

EXPERT CONSENSUS STATEMENT

Targeted Neonatal Echocardiography in the Neonatal Intensive Care Unit: Practice Guidelines and Recommendations for Training

Writing group of the American Society of Echocardiography (ASE) in collaboration with the European Association of Echocardiography (EAE) and the Association for European Pediatric Cardiologists (AEPC)

Luc Mertens, MD, PhD, FASE, FESC, Istvan Seri, MD, PhD, HonD, Jan Marek, MD, PhD, FESC, Romaine Arlettaz, MD, Piers Barker, MD, FASE, Patrick McNamara, MD, MB, FRCPC, Anita J. Moon-Grady, MD, Patrick D. Coon, RDCS, FASE, Shahab Noori, MD, RDCS, John Simpson, MD, FRCP, FESC, and Wyman W. Lai, MD, MPH, FASE, *Toronto, Ontario, Canada; Los Angeles and San Francisco, California; London, United Kingdom; Zurich, Switzerland; Durham, North Carolina; Philadelphia, Pennsylvania; New York, New York*

(J Am Soc Echocardiogr 2011;24:1057-78.)

Keywords: Echocardiography, Neonatal intensive care unit, Neonatologists, pediatric cardiologists, Preterm neonate, Term neonate

From The Labatt Family Heart Center, The Hospital for Sick Children, Toronto, Ontario, Canada (L.M., P.M.); Children's Hospital Los Angeles, Los Angeles, California (I.S., S.N.); Great Ormond Street Hospital, London, United Kingdom (J.M.); University Hospital Zurich, Zurich, Switzerland (R.A.); Duke University Hospital, Durham, North Carolina (P.B.); the University of California, San Francisco, California (A.J.M.-G.); The Cardiac Center at the Children's Hospital of Philadelphia, Philadelphia, Pennsylvania (P.D.C.); Evelina Children's Hospital, London, United Kingdom (J.S.); and Morgan Stanley Children's Hospital of New York Presbyterian, New York, New York (W.W.L.).

The following authors reported no actual or potential conflicts of interest in relation to this document: Luc Mertens, MD, PhD, FASE, FESC, Jan Marek, MD, PhD, FESC, Romaine Arlettaz, MD, Piers Barker, MD, FASE, Patrick McNamara, MD, MB, FRCPC, Anita J. Moon-Grady, MD, Patrick D. Coon, RDCS, FASE, Shahab Noori, MD, RDCS, John Simpson, MD, and Wyman W. Lai, MD, MPH, FASE. The following author reported a relationship with one or more commercial interests: Istvan Seri, MD, PhD, HonD, served as a scientific consultant for Somanetics Corporation (Troy, MI) until 2010.

Attention ASE Members:

ASE has gone green! Visit www.aseuniversity.org to earn free continuing medical education credit through an online activity related to this article. Certificates are available for immediate access upon successful completion of the activity. Nonmembers will need to join ASE to access this great member benefit!

Reprint requests: American Society of Echocardiography, 2100 Gateway Centre Boulevard, Suite 310, Morrisville, NC 27560 (E-mail: ase@asecho.org).

Writing Group of the American Society of Echocardiography (ASE) in collaboration with the European Association of Echocardiography (EAE) and the Association for European Paediatric Cardiology (AEPC).

0894-7317/\$36.00

Copyright 2011 by the American Society of Echocardiography.

doi:10.1016/j.echo.2011.07.014

TABLE OF CONTENTS

Abbreviations 1058

1. Targeted Neonatal Echocardiography: Background and Indications 1058
 - 1.1. Cardiovascular Adaptations in the Neonatal Period 1058
 - 1.2. Indications for TNE 1059
 - 1.2.1. Indications for TNE With Standard Imaging (Standard TNE) 1059
 - 1.2.2. Indications for TNE With Focused Imaging (Focused TNE) 1062
2. Targeted Neonatal Echocardiography: Practical Aspects 1063
 - 2.1. General Aspects of TNE 1063
 - 2.1.1. Technical and Safety Requirements for Performing TNE 1063
 - 2.1.2. Guidelines for Image Acquisition in the NICU 1063
 - 2.1.3. Components of Standard TNE 1064
 - 2.1.3a. Evaluation of LV Systolic Function 1064
 - 2.1.3b. Assessment of LV Diastolic or Combined Function 1065
 - 2.1.3c. Evaluation of RV Function 1065
 - 2.1.3d. Assessment of Atrial-Level Shunt 1065
 - 2.1.3e. Assessment of PDA 1066
 - 2.1.3f. Assessment of RVSp and PA Pressures 1066
 - 2.1.3g. Assessment of Systemic Blood Flow 1066
 - 2.1.3h. Assessment of Pericardial Fluid 1067
 - 2.2. TNE for Specific Neonatal Conditions 1067
 - 2.2.1. Suspected PDA 1067
 - 2.2.2. Perinatal Asphyxia 1068
 - 2.2.3. Neonatal Hypotension 1068
 - 2.2.4. Suspected Persistent Pulmonary Hypertension of the Newborn (PPHN) 1069
 - 2.2.5. CDH 1069
 - 2.2.6. Suspected Effusion 1070
 - 2.2.7. Central Line Placement 1070
 - 2.2.8. ECMO Cannulation 1071

Abbreviations

AAP = American Academy of Pediatrics
AEPC = Association for European Paediatric Cardiology
ASE = American Society of Echocardiography
CDH = Congenital diaphragmatic hernia
CHD = Congenital heart disease
EAE = European Association of Echocardiography
ECMO = Extracorporeal membrane oxygenation
EF = Ejection fraction
LV = Left ventricular
MPI = Myocardial performance index
mVCFc = Mean velocity of circumferential fiber shortening
NICU = Neonatal intensive care unit
PA = Pulmonary artery
PDA = Patent ductus arteriosus
RA = Right atrial
RV = Right ventricular
RVSp = Right ventricular systolic pressure
SF = Shortening fraction
SVC = Superior vena cava
TEE = Transesophageal echocardiography
TNE = Targeted neonatal echocardiography
TVI = Time-velocity integral
2D = Two-dimensional
VLBW = Very low birth weight

3. Training and Accreditation in Targeted Neonatal Echocardiography 1071
 - 3.1. Overview of Existing Training Guidelines 1072
 - 3.1.1. US Pediatric Echocardiographic Guidelines 1072
 - 3.1.2. European Pediatric Echocardiographic Guidelines 1072
 - 3.2. Proposal for Training in TNE 1073
 - 3.2.1. Core Training in TNE 1073
 - 3.2.2. Advanced Training in TNE 1074
 - 3.3. Supervision of Training 1074
 - 3.4. Evaluation 1074
 - 3.5. Maintenance of Competence and Quality Assurance for TNE 1074

1. TARGETED NEONATAL ECHOCARDIOGRAPHY: BACKGROUND AND INDICATIONS

The role of echocardiography in the neonatal intensive care unit (NICU) has changed over the past few years. Previously, nearly all echocardiographic studies in the NICU were performed by pediatric cardiologists to diagnose or monitor congenital heart disease (CHD) and to screen for patent ductus arteriosus (PDA). More recently, neonatologists have become interested in the echocardiographic assessment of hemodynamic instability in infants. The terms *functional echocardiography* and *point-of-care echocardiography* have been introduced to describe the use of echocardiography as an adjunct in the clinical assessment of the hemodynamic status in neonates.¹⁻⁴ The increasing availability of echocardiography, with miniaturization of the

studies performed on infants without any clinical suspicion of CHD. If CHD has been excluded, subsequent studies in children with structurally normal hearts can focus on hemodynamic or functional assessment. The initial echocardiographic examination should always be a comprehensive study of both anatomy and function that is to be interpreted by a pediatric cardiologist within a reasonable time frame. Some structural defects, such as anomalous pulmonary venous return or coarctation of the aorta, can be difficult to detect using echocardiography and require extensive training and continued practice. Once significant congenital defects have been ruled out, more focused studies can be performed and interpreted by a trained echocardiographer for specific indications, as defined later in this document. We propose to use the term *targeted neonatal echocardiography* (TNE) for the more focused studies. The aims of the current document are: (1) to review the current indications of TNE; (2) to define recommendations for the performance of TNE; and (3) to propose training requirements for the operators performing and interpreting TNE.

1.1. Cardiovascular Adaptations in the Neonatal Period

The neonatal cardiovascular system differs from those of fetal, pediatric, and adult patients. At term, a neonate must successfully transition through abrupt changes in the cardiorespiratory system, including changes in lung volume and compliance and changes in left and right heart preload and afterload. Intracardiac and extracardiac shunts via the foramen ovale and ductus arteriosus, physiologic in the fetus, have varying effects on immediate postnatal hemodynamics. The neonatal heart may also have to cope with structural heart disease and/or extracardiac congenital and acquired conditions, such as congenital diaphragmatic hernia (CDH), sepsis, or pulmonary hypertension, that are tolerated differently compared with an older child. In the setting of a preterm delivery, the immaturity of the cardiovascular system and other organ systems makes it more difficult for the neonate to appropriately respond to the challenges of postnatal transition and extrauterine existence. Detailed understanding of fetal, transitional, and neonatal cardiovascular physiology is necessary to enable understanding of echocardiographic information obtained during the perinatal period.

The Transition From Fetus to Neonate. It is important for those performing TNE to understand the normal development of the myocardium and cardiopulmonary circulation and how preterm delivery may disrupt this process. In the fetus, myocytes are smaller and typically have a single nucleus, compared with the multinucleated myocytes that are prevalent postnatally.⁶ Although the fetus has a higher indexed myocardial mass,⁷ the fetal myocardium is less organized at the cellular level, with fewer sarcomeres per unit mass, different isoforms of contractile proteins,⁸ a developing sarcoplasmic reticulum,⁹ an overall higher water content,¹⁰ and a decreased number of mitochondria.¹¹ In addition, the heart is enclosed within a poorly compliant thorax.¹² As a result of these factors, the fetal heart is less compliant and less contractile than a term newborn or adult heart. These differences are manifested in the developmentally regulated limited fetal cardiac response to changes in preload or afterload, with heart rate changes being the major mechanism to alter fetal cardiac output, although some response to preload occurs if afterload remains constant.¹³⁻¹⁸ The fetal right and left ventricles also differ in myofiber architecture throughout gestation, with the right ventricle less tolerant to increases in afterload, despite its contributing slightly more to the combined ventricular output than the left ventricle during fetal life.¹⁵ The fetal pulmonary vasculature also exhibits significant differences from the adult pulmonary circulation.¹⁰ In the

technology, has resulted in more widespread use of echocardiography in NICUs around the world.⁵ Perhaps the most significant challenge for the application of so-called functional studies is that newborns in the NICU with hemodynamic instability are at a much higher risk for having underlying CHD. In addition, newborns in the NICU are unique in that they are in the process of transition from fetal to postnatal circulation.

In this document, we make clear distinctions between initial echocardiographic studies in neonates with the suspicion of CHD and

fetus, the pulmonary arteries and larger preacinar vessels demonstrate significant elastin in their medial layer, with a relative paucity of pulmonary smooth muscle, in contrast to the more distal preacinar and acinar vessels, which have a predominance of pulmonary smooth muscle in the media, and the most distal intra-acinar vessels, with no smooth muscle medial layer. These differences all result in the fetal pulmonary vascular bed being characterized by high vascular resistance, limiting fetal pulmonary blood flow from 11% to 22% of the combined cardiac output from early to late gestation, respectively.

