complications. 1473 per 10,000.

Of the 129 total cases, there was only one case reporting an intraoperative adverse event with a high likelihood of being related to TEE. This incidence rate of 0.77% (77 per 10,000) is consistent with the literature existing on adult and pediatric TEE safety studies.[21] Literature on postoperative adverse events related to intraoperative TEE use in pediatric patients was limited to the incidence of dysphagia.[25] The sample included no instance of dysphagia. Our review enumerated six postoperative adverse events (4.65%, 465 per 10,000) of which had a high likelihood of being related to TEE. Three of these events were classified as major and three were classified as minor. Major postoperative events included blood draining from nasogastric/orogastric tubes and blood tinged secretions suctioned from the endotracheal tube. Minor events were patient reported as sore throat and voice hoarseness.

DISCUSSION

As noted in the results, there was one patient that spent 27 days in the ICU and there was one patient that expired. These patients, henceforth referred to as **Patients A** and **B** respectively, are represented in **Figure 31**, but were not included in further incidence rates.

A brief highlight of hospital course for **Patients A** and **B**:

Patient A was admitted to the operating theatre for closure of an ASD and possible repair of the mitral valve. Intraoperatively, repair of a prolapsed mitral valve was deemed necessary. Over the course of the operation, the patient experienced an arrhythmia (ST elevation). Intraoperative TEE examination observed poor biventricular systolic function. Postoperatively this patient experienced multiple arrhythmias, including atrial flutter, ventricular tachycardia, and a ventricular fibrillation arrest requiring cardiopulmonary resuscitation. One day postop the patient was placed on extracorporeal membrane oxygenation (ECMO). Catheterization lab examination after transfer to ECMO demonstrated poor right ventricle function. As noted in the introduction, the mitral valve exists and is the passage point between the right atrium and right ventricle. The patient recovered from this course; ECMO was discontinued after 7 days and the patient was transferred to the ward after 27 days.

Patient B underwent a TEE examination in the catheterization lab for assessment of chronic heart failure approximately 18 months status post heart transplant. A left ventricular assist device (LVAD) had been implanted approximately five months post transplant. The patient had been intubated, characterized as being in critical condition, and was being cared for in the ICU prior to this examination. It was decided to terminate artificial ventilations and the LVAD three days after the TEE examination. To that end, the patient ultimately expired.

Amongst the research team, it is consensus that although **Patients A** and **B** qualified for the study based upon the inclusion parameters, their challenging hospital course was due to the risks surrounding surgical intervention (**Patient A**) and the risks accompanying the specific medical history (**Patient B**).

In future studies, it would be recommended to include a broader diagnostic range of patients. This study was limited in that there was no control group to compare our treatment sample against. This limitation existed because of the preexistence of an institutional policy, whereby every patient undergoing surgical palliation for CHD undergoes intraoperative TEE. This practice was established prior to the onset of this safety study because it was commonly perceived in the clinic that there was little risk of major complications associated with TEE. This study was designed to formally submit to the academic medical community that which was generally understood to be true and safe by the

clinicians. Boston Children's Hospital is one of the pioneers in pediatric TEE use and employs the experts in the clinical use of pediatric TEE.

Conclusion

It can be concluded that TEE use is not associated with an increased risk of adverse events in pediatric patients if performed according to institutional procedure and recommendations. Intraoperative TEE offers immediate assessment of the adequacy of surgical repair and presence of residual lesions. This information can be used to generate a surgical technical performance score. The ability to detect and correct residual lesions with information provided by intraoperative TEE allows the surgeon to improve technical performance thereby reducing postoperative morbidity.

APPENDIX

Table 10 Comprehensive transesophageal echocardiographic examination. The table lists the suggested 28 views included in a comprehensive transesophageal echocardiographic examination. Each view is shown as a 3D image, the corresponding imaging plane, and a 2D image. The acquisition protocol and the structures imaged in each view are listed in the subsequent columns