The fetus is ideally adapted to these differences, because the fetal circulatory system includes the low-resistance placental circuit; a ductus arteriosus, which permits the right ventricular (RV) output to bypass the high-resistance lungs; and a patent foramen ovale, which permits mixing of the ductus venosus, hepatic, portal, and ultimately inferior vena caval venous flow with left atrial blood. During normal gestation, a large increase in fetal cardiac output is facilitated,¹⁹ and a gradual increase in cardiac contractility,^{10,20,21} sympathetic innervation, growth of cardiac chambers,²¹ growth of the lungs and the pulmonary vasculature, and redistribution of flow to the various fetal organs¹² take place. If this process is interrupted, as in the case of premature birth, further development occurs under very different and often adverse circumstances.

With delivery, there is an abrupt increase in systemic afterload, with removal of the low-resistance placenta and via peripheral vasoconstriction in response to the labor-induced endogenous hormone release and the cold stress encountered by moving to the extrauterine environment. Preload to the right heart decreases because of the cessation of umbilical venous return.¹⁰ Simultaneously, there is a decrease in pulmonary vascular resistance due to lung expansion and increased partial pressure of oxygen in the alveoli and the exposure of the pulmonary vascular bed to higher pulmonary artery (PA) partial pressure of oxygen and endocrine and paracrine pulmonary vasodilators.^{10,22} These changes lead to decreased RV pressures and a decreased constraining effect of the right ventricle within the pericardium. Intrapericardial pressure is also reduced with spontaneous ventilation producing intrathoracic pressures that are lower than atmospheric. These right-heart changes help the left ventricle adapt to the increased preload resulting from increased pulmonary venous return.¹⁸

In the term infant, the ductus venosus is functionally closed almost immediately with cessation of umbilical venous flow. Similarly, the flap of the foramen ovale quickly covers the fossa ovalis in the setting of higher left atrial pressures produced by increased pulmonary venous return and increased left ventricular (LV) afterload.²² The ductus arteriosus closes slightly more slowly, over the first several hours or days, in response to a higher partial pressure of oxygen, decreased local and circulating prostaglandin E₂ and other vasoactive factors, and a fully developed muscular medial layer.²² Myocardial contractility is also affected by increased levels of thyroid hormone, corticosteroids, and the catecholamine surge that occurs with labor and delivery.²³

The transition from fetal to postnatal life is more complicated in the preterm infant. The preterm LV myocardium is exposed to an abrupt increase in afterload while still relatively immature and thus may be less tolerant of the concurrent changes in preload conditions brought on by the presence of now pathologic atrial and ductal shunts.^{11,24} The preterm infant is also faced with immaturity of all organ systems, the preexisting intrauterine milieu that led to preterm delivery, and the resultant need for surfactant administration, ventilatory support, and vasoactive medications.^{11,13}

TNE can be a useful clinical adjunct to the overall assessment of the cardiovascular status of preterm and term neonates during normal and abnormal transition to extrauterine life. Ventricular systolic function can be noninvasively assessed using qualitative and quantitative methods; the direction and magnitude of atrial and ductus arteriosus shunting can be determined; and pressure estimations, particularly of the right ventricle and PA, can be made.

Recommendations: Every echocardiographer performing and interpreting TNE should be familiar with the normal neonatal cardiovascular adaptations and the effect of prematurity and disease on the neonatal cardiovascular system. This is crucial to understanding the findings of TNE.

1.2. Indications for TNE

TNE is proposed to “describe the bedside use of echocardiography to longitudinally assess myocardial function, systemic and pulmonary blood flow, intracardiac and extracardiac shunts, organ blood flow and tissue perfusion.”¹ The primary goals of TNE are to provide non-invasive information on the underlying cardiovascular pathophysiology causing hemodynamic instability and the response to treatment in an individual patient over time. We are aware that the current indications for TNE have been primarily established on the basis not of large clinical studies or trials but of clinical experience in a growing number of neonatal units and recent observational studies. Therefore, it is currently difficult to define the most appropriate use criteria for TNE, because it remains a constantly evolving ultrasound application. It is important to realize that TNE is not intended as a substitute for the evaluation of a neonate with suspected CHD by a qualified pediatric cardiologist. *If structural CHD or significant arrhythmia is clinically suspected in a neonate*, the infant should be clinically assessed by a pediatric cardiologist, and echocardiography should be performed by a person trained in pediatric echocardiography (at least core-level training, as defined later in this document) and reviewed by a pediatric cardiologist.^{25,26} Clinical suspicion includes the presence of cyanosis, signs of circulatory shock, clinical signs of heart failure, the presence of a murmur, arrhythmia, and abnormal pulses in upper and/or lower extremities. In *infants without any clinical suspicion for CHD*, the first echocardiographic study must be a comprehensive examination assessing both structure and function. This initial study can be performed by a person with at least core training in TNE or a core pediatric echocardiographer. The initial interpretation of this comprehensive study can be done by an advanced TNE-trained person, but it is recommended that the study be reviewed within a reasonable time period by a pediatric cardiologist. If this level of expertise is not readily available in the NICU, the use of telemedicine technology (either real-time or store-and-forward transmission of images in a timely manner) is strongly encouraged.

1.2.1. Indications for TNE With Standard Imaging (Standard TNE). In this document, we distinguish between “TNE with standard imaging (standard TNE)” and “TNE with focused imaging (focused TNE).” Standard, or full, TNE is a study including the different components as defined in Table 1 and further discussed in the next section of this document. The indications are listed below:

- Clinically suspected PDA, especially in very low birth weight (VLBW) neonates during the first 24 to 72 postnatal hours and beyond
- Assessment of infants with perinatal asphyxia
- Abnormal cardiovascular adaptation presenting with hypotension, lactic acidosis, or oliguria during the first 24 postnatal hours and beyond in VLBW infants to diagnose low systemic blood flow state

Table 1 Components of TNE

Component of TNE	Technique	View	Essential	Optional	Remarks	Normal reference data
LV systolic function						
LV end-diastolic diameter	2D or M-mode	Parasternal short-axis	Yes	No	M-mode higher temporal resolution	Nagasawa (2010) ³²
	2D	Subxiphoid short-axis				Zecca <i>et al.</i> (2001) ³⁰
						Skelton <i>et al.</i> (1998) ³¹
						Kampmann <i>et al.</i> (2000) ³³
LV end-systolic dimension	2D or M-mode	Parasternal short-axis	Yes	No		Nagasawa (2010) ³²
	2D	Subxiphoid short-axis				Zecca <i>et al.</i> (2001) ³⁰
						Skelton <i>et al.</i> (1998) ³¹
						Kampmann <i>et al.</i> (2000) ³³
LV end-diastolic posterior wall thickness	2D or M-mode	Parasternal short-axis	Yes	No		Nagasawa (2010) ³²
	2D	Subxiphoid short-axis				Zecca <i>et al.</i> (2001) ³⁰
						Skelton <i>et al.</i> (1998) ³¹
						Kampmann <i>et al.</i> (2000) ³³
LV end-diastolic septal wall thickness	2D or M-mode	Parasternal short-axis	Yes	No		Nagasawa (2010) ³²
	2D	Subxiphoid short-axis				Zecca <i>et al.</i> (2001) ³⁰
						Skelton <i>et al.</i> (1998) ³¹
						Kampmann <i>et al.</i> (2000) ³³
LV SF	2D or M-mode	Parasternal short-axis	If normal LV shape/ normal septal motion	No		Nagasawa (2010) ³²
	2D	Subxiphoid short-axis				Zecca <i>et al.</i> (2001) ³⁰
						Skelton <i>et al.</i> (1998) ³¹
						Kampmann <i>et al.</i> (2000) ³³
LV EF	Biplane Simpson	Apical four-chamber and two-chamber	If abnormal LV shape/septal motion	If normal LV shape/ septal motion		
	3D volumes	Apical views	No	Yes	Requires validation	
mVCFc	2D or M-mode	Parasternal short-axis	No	Yes	mVCFc is preload independent	Colan <i>et al.</i> (1992) ³⁶
						Rowland and Gutgesell (1995) ³⁷
LV diastolic function						
LA dimension	2D or M-mode	Parasternal long-axis	No	Yes		Kampmann <i>et al.</i> (2000) ³³
LA major axis	2D	Apical four-chamber	No	Yes		

(Continued)

Table 1 (Continued)

Component of TNE	Technique	View	Essential	Optional	Remarks	Normal reference data
LA minor axis	2D	Apical four-chamber	No	Yes		
MV E-wave peak velocity	PW Doppler	Apical four-chamber	Yes	Yes		Riggs <i>et al.</i> (1989) ⁴⁵
						Schmitz <i>et al.</i> (1998) ⁴⁶
						Schmitz <i>et al.</i> (2004) ⁴⁷
						Harada <i>et al.</i> (1994) ⁴⁴
MV A-wave peak velocity	PW Doppler	Apical four-chamber	Yes	Yes		Riggs <i>et al.</i> (1989) ⁴⁵
						Schmitz <i>et al.</i> (1998) ⁴⁶
						Schmitz <i>et al.</i> (2004) ⁴⁷
						Harada <i>et al.</i> (1994) ⁴⁴
MV E/A ratio						Riggs <i>et al.</i> (1989) ⁴⁵
						Schmitz <i>et al.</i> (1998) ⁴⁶
						Schmitz <i>et al.</i> (2004) ⁴⁷
						Harada <i>et al.</i> (1994) ⁴⁴
Pulmonary venous flow pattern	PW Doppler	Apical four-chamber	No	Yes	Influenced by atrial shunt	Ito <i>et al.</i> (2002) ⁴⁹
Peak MV annular velocity early diastolic E'	Tissue Doppler	Apical four-chamber	No	Yes		Mori <i>et al.</i> (2004) ⁵⁰
Peak MV annular velocity late diastolic A'	Tissue Doppler	Apical four-chamber	No	Yes		Mori <i>et al.</i> (2004) ⁵⁰
Assessment of pulmonary hypertension						
TR peak velocity	CW Doppler	Apical four-chamber view	Yes	No	Depends on angulation	
		Parasternal RV inflow view			Not reliable if TR jet is trivial	
Pulmonary regurgitation early diastolic velocity	PW/CW Doppler	Parasternal short-axis	Yes	No	Correlates well with mean PA pressure	
		Parasternal long-axis RVOT				
Pulmonary regurgitation late diastolic velocity	PW/CW Doppler	Apical four-chamber view	No	Yes	Correlates with end-diastolic PA pressure	
		Parasternal RV inflow view				

(Continued)

Table 1 (Continued)

Component of TNE	Technique	View	Essential	Optional	Remarks	Normal reference data
Assessment of RV function						
Tricuspid annular plane systolic excursion	M-mode	Apical four-chamber view	No	Yes	Correlates with EF	Koestenberger <i>et al.</i> (2009) ⁵⁵
Fractional area change	2D	Apical four-chamber view	No	Yes	Moderate correlation with EF	
Assessment of PDA						
Narrowest dimension of duct	2D or color Doppler	Ductal/suprasternal	Yes	No		
Shunt directionality	Color/CW/PW Doppler	Ductal/suprasternal	Yes	No		
Peak and mean gradient of ductal flow	CW/PW Doppler	Ductal/suprasternal	Yes	No	Obtain arterial blood pressure at the same time	
Assessment of atrial-level shunt						
Shunt directionality	Color Doppler	Subxiphoid long-axis/short-axis	Yes	No		
Peak and mean gradient of intra-atrial shunt	PW/CW Doppler	Subxiphoid long-axis/short-axis	No	Yes	Provides information on LA pressures	
Assessment of cardiac index (LVOT method)						
LVOT diameter measurement	2D	Parasternal long axis	No	Yes		
Velocity-time integral of PW in LVOT	PW Doppler	Apical five-chamber view	No	Yes	Dependent on alignment and correct point placement	
Assessment of pericardial effusion						
Measurement of pericardial effusion in diastole						
Respiratory variation on mitral/tricuspid inflow	2D	Different views	No	Yes		
	PW Doppler	Apical four-chamber	Yes if effusion	No		

CW, Continuous wave; LA, left atrial; LVOT, LV outflow tract; MV, mitral valve; PW, pulsed wave; RVOT, RV outflow tract; 3D, three-dimensional.

- d. Suspected persistent pulmonary hypertension in neonates
e. CDH

1.2.2. Indications for TNE With Focused Imaging (Focused TNE).

- a. Suspected effusion, either pericardial or pleural
b. Central line
c. Extracorporeal membrane oxygenation (ECMO) cannulation

Outside of these limited indications for focused imaging, we recommend performing a standard TNE for the other indications. For any indication, the first study must always be a full comprehensive

study, or if focused TNE is performed in emergency situations such as pericardial tamponade, this should be followed by a comprehensive study as soon as the patient has been hemodynamically stabilized. Standard TNE can be considered as a functional follow-up study for patients without structural heart disease. The frequency with which these studies can be performed in the NICU is outside the scope of the current writing group, as no good scientific data exist on its use.

Recommendations: If strong clinical suspicion of CHD or arrhythmia is present in a newborn, the infant should be

Table 2 Different types of studies and minimal training requirements for the performance of initial echocardiography in neonates

Study type	Training of performer	Training of interpreter	Additional imaging required
Suspicion of CHD (cyanosis, shock, congestive heart failure, murmur, arrhythmia, or abnormal pulses)			
Comprehensive	Core pediatric	Pediatric cardiologist	None
No suspicion of CHD	Minimum training of performer	Minimum training of interpreter	
Initial study			
Comprehensive	Core TNE or core pediatric	Advanced TNE or pediatric cardiologist	If read by advanced TNE, interpretation by pediatric cardiologist is strongly recommended within reasonable time
Focused TNE	Core TNE or core pediatric	Advanced TNE or pediatric cardiologist	Must be followed by comprehensive study
No CHD: follow-up study			
Standard TNE	Core TNE or core pediatric	Advanced TNE or pediatric cardiologist	
Focused TNE	Core TNE or core pediatric	Core TNE or pediatric cardiologist	

clinically assessed by a pediatric cardiologist, and comprehensive echocardiography should be performed and interpreted by a pediatric cardiologist. In hemodynamically unstable newborns without any clinical suspicion of CHD, the initial echocardiographic examination should always be a comprehensive study that can be performed by a core TNE person and initially interpreted by an advanced TNE person. However, it is strongly recommended that this initial study be read by a pediatric cardiologist within a reasonable time period. In the follow-up of children in whom CHD has been excluded, standard TNE can be performed as a targeted functional study for certain indications. Performance of these studies requires core training in TNE, and they should be interpreted by a person with advanced training in TNE. Focused TNE may be indicated for the evaluation and follow-up for a limited number of specific indications (effusions and lines). TNE should not be used in the follow-up of structural heart disease. See Table 2 for a summary of these recommendations.

2. TARGETED NEONATAL ECHOCARDIOGRAPHY: PRACTICAL ASPECTS

2.1. General Aspects of TNE

2.1.1. Technical and Safety Requirements for Performing TNE. All ultrasound systems used for imaging neonatal hearts should include two-dimensional (2D), M-mode, and full Doppler capabilities and should display a simultaneous electrocardiographic tracing. A range of multifrequency probes should be available so that the operator can select the best probe depending on the size of the infant, the available imaging windows, and the information that is to be obtained. High-frequency probes (8–12 MHz) should be available on the machines used in the NICU. System settings should be optimized to image neonates and VLBW infants. When performing examinations on

unstable infants, special precautions may need to be taken not to cause further cardiorespiratory instability in this population. These include but are not limited to the following actions:

1. Attention to skin integrity and prevention of infection: Infection prevention is of utmost importance, because preterm and term infants have an immature humoral immune system and a tendency toward poor skin integrity. Use of connecting cables from the monitoring equipment already in use to the ultrasound system, rather than placement of additional electrodes for electrocardiographic acquisition, should be considered whenever possible to minimize skin trauma. Infection prevention measures differ among neonatal units. Therefore, it is recommended that individualized practice guidelines for infection prevention during echocardiographic studies be developed and that practitioners of TNE be aware of and adhere to local guidelines.
2. Attention to maintenance of body temperature and neutral thermal environment: During the scan, the infant should be kept warm, and body temperature should be monitored. Warmed gel should be used to minimize the effect of direct skin cooling on the patient's body temperature. Opening of incubators should be kept at a minimum, with the use of portals designed for handling rather than unnecessary opening of the unit.
3. Cardiorespiratory monitoring: Premature and sick term neonates may become increasingly unstable with stimulation, and even light pressure on the abdomen and chest can influence chest expansion and venous return to the heart in small infants. Because the sonographer is primarily focused on image acquisition, assistance by additional staff members for monitoring cardiorespiratory stability during the scan may be useful. The duration of scanning should be minimized, particularly in critically ill infants.

Recommendations: The ultrasound systems used for TNE should be optimized for imaging the neonatal heart. When imaging a potentially unstable neonate or VLBW infant, special attention is required for the prevention of infection, maintenance of body temperature, and monitoring of cardiorespiratory function.

2.1.2. Guidelines for Image Acquisition in the NICU. The first echocardiographic study performed in a neonate should include a full morphologic and hemodynamic assessment of cardiac anatomy and

physiology using a segmental approach. American Society of Echocardiography (ASE) guidelines and standards for the performance of pediatric echocardiography have been published,²⁷ and these guidelines should be applied to neonatal scanning to ensure that no congenital defects are missed and that a full functional evaluation is obtained. On the basis of these guidelines, standardized echocardiography protocols should be developed and applied. Initial studies should include the different imaging windows (subxiphoid, parasternal, apical, and suprasternal) to complete the segmental analysis. A full assessment of cardiac structure should include imaging of atrial situs and position of the heart in the chest; systemic venous return; biatrial size and morphology; presence of an atrial communication; atrioventricular connection and function; biventricular morphology, size, and function; ventricular septal anatomy; structure and function of the ventriculoarterial connection; presence of a PDA; coronary artery anatomy; aortic arch and PA anatomy; pulmonary venous return; and presence of pericardial effusion.^{27,28} Full, standardized image acquisition during the initial scan should allow the pediatric cardiologist reviewing the study to rule out CHD. After this initial assessment, more targeted studies can be performed. The ASE has also published guidelines on quantification methods used in pediatric echocardiography.²⁹ We recommend following these quantification guidelines when performing TNE. For the quantification of chamber dimensions as well as the dimensions of cardiac structures, this implies reporting the measurements as Z scores when these are available.

2.1.3. Components of Standard TNE. Every standard targeted neonatal echocardiographic study should include

1. Evaluation of LV systolic function
2. Evaluation of LV diastolic function
3. Evaluation of RV function
4. Assessment of atrial-level shunt
5. Assessment of PDA
6. Evaluation of RV systolic pressure (RVSp) and PA pressures
7. Assessment of systemic blood flow
8. Assessment of pericardial fluid

The overall standard targeted neonatal echocardiographic examination and the suggested measurements are summarized in Table 1.

2.1.3a. Evaluation of LV Systolic Function.—Hemodynamic instability in the neonate can be caused by LV dysfunction, and assessment of LV systolic function is a key component of TNE. The pediatric quantification guidelines can be partially used in the neonatal population.

Several standard techniques for the evaluation of LV systolic function can be applied to neonates and preterm infants. Although subjective qualitative assessment of LV systolic function can easily be performed, it is prone to interobserver and intraobserver variability; therefore, quantitative measures are preferred. Most standard techniques for LV systolic functional assessment are based on the assessment of LV dimensions or LV size. LV dimensions should be measured on the basis of M-mode or 2D images obtained from the short-axis or long-axis views at the level just distal to the leaflet tips of the mitral valve at end-diastole.²⁹ M-mode imaging has higher temporal resolution, which can be an advantage in cases of high heart rates but low spatial resolution. Two-dimensional echocardiography has higher spatial but lower temporal resolution. Normal values for LV dimensions in term and preterm infants have been published.³⁰⁻³³ Increased LV end-diastolic dimensions suggest either volume loading (in the case of shunt lesions or valve regurgitation) or can be a sign of

LV dysfunction in the case of dilated cardiomyopathy. Increase in wall thickness can occur in the context of pressure loading or infiltrative disorders. Assessment of global LV systolic function is generally based on geometric quantification either linear by measuring percentage **shortening fraction** (SF) or volumetric by calculating **ejection fraction** (EF). The pediatric quantification recommendations suggest calculating SF from the measurement of LV dimensions obtained from 2D parasternal or subxiphoid short-axis views, with measurements averaged over three cardiac cycles.²⁹ In neonates and especially in preterm infants with high heart rates and with concomitant respiratory disease or lung interference, there might be an advantage to using M-mode measurements. In neonates, the use of SF (on 2D or M-mode imaging) can be limited by septal flattening or paradoxical motion of the ventricular septum due to the interaction between the hypertrophied and relatively high-pressure right ventricle and the left ventricle. In case of abnormal septal motion or ventricular geometry, measurement of LV EF using the biplane Simpson's and five-sixths area \times length methods are accepted alternatives. Poor imaging windows due to lung interference can be an important limitation. Current three-dimensional techniques for volumetric quantification in newborns have not been validated. When interpreting the SF and EF measurements, the influence of preload and afterload should be taken into account. This may be especially important when comparing measurements before and immediately after ductal closure.^{34,35} Removal of the left-to-right shunt reduces LV preload, and removal of the low-resistance pulmonary circulation increases mean arterial pressure and LV afterload. Therefore it is not surprising that LV SF and EF are reduced immediately after surgical duct ligation.^{34,35}

To overcome the problem of load dependency, alternative measurements of LV function may be considered. LV heart rate–corrected **mean velocity of circumferential fiber shortening** (mVCFc; calculated as SF/LV ejection time corrected for heart rate [ejection time/ $\sqrt{\text{RR interval}}$]) is less preload dependent than SF; as an ejection parameter, however, it is afterload dependent. This measurement is not recommended as a routine measurement in TNE but might provide additional information. If LV geometry is normal, there is a linear relationship between mVCFc and wall stress.^{36,37} This stress-velocity relationship can be used as a load-independent measure of myocardial contractility.³⁸ The clinical applicability of the stress-velocity relationship is not well studied in neonates and infants, with only limited research data available on the feasibility and reliability in a preterm population.³⁹ There is some evidence that mVCFc correlates with cardiac troponin levels in the early neonatal period,²⁸ but further data are needed. Newer functional echocardiographic techniques, including tissue Doppler methods and deformation imaging (strain and strain rate imaging), have recently been studied in neonates, but further validation and methodologic improvements are needed before they can be recommended for use in routine clinical practice.^{40,41}

Recommendations: Quantitative assessment of LV systolic function is an essential component of TNE. It requires the estimation of LV dimensions on the basis of M-mode or 2D measurements. LV end-diastolic dimension and septal and posterior wall thickness should be measured. On the basis of M-mode or 2D imaging, SF can be measured if there are no regional wall motion abnormalities and if septal motion is normal. In the case of wall motion abnormalities or abnormal septal motion, EF should be calculated using a biplane volumetric measurement (biplane Simpson's or five-sixths area \times length method). Optional techniques include mVCFc and wall stress measurements.