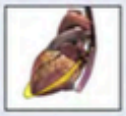
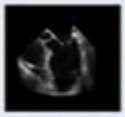
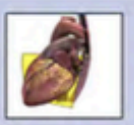
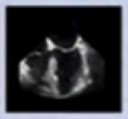
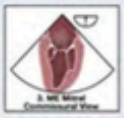
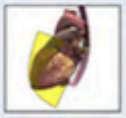
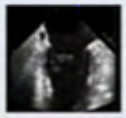
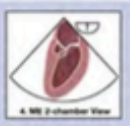
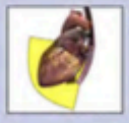
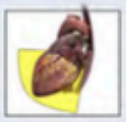
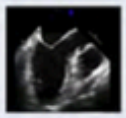
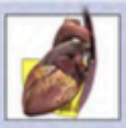
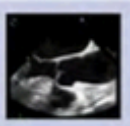
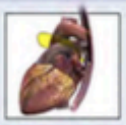
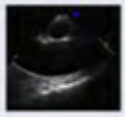
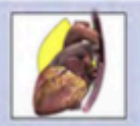
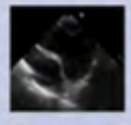
Imaging Plane	3D Model	2D TEE Image	Acquisition Protocol	Structures Imaged
Midesophageal Views				
			**Transducer Angle:** ~ 0 - 10° **Level:** Mid-esophageal **Maneuver** (from prior image): NA	Aortic valve LVOT Left atrium/Right atrium Left ventricle/Right ventricle/IVS Mitral valve (A_2A_1-P_1) Tricuspid valve
			**Transducer Angle:** ~ 0 - 10° **Level:** Mid-esophageal **Maneuver** (from prior image): Advance ± Retroflex	Left atrium/Right atrium IAS Left ventricle/Right ventricle/IVS Mitral valve (A_2A_1-P_2P_1) Tricuspid valve
			**Transducer Angle:** ~ 50 - 70° **Level:** Mid-esophageal **Maneuver** (from prior image): NA	Left atrium Coronary Sinus Left ventricle Mitral Valve (P_3- $A_3A_2A_1$ - P_1) Papillary muscles Chordae tendinae
			**Transducer Angle:** ~ 80 - 100° **Level:** Mid-esophageal **Maneuver** (from prior image): NA	Left atrium Coronary sinus Left atrial appendage Left ventricle Mitral valve (P_3- $A_3A_2A_1$)
			**Transducer Angle:** ~ 120 - 140° **Level:** Mid-esophageal **Maneuver** (from prior image): NA	Left atrium Left ventricle LVOT RVOT Mitral valve (P_2- A_2) Aortic valve Proximal ascending aorta
			**Transducer Angle:** ~ 120 - 140° **Level:** Mid-esophageal **Maneuver** (from prior image): Withdrawl ± anteflex	Left atrium LVOT RVOT Mitral valve (A_2- P_2) Aortic valve Proximal ascending aorta
			**Transducer Angle:** ~ 90 - 110° **Level:** Upper-Esophageal **Maneuver** (from prior image): Withdrawl	Mid-ascending aorta Right pulmonary artery
			**Transducer Angle:** ~ 0 - 30° **Level:** Upper-Esophageal **Maneuver** (from prior image): CW	Mid-ascending aorta (SAX) Main/bifurcation pulmonary artery Superior vena cava

Table 10 Continued

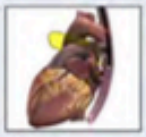
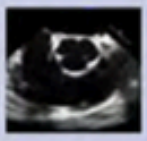
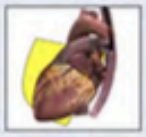
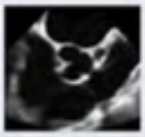
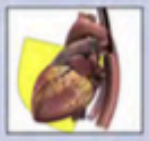
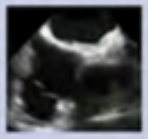
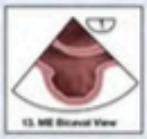
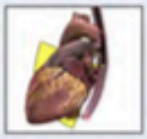
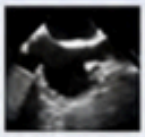
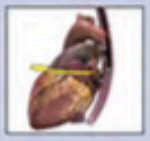
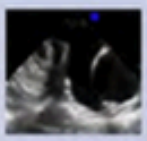
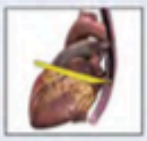
			**Transducer Angle:** ~ 0 - 30° **Level:** Upper-esophageal **Maneuver** (from prior image): CW, Advance	Mid-ascending aorta Superior vena cava Right pulmonary veins
			**Transducer Angle:** ~ 25 - 45° **Level:** Mid-esophageal **Maneuver** (from prior image): CCW, Advance, Anteflex	Aortic valve Right atrium Left atrium Superior IAS RVOT Pulmonary Valve
			**Transducer Angle:** ~ 50 - 70° **Level:** Mid-esophageal **Maneuver** (from prior image): CW, Advance	Aortic valve Right atrium Left atrium Superior IAS Tricuspid Valve RVOT Pulmonary Valve
			**Transducer Angle:** ~ 50 - 70° **Level:** Mid-esophageal **Maneuver** (from prior image): CW	Right atrium Left atrium Mid-IAS Tricuspid Valve Superior vena cava Inferior vena cava/coronary sinus
			**Transducer Angle:** ~90 - 110° Level: Mid-esophageal **Maneuver** (from prior image): CW	Left atrium Right atrium/appendage IAS Superior vena cava Inferior vena cava
			**Transducer Angle:** ~ 90 - 110° **Level:** Upper-esophageal **Maneuver** (from prior image): Withdraw, CW for the right veins, CCW for the left veins	Pulmonary vein (upper and lower) Pulmonary artery
			**Transducer Angle:** ~90 - 110° **Level:** Mid-esophageal **Maneuver** (from prior image): Advance	Left atrial appendage Left upper pulmonary vein

Table 10, Hahn et al., 2013[7]

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Division of Perioperative Medicine
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- Stocking of medications for anesthesia carts
- Anesthesia machine cleaning and airway setup for operating room cases

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Graduate Research Assistant — Jul 2014 – Present

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Fallon Ambulance Service — Quincy, MA
Department of Training and Education
BLS Training Assistant — Dec 2014 – Present

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Department of Operations
Emergency Medical Technician – Basic

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- Assisting physicians in various sterile procedures

Northeastern University — Nahant, MA
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Undergraduate Research Assistant — Jan 2011 – Mar 2012

- Data collection, analysis, and manuscript production of embryological/ecological mammal study

Genesis HealthCare Brookline, MA
Genesis Rehabilitation Services
Rehabilitation Technician Jan – Jun 2010

- Assisting occupational and physical therapists in treatment of patients
- Conducting maintenance therapy programs
- Toileting/hygiene of dependent patients, functional transfers, reporting/monitoring vitals