2.1.3b. Assessment of LV Diastolic or Combined Function.—In contrast to systolic dysfunction, the impact of diastolic dysfunction on neonatal hemodynamics is less clear and more difficult to define by echocardiography. In children and adults, evaluation of diastolic function relies on a combination of different measurements, including mitral inflow, pulmonary venous flow, and tissue velocity measurements of the mitral annulus.^{42,43} In infants, the available data on diastolic function assessment are limited and based mainly on analysis of mitral inflow patterns.⁴⁴⁻⁴⁷ In normal neonates, important changes in mitral inflow patterns are observed during the first days and weeks of life. During the first week of life, there is a gradual change from a fetal filling type with more dependence on filling during atrial contraction (A wave) toward a more mature filling pattern with higher early filling (E wave). This change is characterized by progressive increase in E-wave velocities, increase in the E/A ratio, and early filling fraction. In preterm infants, this change is more pronounced.⁴⁸ The difficulty when using the mitral inflow pattern and velocities in infants is that often the E and A waves are fused related to high heart rates. E-wave velocities are also sensitive to changes in preload, as in patients with PDAs with left-to-right shunting, because increased pulmonary flow increases left atrial pressures, resulting in increased E-wave velocities across the mitral valve. The use of pulmonary venous inflow is less affected by heart rate, but residual shunts at the atrial, ductal, or ventricular level will influence the pulmonary venous flow patterns.⁴⁹ Tissue Doppler velocities for the assessment of diastolic function have not been well explored in the neonatal population. Changes in myocardial velocities have been observed in both ventricles.^{50,51} Limited data are available on the effect of disease on tissue velocities, limiting its practical use in clinical practice. Further research is needed in the neonatal and infant populations.

Assessment of volume status and decisions on fluid replacement therapy are clinically challenging in term and preterm infants. However, preload is an important determinant of cardiac output in this population, and decreased preload can be an important reason for decreased cardiac output. Because of decreased myocardial compliance and the limited capacity of the neonatal heart to cope with increased preload, overaggressive fluid replacement therapy can be detrimental. Noninvasive assessment of filling status would be beneficial for neonatal management optimization. Because it is impossible to calculate circulatory volume, filling pressures are used as a substitute for preload. It is extremely difficult to noninvasively assess filling pressures and filling status in neonates using Doppler or tissue Doppler parameters. Inferior vena cava diameter or collapsibility and measurement of LV end-diastolic dimension have been suggested as surrogates of preload (volume status) in spontaneously breathing infants, but utility may be decreased in those maintained on positive-pressure ventilation. The use of measurements of chamber dimensions as an indicator of filling status must take into account additional factors, including cardiac function, heart rate, afterload, and RV-LV interaction. Therefore, although the assessment of intravascular volume status is considered to be integral part of the hemodynamic assessment, no clear recommendations for quantification can be made at present; qualitative assessment on the basis of inferior vena cava and cardiac chamber size by an experienced observer with knowledge of the clinical status of the neonate may be the most informative.

The **myocardial performance index** (MPI) has been proposed as a relatively simple way to assess combined systolic and diastolic performance of the heart simultaneously. MPI combines the isovolumic relaxation and contraction times, corrected for the ejection time (MPI = [isovolumic contraction time + isovolumic relaxation time]/

ejection time). Normal values in healthy neonates range from 0.25 to 0.38,⁵² with higher values obtained in the presence of abnormal prolongation of isovolumic time with respect to ejection time. The disadvantages of MPI are that it is nonspecific with respect to abnormalities of systolic versus diastolic function and it is influenced by preload and afterload changes.⁵³ This makes it of limited use in hemodynamically unstable infants. In addition, the reproducibility of MPI in infants with higher heart rates has not been well studied.

Recommendations: Although the assessment of diastolic function and filling pressures should ideally be part of TNE, currently data are inadequate to permit any recommendation regarding the use of echocardiographic data in the fluid management of neonates and infants. Thus, this should be considered an optional component of standard TNE until further data sustain its use.

2.1.3c. Evaluation of RV Function.—The evaluation of RV function should be an integral part of TNE, especially in patients with pulmonary hypertension, but it is difficult to perform, because there is no good quantitative parameter for the assessment of RV function.⁵⁴ For the estimation of **RV size**, the ASE pediatric quantification guidelines recommend the measurement of end-diastolic diameters at the basal and mid cavity levels, end-diastolic length, and end-diastolic and end-systolic planimeted areas in apical four-chamber views.²⁹ For the assessment of **RV function**, the pediatric guidelines recommend quantitative measurements such as fractional area change and tricuspid annular plane systolic excursion, but these measurements require further validation in the neonatal population. Because tricuspid annular plane systolic excursion is dependent on heart size, the normal values change with growth.⁵⁵ Tissue Doppler and RV strain measurements have great potential but need further validation.⁵⁴ In daily practice, qualitative assessment of RV function is often used, but this requires expertise, especially in the newborn and infant populations.

Recommendations: The assessment of RV size and function should be part of TNE. Qualitative visual assessment remains the most commonly used technique in routine clinical practice. Two-dimensional measurements, including tricuspid annular plane systolic excursion and fractional area change, can be used for quantitative serial follow-up.

2.1.3d. Assessment of Atrial-Level Shunt.—A key component of TNE is the assessment of intracardiac and extracardiac shunting and its contribution to hemodynamic or respiratory instability. Assessment of shunting across the atrial septum (patent foramen ovale or atrial septal defect) is therefore a required part of the TNE.

Atrial shunting can be best evaluated from subxiphoid long-axis or short-axis views of the atrial septum. Color Doppler imaging is used to view the atrial shunt and shunt direction. Because velocities can be low, it might be necessary to lower the color scale. For TNE, the most important aspect is shunt direction. Normally, left atrial pressures are higher compared with right atrial (RA) pressures and a left-to-right shunt is present, although a bidirectional shunt can still be normal in the neonatal period. Right-to-left shunting is abnormal and in the absence of structural heart disease suggests elevated right-sided filling pressures, often related to pulmonary hypertension and RV hypertrophy. Bidirectional and right-to-left shunting can contribute to reduced arterial oxygenation. Apart from shunt direction, pulsed-wave or continuous-wave Doppler can be used to assess the pressure gradient across the atrial septum. The calculation of the mean gradient gives information on the pressure difference between left and right atria and the difference in filling pressures.

Recommendations: TNE should include evaluation for the presence, size, and direction of atrial-level shunting.

2.1.3e. Assessment of PDA. — Assessment of ductal patency, determination of ductal shunt direction, and measurement of ductal pressure gradients are an important part of every targeted neonatal echocardiographic study.

1. Visualization of the PDA: The PDA can be visualized from the subxiphoid, modified left parasternal (“ductal”), and suprasternal windows in infants using standard high-frequency ultrasound probes. Keeping the head in the neutral position, or using a small shoulder roll to place the patient in a mildly extended and/or mildly left lateral decubitus position, may facilitate imaging of the PDA in its entirety. From the modified left parasternal and suprasternal windows, the distal aortic arch may be evaluated to exclude significant aortic coarctation. These views may be suboptimal in the presence of significant lung disease, pneumothorax, or pneumomediastinum. Accurate determination of aortic arch sidedness is very important, especially when surgical ligation is considered. Ductal size is usually measured by 2D imaging at the narrowest point, which usually is toward the pulmonary end of the duct, where it constricts first.
2. Assessment of shunt direction and gradient: Color Doppler mapping facilitates visualization of the PDA and allows evaluation of the direction of flow through the duct. Shunt direction reflects the difference between aortic and PA pressures and the relative resistance of the pulmonary and systemic circulation. It is crucial to have a simultaneous electrocardiographic tracing to identify systole and diastole. Normally a left-to-right shunt is present, which can cause diastolic retrograde flow in the abdominal aorta. The degree of diastolic flow reversal in the descending aorta provides information on the amount of diastolic left-to-right shunting through the duct.⁵⁶ If PA pressures are suprasystemic, right-to-left shunting will occur during systole and more rarely also in diastole if PA diastolic pressures exceed aortic diastolic pressures. Therefore, the duration of the right-to-left shunt and the presence or absence of holodiastolic retrograde flow by pulsed-wave Doppler in the descending aorta at the level of the diaphragm provide important information on the degree of pulmonary hypertension and can be assessed during follow-up and treatment. For gradient calculation, pulsed-wave or continuous-wave Doppler interrogation should be performed parallel to the direction of the ductal flow jet, as seen on color Doppler mapping. This Doppler gradient can then be used to assess PA pressures, by comparing the peak and mean Doppler gradients to simultaneous systemic arterial systolic and mean arterial blood pressures. The mean pressure is only relevant if there is no bidirectional shunt. Measurement of the peak instantaneous PDA gradients may require the use of continuous-wave Doppler, whereas information on the location of narrowing may be better evaluated by pulsed-wave Doppler.

Recommendations: TNE should determine the presence of a ductus arteriosus, the direction and characteristics of the shunt across the duct, and the pressure gradient between the aorta and the PA. The hemodynamic significance is further assessed by studying the degree of volume overload by measuring LV dimensions.

2.1.3f. Assessment of RVSp and PA Pressures. — Changes in pulmonary vascular resistance occur during the first weeks of life, so the assessment of PA pressures is an important component of every targeted neonatal echocardiography study. The most consistent technique to assess RVSp is measurement of the peak velocity of a tricuspid regurgitant jet.⁵⁷ In the absence of RV outflow tract obstruction, RVSp represents systolic PA pressure. An adequate spectral trace is necessary to avoid underestimation of the true gradient. To obtain the absolute value of RVSp, RA pressure should be added to the tricuspid regurgitant gradient measurement. RA pressure can be measured invasively in the NICU or can be estimated indirectly. For infants and children with no obvious RA dilatation, RA pressure of 5

mm Hg is assumed. On the basis of the velocity of the tricuspid regurgitant jet, RVSp can be calculated, using the simplified Bernoulli equation, as $RVSp = 4(\text{tricuspid regurgitant peak velocity (m/sec)})^2 + \text{RA pressure}$.

The pulmonary regurgitation jet may also be used to assess end-diastolic PA pressure. This also requires technical optimization of the Doppler signal to avoid underestimation and also requires estimation of RA pressures. It has also been shown that a good correlation exists between the peak diastolic velocity of the pulmonary regurgitant jet and the mean PA pressure measured during cardiac catheterization.⁵⁸ This is a useful relationship, because mean PA pressure is an important component in the estimation of pulmonary vascular resistance. As mentioned in the previous section, the shunt direction and Doppler-derived pressure gradient across a PDA can be used for assessment of PA pressures. It should be taken into account that for the assessment of pressure gradients across a PDA, application of the Bernoulli equation may be limited because of the long and sometimes tortuous nature of the duct.

Recommendations: Estimation of RVSp and PA pressures is an essential component of TNE and is based on Doppler measurements of tricuspid and pulmonary regurgitant jets. The Doppler-derived pressure gradient across a PDA can also be used for assessment of PA pressures.

2.1.3g. Assessment of Systemic Blood Flow. — Noninvasive quantitative echocardiographic measurement of cardiac output would be a useful adjunct to the clinical assessment in infants with hemodynamic instability. Unfortunately, no straightforward echocardiographic technique is available. The most commonly used technique is Doppler estimation of LV stroke volume. This is performed by multiplying the time-velocity integral (TVI) on the basis of a pulsed Doppler tracing in the LV outflow tract just below the aortic valve by the cross-sectional area at the site, usually by measurement of diameter and calculation of area as $\pi(D/2)^2$. LV output can then be calculated as

$$LV \text{ output (mL/min)} = TVI \text{ (cm)} \times \pi \times (D/2)^2 \text{ (cm}^2\text{)} \times \text{heart rate.}$$

This can then be indexed to body surface area to yield the LV cardiac index. Normal values for the LV cardiac index range from 1.7 to 3.5 L/min/m². It should be noted, however, that because the structures measured are small, and measurement errors are amplified by the exponent used in the area calculation, significant problems with reproducibility may be encountered. Good standardization of the method is required (alignment with flow in the LV outflow tract, placement of sample volume, and measurement of LV outflow tract diameter). Trends in TVI can be used to indicate changes in cardiac output, even if an absolute value is not calculated. Unfortunately, the presence of a PDA renders this method of assessment of systemic flow useless.

As a substitute for the LV output Doppler method, investigators have proposed measuring superior vena cava (SVC) flow as a method for assessing systemic flow.⁵⁹ The TVI is measured from a subxiphoid trace, and a high suprasternal view is used to measure the diameter of the SVC using M-mode or 2D imaging. These measurements are averaged over 5 to 10 beats to account for respiratory variability. Although the presence of critically low (<40 mL/kg/min) SVC blood flow during the first postnatal day is an independent risk factor for poor long-term neurodevelopmental outcomes in very preterm neonates,¹⁴ the utility of SVC blood flow to determine the timing and type of intervention in this patient population is not known. In

addition, this method has several significant limitations. First, its intra-observer and interobserver variability can be significant because of difficulties with the proper alignment of SVC flows and the measurement of SVC dimensions. Second, SVC flow does not directly reflect systemic output and is influenced by intrathoracic pressures and atrial pressures. The use of SVC flow requires further validation before being incorporated into standard clinical practice.

Recommendations: TNE can include a measurement of cardiac index using the LV output method. Both acquisition and analysis need to be well standardized and optimized to guarantee maximal reproducibility. In the presence of a PDA, LV output measurement does not reflect systemic blood flow. The SVC method may be used to follow changes in cardiac output when a PDA is present, but caution is required when interpreting the findings.

2.1.3h. Assessment of Pericardial Fluid.—Hemodynamic instability in a term or preterm infant can be caused by the presence of a pericardial effusion. Echocardiography is an ideal technique to detect the presence of pericardial fluid, assess its hemodynamic significance, and guide pericardiocentesis. Subxiphoid coronal imaging may be sufficient to establish the diagnosis. For pericardial effusions not associated with clinical tamponade, it is suggested to consult with a pediatric cardiologist, pediatric surgeon, or pediatric cardiothoracic surgeon to discuss medical or interventional therapy. Large volumes of pericardial fluid may be well tolerated by the infant when the fluid accumulated slowly or was already present in utero. Conversely, a small but rapidly enlarging pericardial effusion may cause cardiac tamponade. Echocardiographic evidence of RA collapse at the onset of systole and RV collapse in diastole are signs of hemodynamic compromise.⁶⁰ Distension of the inferior vena cava may also indicate elevation of central venous pressure but is nonspecific. Spectral Doppler flow studies have shown marked respiratory variation in transvalvular flow velocities in tamponade, but these Doppler waveforms may be difficult to interpret in mechanically ventilated infants. Normal inspiratory variation in peak tricuspid E-wave velocity may be up to 25% and mitral up to 10% in spontaneously breathing infants.⁶¹ Doppler waveform tracing may not be useful for assessing cardiac tamponade as E and A waves fuse because of high heart rates in neonates. The involvement of a pediatric cardiologist is strongly recommended for pericardial effusion assessment, because the interpretation of detailed functional and hemodynamic information requires a high level of expertise in echocardiography.

Serial examinations of pericardial effusions can provide semiquantitative and qualitative information. These examinations should follow similar protocols and use similar imaging planes so that quantitative comparisons can be made.

Recommendations: Generally, a pericardial effusion is measured from the epicardial surface of the heart to its maximum dimension on 2D imaging at end-diastole. Although there is no recognized standard for the measurement of effusions, measurement of the maximum dimension at end-diastole with identification of the location is recommended. For serial effusion assessment, consistent image projections should be used.

2.2. TNE for Specific Neonatal Conditions

2.2.1. Suspected PDA. Definition and Scope of the Problem.—Although essential for the normal fetal circulation, persistent ductal

patency may have significant deleterious effects in preterm or ill term infants. PDAs are found in about half of babies born at <29 weeks of gestation and/or weighing <800 g^{62,63} and is therefore a common problem encountered in the NICU. Failure of ductal closure, coinciding with the normal postpartum fall in pulmonary vascular resistance, results in a left-to-right ductal shunt. The consequences may include pulmonary overcirculation and/or systemic hypoperfusion, both of which may be associated with significant morbidity. The clinical impact is dependent on the magnitude of the shunt, comorbid conditions, and the ability of the neonate to initiate compensatory mechanisms. The increased pulmonary flow, and accumulation of interstitial fluid secondary to the large ductal shunt, contributes to decreased lung compliance.⁶⁴ The cumulative effects of increasing or prolonged ventilator requirements may increase the risk for chronic lung disease.^{65,66} Preterm infants have a limited capacity for increasing stroke volume in response to increased volume load on the LV myocardium. A large left-to-right shunt increases LV filling pressures, and this might be more pronounced in preterm infants because LV compliance might be lower. The inadequate stroke volume response with the “steal” of blood from the systemic circulation contributes to a decreased systemic perfusion. A large ductus results in significant diastolic shunting with retrograde diastolic abdominal aortic flow that influences renal and intestinal perfusion. Low diastolic aortic pressure can further compromise coronary perfusion, which is already influenced by increased LV diastolic pressures. All of these hemodynamic complications of a large PDA create significant potential morbidity, including renal insufficiency, necrotizing enterocolitis, intraventricular hemorrhage, and myocardial ischemia.^{67,68}

Indications for Echocardiography.—If a PDA is suspected on clinical grounds, echocardiography may be indicated. The first study should always be a comprehensive echocardiographic study to exclude associated CHD. This study can be performed by a core TNE-trained person and interpreted by an advanced TNE physician. It is highly recommended that this initial study be reviewed by a pediatric cardiologist. TNE can subsequently be performed to follow either spontaneous closure of the ductus or to assess the effect of therapy on closure.

Imaging Techniques.—The standard full targeted neonatal echocardiographic imaging protocol should be performed in the follow-up of patients with suspected PDA, including the different components.

Guidance of Clinical Decision Making.—Assessment of the hemodynamic significance of a PDA can be performed by combining different echocardiographic measurements.⁶⁹ These include the following:

Ductal size: A minimal ductal diameter >1.5 to 2.0 mm is generally considered a hemodynamically significant ductus.

Transductal flow: The direction and volume of the transductal shunt is dependent on the transductal (pulmonary vs systemic) gradient, which is influenced by the difference between the systemic and pulmonary vascular resistance and by the ductal size. Assessing shunt direction and gradient is important.

Left-heart size: The quantification of left-heart size reflects the chronic effect of LV volume loading due to the left-to-right shunt through the ductus. LV end-diastolic dimension can be measured on the basis of M-mode or 2D measurements. A dilated left ventricle indicates the presence of a large shunt. The left atrial/aorta ratio can be used as an indicator of shunt size, with a ratio > 1.4 indicating a significant left-to-right shunt.

Mitral inflow: In the presence of a ductal left-to-right shunt, pulmonary venous flow increases, and the rise in left atrial pressure will result in increased transmitral flow (in the absence of a significant atrial left-to-right shunt). Thus, an increase in early mitral inflow velocities can reflect the amount of ductal shunting, assuming the absence of an atrial shunt, mitral valve stenosis, or significant mitral regurgitation. In neonates with large left-to-right shunts, the increased early transmitral flow can result in an E/A ratio > 1.0 . The tracing reverts to the typical preterm E/A ratio < 1.0 after PDA ligation. However, the measurement is of limited usefulness in isolation and is unlikely to be valuable in the presence of a patent foramen ovale.

Ductal "steal": A large ductus with left-to-right shunting will result in significant retrograde flow from the thoracic and abdominal aorta. The amount of retrograde diastolic flow may be $> 50\%$ of total aortic flow in neonates with a large ductus. Several indices based on pulmonary, aortic, and peripheral artery flow velocity patterns have been proposed as objective methods in assessment of the magnitude of ductal steal. However, the utility of these indices to predict outcomes needs further validation. At present, only qualitative assessment of the descending aortic pulsed-wave Doppler tracing (for the presence or absence of retrograde diastolic flow) is recommended, because the presence of holodiastolic retrograde flow suggests at least a moderate amount of left-to-right ductal shunting.

Early after ductus ligation, some preterm infants become hemodynamically unstable because of acute changes in preload and afterload.^{34,35} TNE can be helpful in determining the underlying mechanism.

Recommendations: In every neonate with a clinical suspicion of a PDA, a comprehensive echocardiographic study should be performed before medical or surgical treatment to exclude ductal-dependent congenital heart defects and define arch sidedness. Subsequent standard TNE helps in defining the hemodynamic significance of the PDA and is useful in clinical follow-up documenting spontaneous closure or the effect of treatment. In preterm infants with hemodynamic instability after ductus ligation, TNE can be helpful in identifying the cause.

2.2.2. Perinatal Asphyxia. Definition and Scope of the Problem.—Hypoxic-ischemic encephalopathy is defined by persistent low Apgar scores (0–3) for > 5 min and profound metabolic or mixed acidosis (pH < 7.0) on an umbilical cord blood gas. Neonatal neurologic sequelae (e.g., seizures, coma) and multiple-organ involvement is a relatively common occurrence with an estimated incidence of 0.5% to 2% of live births despite modern intrapartum monitoring. Birth asphyxia is the cause of 23% of all neonatal deaths worldwide. In recent years, there have been several randomized controlled trials investigating the impact of mild therapeutic hypothermia in reducing both morbidity and mortality in these infants.

Asphyxia has been shown in several studies to result in clinically significant persistent pulmonary hypertension (see below) and in myocardial involvement including clinical, electrocardiographic, echocardiographic, and biochemical changes consistent with ischemic damage in up to two thirds of affected infants.⁷⁰⁻⁷² Decreased cardiac output,⁷²⁻⁷⁴ as a direct result of insult to the myocardium, may significantly complicate perinatal management and contribute to morbidity and mortality.⁷⁵ Additionally, therapeutic interventions, including whole-body hypothermia, selective head cooling, and the use of medications such as phenobarbital and midazolam can have additional hemodynamic effects. Therapeutic hypothermia alters systemic and/or pulmonary hemodynamics through increasing vascular resis-

tance and lowering resting heart rate, which reduces cardiac output. Therefore, assessment and appropriate management of cardiovascular manifestations of asphyxia and treatment, particularly in the setting of clinically evident low cardiac output state, may be helpful to clinicians caring for these patients. TNE may be useful, as data suggest that approximately 30% to 50% of infants with perinatal asphyxia exhibit echocardiographic evidence of ventricular dysfunction, suggested by decreased LV fractional shortening, decreased qualitative RV function, decreased peak systolic annular tissue Doppler velocities, and increased MPI.^{72,76,77}

Indications for Echocardiography.—All neonates with clinical evidence of asphyxia should be evaluated for myocardial injury by clinical hemodynamic evaluation and the use of biomarkers for myocardial damage (e.g., troponin). If there is no clinical evidence of cardiovascular compromise and no elevation of biomarkers, echocardiography is unlikely to be useful. If there are clinical manifestations suggesting poor end-organ perfusion, comprehensive echocardiography may be helpful for identifying possible underlying structural or functional heart disease. If abnormalities are detected, standard TNE can be used to monitor functional recovery and the hemodynamic effects of treatment.

Imaging Techniques.—The initial study should be a comprehensive study. Follow-up studies should use the standard targeted neonatal echocardiographic imaging protocol.

Guidance of Clinical Decision Making.—*Evaluating the effect of therapy:* Early (< 6 hours of life) mild to moderate hypothermia improves survival without disability in moderately to severely asphyxiated infants.⁷⁸⁻⁸² Early experience with therapeutic hypothermia reported hypotension and hypertension, vasodilation, bradycardia, and low cardiac output.⁸³ Several large randomized controlled trials of both whole-body hypothermia and selective head cooling could not demonstrate significant differences between cooled infants and normothermic asphyxiated infants in the degree of hypotension and the need for volume and inotropic support. Although careful mild hypothermia does not seem to decrease blood pressure or impair cardiac function, asphyxia itself may have an effect on both, producing hypotension and poor cardiac output requiring the use of combinations of inotropes, vasodilators, and volume replacement. During the cooling and rewarming phases, the assessment of hemodynamics may be challenging, and there may be a place for the use of TNE in optimizing hemodynamic management. Prospective studies are required to further define normative data and therapeutic thresholds during the cooling and rewarming phases.

Recommendations: Comprehensive echocardiography is indicated in neonates with perinatal asphyxia with clinical or biochemical signs of cardiovascular compromise. Standard TNE, including the assessment of LV function, pulmonary hypertension, and ductal shunting, can help in optimizing therapy. The role of TNE in monitoring the cooling and rewarming phases of hypothermia needs further investigation.

2.2.3. Neonatal Hypotension. Definition and Scope of the Problem.—There is increasing recognition in the neonatal literature that blood pressure, as the dependent variable defining organ perfusion, is only one of the end points of interest.⁸⁴ The use of blood pressure monitoring is based on an assumed proportionality between blood pressure and systemic blood flow.⁸⁵ The relationship between hypotension, cerebral perfusion, and adverse neurodevelopmental

sequelae is open to question. First, the preterm cerebral circulation has been proposed to become pressure passive below a critical blood pressure.^{86,87} Although there is evidence suggesting that neonates with hypotension and impaired cerebral oxygenation are at increased risk for brain injury,⁸⁸ other investigators have demonstrated a lack of relationship between blood pressure and cerebral blood flow.⁸⁹ Second, although some studies have suggested a relationship between adverse neurologic consequences and systemic hypotension,⁹⁰⁻⁹³ recent studies have failed to demonstrate any positive association between blood pressure and adverse neurologic outcomes.⁹⁴⁻¹⁰³ This discrepancy suggests that the association is much more complex than any direct effect of blood pressure on cerebral blood flow and may represent the fact that hypotension is but an epiphenomenon and a marker of possible injury. In addition to blood pressure, other cardiovascular parameters, such as heart rate and capillary refill time, can be monitored. However, these are poorly validated and nonspecific measures of systemic flow.

Hemodynamic assessment using echocardiography has the potential of first identifying structural heart disease as an underlying cause, and when the heart is anatomically normal, it can provide insight into the underlying physiology of hypotension. This includes the assessment of LV function, pulmonary hypertension, and ductal patency. First a comprehensive echocardiographic examination needs to be performed in a child with hypotension. When structural heart disease has been excluded, follow-up standard TNE can be used in the care of the hypotensive preterm neonate. This is currently considered an important area for research, and current data are still too limited to promote serial TNE as a standard of care for this population.

Indications for Echocardiography.—In any neonate presenting with signs of hypotension, CHD needs to be excluded by comprehensive echocardiography. In the absence of structural heart disease, standard TNE can be used in the management of persistent hypotension, because it can be helpful in identifying the underlying mechanisms.

Guidance of Clinical Decision Making.—Traditionally, blood pressure–based assessment and intervention for neonates with hypotension and clinical shock states fail to address the importance of providing adequate systemic perfusion. Initial clinical experience suggests that TNE could be useful in guiding therapeutic decisions such as fluid administration and the use of inotropic and vasoactive agents.

Recommendations: TNE might provide useful additional information for defining the underlying causes and guiding medical management in the follow-up of hypotensive neonates in whom structural heart disease has been ruled out. Further study regarding the role and use of standard TNE for this indication is required before it can be considered a standard of care in the NICU for this indication.

2.2.4. Suspected Persistent Pulmonary Hypertension of the Newborn (PPHN). Definition and Scope of the Problem.—

Persistent PPHN is a common problem, with an incidence of approximately 1 in 500 live births¹⁰⁴ and mortality of up to 20%.¹⁰⁵ It may be associated with perinatal asphyxia and meconium aspiration with pulmonary parenchymal disease. It is defined by a failure of the normal postnatal fall in pulmonary vascular resistance leading to impaired oxygenation, RV failure, and pulmonary-to-systemic shunting. Secondary consequences include low cardiac output because of left-heart preload compromise, itself a result of decreased pulmonary venous return and the mechanical effects of a pressure/volume-loaded right ventricle on left-heart filling. The right heart is functioning at higher pressure and volume, which can cause RV hypertrophy, di-

lation, and failure in severe cases. Inadequate ventilation and decreased LV output can lead to respiratory and metabolic acidosis, which in turn causes myocardial dysfunction, worsening pulmonary hypertension, progressive hypoxia, systemic hypoperfusion, and hypotension. This vicious cycle can then worsen to the point that cardiopulmonary or pulmonary bypass with venoarterial or venovenous ECMO becomes necessary.

Pulmonary hypertension can also be seen in premature infants. Pulmonary hypertension in this setting is characterized by an abnormal vascular bed that has increased muscularization of vascular smooth muscle cells, distal extension of muscle into nonmuscularized vessels, arrested vascular growth, and increased collagen and elastin deposition in the medial arterial layers. These changes are also seen in preterm infants with advanced bronchopulmonary dysplasia leading to chronic pulmonary hypertension, which in extreme cases may progress to cor pulmonale by the first or second year of life. Factors contributing to this pathologic pulmonary vascular remodeling include oxygen toxicity, hypoxemia, and mechanical ventilation.¹⁰⁶

Indications for Echocardiography.—Echocardiography should be considered in any premature infant or neonate with clinically suspected pulmonary hypertension. The first comprehensive echocardiographic study should be aimed at excluding structural heart defects associated with pulmonary hypertension (especially total abnormal pulmonary venous return or left-sided heart problems). For pulmonary hypertension with no structural heart disease, standard follow-up using TNE can be indicated to assess the effect of treatment on PA pressures, RV function, ductal patency, and shunt direction at the ductal and atrial levels.

Imaging Techniques and Guidance of Clinical Decision Making.—Echocardiography in the setting of PPHN may be challenging because of the presence of coexisting lung disease and mechanical ventilation, but imaging the heart from the multiple standard views should be attempted. Serial evaluations may be helpful in documenting response to therapy, particularly when the clinical response is equivocal or difficult to appreciate because of the complexity of the medical situation.

Recommendations: In every child with suspected pulmonary hypertension, comprehensive echocardiography should be performed to rule out structural heart disease. In neonates with PPHN, TNE allows assessment of the effect of treatment on PA pressures, RV function, and shunt direction at the atrial and ductal levels.

2.2.5. CDH. Definition and Scope of the Problem.—Compared with persistent PPHN, CDH is less common, occurring between in 1 in 2,500 to 1 in 4,000 live births.¹⁰⁷ The primary problem stems from the herniation of abdominal organs into the chest cavity during early fetal life, leading to lung hypoplasia and maldevelopment of the pulmonary vasculature and, in some cases, cardiac ventricular hypoplasia.¹⁰⁸ In contrast to neonates with PPHN who have normal gross pulmonary anatomy but abnormal vascular reactivity with or without remodeling of the pulmonary vascular architecture, patients with CDH typically have unilateral PA hypoplasia, ipsilateral to the hypoplastic lung, although in some cases, the contralateral lung and its vasculature may also be affected. Abnormal pulmonary flow in utero and mechanical distortion of the thoracic organs can in turn lead to decreased LV filling and relative LV hypoplasia. The exact mechanisms for these effects remain unclear,¹⁰⁸ and the hypoplasia noted in utero will often resolve postnatally.¹⁰⁹ Clinically, pulmonary hypertension is the hallmark of CDH, with similar secondary effects such as low

cardiac output, inadequate ventilation, and cardiorespiratory collapse necessitating ECMO support.

Indications for Echocardiography.—All infants with CDH should undergo a comprehensive echocardiographic assessment of cardiac anatomy early in the course of postnatal management. Early diagnosis of CHD is mandated in the setting of CDH, which has a 10% to 18% incidence of associated CHD ranging from persisting atrial communications (patent foramen ovale and atrial septal defect) to more complex lesions, which impart a significantly higher mortality.^{108,110,111} More severe forms of CHD, especially those involving functionally single ventricles, are associated with such a poor prognosis that aggressive management may not be justified.¹⁰⁸ Once CHD has been excluded, standard targeted neonatal echocardiographic studies can be used in follow-up. In CDH, TNE with focused imaging can also be used for checking line placement, which may be particularly difficult to assess radiographically because of distorted thoracic anatomy.

Guidance of Clinical Decision Making.—Before surgical repair, a comprehensive echocardiographic study should exclude associated CHD and include a baseline assessment of cardiac function and PA pressures. Subsequent preoperative standard TNE studies should focus on the assessment of pulmonary hypertension, right and LV function, and the presence and direction of ductal and atrial shunting. Although the ductus arteriosus is closing, it is essential to image the aortic arch to exclude the development of a juxtaductal coarctation. After surgical repair, the focus of full TNE will be on pulmonary hypertension and cardiac function but should also include a more detailed assessment of branch pulmonary anatomy and pulmonary venous return. The presence of a pleural effusion on the side of the repair can be easily assessed. If central lines are still present, confirmation of their position should be performed.

Recommendations: Every child with a CDH should undergo a comprehensive echocardiographic study to rule out CHD and to assess the severity of PPHN. Standard TNE can be used to assess the effect of treatment on PA pressures, RV function, and shunt direction at the atrial and ductal levels. Focused TNE can be useful for line placement or in case of ECMO.

2.2.6. Suspected Effusion. Scope of the Problem and Indications for Echocardiography.—Pericardial and pleural effusions in preterm or ill term infants in the NICU may have a variety of etiologies, including infectious, neoplastic, obstructive (usually of the lymphatic system), idiopathic, and iatrogenic (due to perforation associated with indwelling lines or catheters or extravasation of intravenous fluids from an erosion of an indwelling catheter). The use of focused TNE in an acutely hemodynamically unstable neonate, particularly one with electromechanical dissociation, may be lifesaving if cardiac tamponade is present. At the same time, echocardiography can be used to guide pericardiocentesis. After the child has been hemodynamically stabilized, the cause of the pericardial effusion needs to be established, and this requires the performance of comprehensive echocardiography to rule out underlying heart disease such as pericardial tumors, pericarditis, and myocarditis.

Imaging Techniques and Guidance of Clinical Decision Making.—*Pericardial effusion:* See section 2.1.3h.

Pleural effusion: Echocardiography may be of use in detecting the presence of pleural effusions that are not evident on supine chest x-rays; however, it is of limited utility in determining the volume of fluid in the pleural space. If pleural effusions are detected (usually

on subxiphoid axial, coronal, and sagittal 2D imaging), clinical and radiographic correlations are suggested.

Recommendations: TNE with focused imaging is a useful technique for diagnosing pericardial and pleural effusions, assessing their hemodynamic impact, and guiding interventional procedures. For infants with pericardial effusions, comprehensive echocardiography must be performed after hemodynamic stabilization. Focused TNE can also be helpful in monitoring treatment.

2.2.7. Central Line Placement. Definition and Scope of the Problem.—Many sick neonates (preterm or full term) require invasive intravascular circulatory monitoring and treatment via central venous and arterial vessels. Because of immaturity of the thrombogenic and fibrinolytic pathways, neonates are at an increased risk for the development of arterial or venous thrombosis in the presence of an indwelling vascular catheter.^{112,113} In critically ill children, the risk for deep thrombosis or infection is reported to be relatively low (2%–3% and 6%–7%, respectively),^{114,115} but in VLBW neonates (<1,500 g) with central venous line catheters, the reported frequency of thrombosis is about 10%, and catheter infections occur in up to 20% of infants.¹¹⁶ Other studies have estimated the incidence of umbilical vein catheter-related thromboembolic events to be approximately 13%,¹¹⁷ while autopsy studies have estimated that 20% to 65% of infants who die with umbilical vein catheter in situ have evidence of thromboembolic events.¹¹⁸ The insertion of catheters and vascular cannulation is associated with a significant risk for vascular, cardiac, or pericardial injury and infection, including endocarditis,^{119–121} and mycotic aneurysm.

It has been well documented that detailed 2D echocardiography with Doppler assessment detects a much higher frequency of thrombotic complications if routinely performed in all neonates with central catheters.¹²² However, the clinical impact of performing scans to look for “silent” thrombi is uncertain.

Before each scan, the examiner should obtain information about vascular access points, the type of catheter used, and its course. At least one study has demonstrated poor performance of routine echocardiography in the detection of vascular thrombosis associated with central venous lines in the upper-body venous system in children, with sensitivity of only 4% compared with specific vascular ultrasound techniques (which had sensitivity of 88%). Therefore, it is recommended that in case of suspected thrombus, a specific vascular study with special focus on identifying thrombi be performed. In some cases, it can be difficult to localize the tip of the catheter. The use of a small amount of agitated saline injected through the catheter during the echocardiographic exam may be helpful in identifying the line tip.¹²³ For catheters that are radiopaque, the x-ray findings may also be helpful.

Indications for TNE With Focused Imaging.—Focused TNE may be useful in identifying both appropriate catheter position and complications such as thrombosis, infection, abnormal position, line fracture, embolization and vessel occlusion. The identification of vegetations is a major criterion for diagnosing infective endocarditis, but the sensitivity of echocardiography has not been well established in neonates. Therefore, this type of study should be performed by a fully trained pediatric echocardiographer as the evaluation for endocarditis goes beyond the classic indications for TNE.

Imaging Techniques.—*Umbilical arterial catheter:* The catheter may be seen in the subxiphoid views. The best view is the subxiphoid long-axis view below and above the diaphragm. The position of the

catheter tip should be identified. The tip should be without thrombus and the flow in the aorta should be unobstructed, with laminar flow on color flow mapping and with antegrade systolic peak pulse wave of velocity < 1 m/sec on pulsed Doppler.

Umbilical venous catheter: The locations of the hepatic segment of the inferior vena cava, hepatic vein, and ductus venosus are determined from the subxiphoid long-axis view below and above the diaphragm. The tip of the catheter should be without thrombus, and the inferior vena cava and hepatic veins should be unobstructed with laminar flow on color flow mapping. Phasic respiratory variation on pulsed Doppler interrogation should be seen in spontaneously breathing children.

Central venous catheters: For catheters inserted into femoral or sphenous vein, the hepatic segment of the inferior vena cava, the hepatic vein, and the junction of the inferior vena cava with the right atrium are imaged using the subxiphoid long-axis sweeps below and above the diaphragm. Imaging and functional assessment are similar to the catheter placed through the umbilical vein. For catheters placed into the SVC, the proximal SVC connection with the right atrium is visualized from the subxiphoid "bicaaval" view, from the high right parasternal view, and from suprasternal views. The suprasternal coronal or short-axis plane is used to visualize the left innominate vein and its connection to the SVC. The presence of a left SVC should be excluded by suprasternal views with leftward angulation. In the same view, blood return from left subclavian vein can be detected by color flow mapping. Suprasternal coronal and sagittal views tilted rightward are used to determine the connection of the right SVC with the right atrium. The catheter tip should be without thrombus, and all systemic veins patent with laminar flow on color flow mapping, with phasic respiratory variation on pulsed Doppler interrogation in spontaneously breathing children.

Recommendations: Focused TNE can be used for identifying catheter tip position after line placement and potential complications such as line thrombosis or infection. Echocardiography to rule out vegetations should be performed or interpreted by a pediatric cardiologist.

2.2.8. ECMO Cannulation. Definition and Scope of the Problem.—Venovenous or venoarterial ECMO is an important treatment tool in the management of near-term and term neonates with severe hypoxemic respiratory failure, circulatory failure, or both. More than 19,000 patients in the registry of the Extracorporeal Life Support Organization are under the category of neonatal respiratory failure, with 77% overall survival reported to discharge.¹²⁴ In the present document, we only discuss ECMO for respiratory failure where TNE with focused imaging can be useful for assessing cannula position. Discussion of the use of echocardiography in the context of cardiovascular ECMO is beyond the scope of this document.

Indications for Echocardiography.—Proper cannula position is essential for optimal function of the ECMO circuit; therefore, accurate determination of cannula position is essential. Recent literature has suggested that echocardiography is more accurate than chest radiography for determining cannula position, and there was higher (24% vs 7%) need for reintervention when cannula position was actively screened by echocardiography.¹²⁵⁻¹²⁷ The use of intraoperative imaging during cannula insertion significantly reduces the rate of repositioning from 18% to 3%.¹²⁸ TNE with focused imaging is therefore indicated after cannula placement and when problems with the function of the cannula are suspected. In addition to the assessment of cannula position, echocardiography can be indicated to assess cardiac function, the presence of an atrial communication, and ductal shunting.

Imaging Techniques.—TNE with focused imaging is performed immediately after cannulation is finished, the cannulae are fixed, and the patient placed back into the "resting" position. Scanning is generally performed in sterile or semisterile environment, though protocols may vary by institution. Neonates may be cannulated via the neck vessels (internal jugular for venovenous, internal jugular and internal carotid for venoarterial) or via sternotomy directly (RA and aortic). Only neck cannulation is discussed here.

Venous cannulation: The venous cannula is placed percutaneously or via surgical cut-down in the right internal jugular vein and through the SVC into the right atrium. Complications can include cannula misplacement or dislodgment (in the azygous vein, abutting the atrial septum, occluding the coronary sinus, protruding through the tricuspid valve, or penetrating into the inferior vena cava), intrapericardial penetration, thrombosis, and infection. The tip of the venous cannula is visualized from subxiphoid views, four-chamber views, parasternal right inflow views, and modified short-axis views. Left suprasternal coronal or short-axis planes tilted rightward (not interfering with cannula insertion area) with color flow mapping are used to determine the patency of the SVC. The tip of the cannula with metallic and plastic component separation should be identified. Color flow aliasing, caused by flow acceleration at the site of perforations, will help correctly identify the catheter tip, which should be without thrombus and separate from surrounding structures. The flow within the cannula is monophasic and without respiratory variation on pulsed-wave Doppler interrogation. Proper function of the cannula can be demonstrated by a relatively small right atrium, a nondilated inferior vena cava, and flow on color flow mapping diverted into the cannula from the inferior vena cava as well as from left atrium (through an atrial communication). Reevaluation of cannula position should be performed whenever there is evidence of inadequate drainage despite appropriate sized venous cannulae. Inadvertent cannulation of the azygous vein should be suspected and excluded in cases of CDH or when there is significant compression or absence of the inferior vena cava resulting in dilation of the azygous vein.¹²⁹

Aortic cannulation: The aortic cannula is inserted into the right carotid artery with the tip ideally placed high in the ascending aorta. Complications may include cannula misplacement (deep in the aortic root, in the left ventricle through the aortic valve, or intrapericardial perforation), aortic regurgitation, aortic wall dissection, and cannula infection. Parasternal long-axis and suprasternal aortic arch views are used to ensure that the arterial cannula is well away from the aortic valve and sinuses of Valsalva. Color flow mapping with aliasing helps identify the tip of the cannula and the direction of the jet, which dominantly supplies the descending aorta. Abnormal aortic cannula position should be suspected when there is evidence of inadequate oxygen delivery (low mixed venous saturations, poor perfusion, or hypotension) despite seemingly adequate circuit flow.

Recommendations: Focused TNE with focused imaging is a useful tool for neonates on ECMO, especially for evaluation of cannula position. When assessing PA pressure and ventricular performance, the impact of venoarterial ECMO on ventricular filling must be considered. Every child on ECMO must undergo comprehensive echocardiography.

3. TRAINING AND ACCREDITATION IN TARGETED NEONATAL ECHOCARDIOGRAPHY

Training recommendations for pediatric echocardiography, endorsed by European and North American professional organizations, have

Table 3 Summary of training requirements

	Training level			
	Core/basic	Advanced	Expert	Accreditation
ACC/AHA/ASE pediatric echocardiography				
Number of studies	150 studies performed 150 studies reviewed	200 additional studies performed 200 additional reviewed	Not defined	None
Duration of training	4–6 mo	Additional 9–12 mo		
AEPC pediatric echocardiography				
Number of studies	250 studies performed	750 studies performed in total	2,000 studies performed in total	EAE congenital echocardiography exam
Duration of training	Not defined	1 y	Not defined	
TNE guidelines				
Number of studies	150 studies reviewed 150 studies performed	150 additional studies reviewed 150 additional studies performed	Not defined	None
Duration of training	4–6 mo	Additional 4–6 mo	Not defined	None

been published.^{25,26} Because the recommendations of the current writing group on TNE should be interpreted in the context of the existing recommendations for training in pediatric echocardiography and other forms of more specialized or focused echocardiography, we first provide an overview of the published training guidelines (Table 3).

3.1. Overview of Existing Training Guidelines

3.1.1. US Pediatric Echocardiographic Guidelines. The US training guidelines for pediatric echocardiography were published in 2005, supported by the American College of Cardiology, the American Heart Association, and the American Academy of Pediatrics (AAP).²⁶ The guidelines were also endorsed by the ASE and the Society of Pediatric Echocardiography. These guidelines distinguish between two levels of expertise: core and advanced levels.

Core Level.—The core level is defined as “the ability to perform and interpret transthoracic echocardiography in normal infants, children and adolescents, and in those with childhood heart disease, with consultation as needed.” It requires a basic understanding of the physical principles of ultrasound and clinical ultrasound equipment. The core level does not include the skills to perform and interpret transesophageal echocardiography (TEE) and fetal echocardiography. For the core level, **4 to 6 months** of dedicated training in a pediatric echocardiography laboratory is required. The echocardiographer should perform and interpret ≥ 150 pediatric echocardiographic studies, of which ≥ 50 should be on children aged < 1 year. Additionally, 150 echocardiograms should be reviewed by the trainee.

Advanced Level.—The advanced level is defined as “special expertise in performance and interpretation of transthoracic echocardiography in all forms of congenital and acquired pediatric heart disease, including the adult with CHD, enabling the practitioner to function independently.” This also includes the expertise to perform TEE and fetal echocardiography. By completing this level of training, the echocardiographer should be able to supervise

the training and performance of sonographers, fellows, and other practitioners. In addition to the training requirements described for core-level training, the advanced level requires **an additional 9 to 12 months** of dedicated training in echocardiography. During this period, the trainee should perform and interpret 200 studies (50 on patients aged < 1 year), review 200 studies, and perform 50 fetal studies and 50 transesophageal studies. In the United States, there is no formal certification process specifically organized for certification in pediatric or congenital echocardiography.

3.1.2. European Pediatric Echocardiographic Guidelines.

The European pediatric echocardiographic training guidelines have been published by the Association for European Paediatric Cardiology (AEPC) in 2005.²⁵ In these guidelines, three levels of expertise are distinguished: basic, advanced, and expert levels. For the basic level, the echocardiographer should have demonstrated the ability to perform and interpret echocardiographic studies in patients with simple forms of congenital cardiac diseases and acquired childhood diseases of the heart. This requires the supervised performance of 250 echocardiographic studies. The advanced level should allow the trainee to interpret more complex forms of CHD and also to perform and interpret TEE and fetal echocardiography under supervision. This level of training requires the performance and interpretation of 750 additional studies in children with congenital and acquired heart disease. The expert level is the level required for echocardiography laboratory directors or for those supervising training in echocardiography. It includes the performance of a total of 2,000 echocardiographic studies, including fetal echocardiography and TEE. In Europe, there is an accreditation for congenital echocardiography organized by the European Association of Echocardiography (EAE) in collaboration with the AEPC as well as the Grown-Up Congenital Heart Disease Working Group within the European Society of Cardiology. The theoretical examination (consisting of multiple-choice questions and a video case examination) was replaced in 2010 by assessment at training centers of the

Table 4 Cognitive and practical skills for core and advanced TNE training levels

Competency	Cognitive	Practical
Core TNE training	<ul style="list-style-type: none"> Understanding of the physics of ultrasound and its practical applications Understanding of the indications and limitations of an echocardiographic examination Understanding of cardiovascular anatomy and its relationship with echocardiographic images Understanding of the principles of pulsed and color Doppler and the application of the principles in clinical practice Understanding of the physiology of the fetal and neonatal transitional circulation Understanding the methods for assessing ventricular function and the factors influencing systolic and diastolic function Understanding of the methods for assessing pulmonary artery pressure and the normal adaptations 	<ul style="list-style-type: none"> Special precautions for scanning neonates, such as temperature stability, infection prevention, minimal touch approach, and limiting scan times Knowledge of machine operation and knobology, including optimal selection of probes and techniques for image optimization for neonatal scanning Be able to obtain the standard pediatric views (subxiphoid, parasternal, apical, and suprasternal) and know how to interpret the images Use of pulsed-wave Doppler, continuous-wave Doppler, and color Doppler to demonstrate blood flow velocities; knowledge of normal velocity patterns Knowledge of the use M-mode and 2D echocardiography to measure wall thickness and chamber dimensions and calculation of FS and EF Know how to perform and interpret images used for the different techniques to assess ventricular systolic and diastolic function Know how to properly store images Ability to communicate the result of an examination and produce a written report
Advanced TNE training	<ul style="list-style-type: none"> Understanding of cardiovascular pathology and the identification of abnormal cardiovascular anatomy on echocardiographic images Understanding of cardiovascular physiology and the effect of different lesions on hemodynamics Understanding the limitations of the methods for assessing ventricular function Understanding of the limitations of the methods for assessing pulmonary artery pressure and the normal adaptations 	<ul style="list-style-type: none"> Be able to rule out structural CHD Be able to obtain images in patients with more difficult windows and in more unstable patients Focus on image optimization during acquisition Use of more advanced Doppler applications and tissue Doppler techniques; interpretation of abnormal findings Know how to interpret measurements used in the assessment ventricular systolic and diastolic function and the influence of loading conditions Know how to assess the hemodynamic importance of pericardial fluid Know how to assess pulmonary artery arterial hypertension in newborns Know how to image central lines and identification of endocarditis Ability to communicate the result of an examination and produce a detailed written report Participate in echocardiography laboratory quality management programs with review of results and diagnostic errors

performance of 10 direct observations of practice, which involves direct observation of the candidate by the trainers performing and interpreting 10 different echocardiographic studies to gauge competence.

Both the US and European training requirements are designed for echocardiographers performing comprehensive pediatric and congenital echocardiography. In summary, the core or basic level includes the ability to perform comprehensive transthoracic echocardiography in neonates and children and the ability to distinguish normal from abnormal. The advanced or expert level includes fetal echocardiography, TEE, and the ability to diagnose complex disease as well as to supervise and train core or basic practitioners.

As ultrasound technology becomes more readily available because of the availability of portable and handheld ultrasound devices, there is more demand for training in so-called focused echocardiography. This includes perioperative TEE, focused echocardiography in the emergency department, and echocardiography in the adult and pediatric intensive care unit and, more recently, in the NICU.

3.2. Proposal for Training in TNE

For the performance of TNE, specific cognitive and technical skills need to be acquired during the training process. On the basis of the existing guidelines, we propose to distinguish between a “core” and an “advanced” training level for TNE. For each level, specific skills need to be acquired.

3.2.1. Core Training in TNE. Table 4 summarizes the cognitive and practical skills that are required to perform TNE. To achieve these core competencies, a training period of **4 to 6 months** entirely dedicated to pediatric echocardiography is recommended. This should allow the performance of >150 studies and the interpretation of an additional 150 studies. To guarantee sufficient exposure to disease, it is advised that no more than 20% of these studies be normal. This will allow the trainee in TNE to become familiar with normal cardiac anatomy and recognize abnormal patterns suggesting the presence of structural heart disease. At the end of this training period, a formal evaluation of the image acquisition competencies should

be completed and approved by the echocardiography laboratory director. The trainee should be able to obtain all standard imaging views and should be able to perform standard TNE that will allow the identification of structural heart disease. After the core training, the trainee should be able to acquire the images according to the standard protocols, but advanced training is required to be able to read and interpret the findings on TNE.

3.2.2. Advanced Training in TNE. Advanced training in TNE is aimed at further developing the complete set of skills as defined in the competency list above, with a specific focus on achieving expertise with TNE. At the end of the training, the candidate should be able to **independently** perform and interpret neonatal TNE for the defined indications. The echocardiographer with advanced training in TNE should be able to reliably rule out CHD on studies with adequate images. This training requires the additional performance of 150 neonatal echocardiographic studies and review of an additional 150 studies. It is suggested that this additional advanced training in TNE include **another 4 to 6 months** of training, mainly in the context of a NICU, supervised directly or indirectly by a pediatric echocardiography laboratory.

3.3. Supervision of Training

Both core and advanced targeted neonatal echocardiographic training should be coordinated by a pediatric echocardiography service within a pediatric cardiology service. This laboratory should be under the supervision of a full-time pediatric echocardiographer qualified to direct a laboratory, with the primary responsibility of supervising the echocardiography laboratory. The laboratory must perform a sufficient number of pediatric transthoracic echocardiographic studies per year. The pediatric echocardiography laboratory should be responsible for performing the initial comprehensive echocardiographic examinations in the NICU. An established interaction on the interpretation of TNE between the NICU and the pediatric echocardiography laboratory creates the optimal environment for training and teaching targeted neonatal studies. Core training in TNE should be performed within a pediatric echocardiography laboratory. Advanced training in TNE could be organized within a NICU but should be supervised by a pediatric echocardiographer or fully trained neonatal echocardiographer who has completed advanced pediatric echocardiographic training as defined by the current American College of Cardiology, American Heart Association, and ASE guidelines for North America and by the AEPC guidelines for Europe. A fully trained targeted neonatal echocardiographer with sufficient expertise could be involved in this advanced targeted neonatal echocardiographic training period.

3.4. Evaluation

The pediatric echocardiography laboratory director, in consultation with the training staff, should evaluate each trainee on a regular basis. There should be in place a system for tracking and cataloging the performance of echocardiograms, including the indications and findings of the studies, in such a way as to facilitate periodic review of the trainee's volume and diversity of experience satisfactory to attain and maintain competence. Formal evaluation through direct observation could be organized for both the core and the advanced level. The implementation of a formal accreditation process for TNE should be considered in the future.

3.5. Maintenance of Competence and Quality Assurance for TNE

After the neonatal echocardiographers have completed the advanced training level in TNE, they should continue to perform a minimum of 100 echocardiographic studies per year to maintain their skills and competence level. Maintenance of competence by regular participation in echocardiographic conferences or training courses is strongly recommended. A structured program for continued education is to be developed.

Crucial for a TNE program is that it be organized according to current professional standards regarding image acquisition, image storage, and reporting. In hospitals with pediatric echocardiography laboratories, this can best be achieved by integration of the TNE activity within the pediatric echocardiography laboratory. This includes standardization of imaging protocols, uniform reporting, and a single imaging archive within the same hospital. In hospitals in which direct access to pediatric echocardiography laboratories is not available, the service should be organized according to generally accepted standards for echocardiography laboratories.^{130,131} This includes meeting operational standards (training of personnel, equipment, protocols, standards for storage, and reporting) as well as participation in quality improvement processes.¹³² All echocardiographic studies should be recorded and the images stored in a manner allowing for immediate availability for review and easy retrieval. The ultrasound systems must include the ability to provide immediate playback with limited video degradation, standardized reports, and long-term storage. Digital storage is strongly recommended, but analog videotape is acceptable. M-mode and spectral Doppler images are generally recorded as static images. Standardized reporting preferentially on a digital reporting system is recommended. Reporting standards should comply with the recommendations of the Intersocietal Commission for the Accreditation of Echocardiography Laboratories.¹³³

In NICU services with no direct access to pediatric cardiology services, telemedicine links between the NICU and the central laboratory could be organized. Telemedicine technology has advanced greatly over the Past 20 years. Real-time video transmission capability has been used since the late 1990s for rapid, remote cardiac evaluation of critically ill neonates.¹³⁴⁻¹³⁶ More recently, it has become possible to transmit complete digital echocardiograms ("store and forward") rapidly over secure high-bandwidth connections,¹³⁷ and success with both real-time and store-and-forward telemedicine echocardiography has been reported in numerous settings, including high-volume level 3 NICUs.¹³⁸ For NICUs without immediate availability of an on-site pediatric cardiologist for consultation, the use of telemedicine for performance and to facilitate rapid interpretation of initial comprehensive echocardiograms and TNE examinations is strongly encouraged. If TNE is being performed in a facility without the availability of a practitioner with at least advanced-level training in TNE as outlined in this document, telemedicine capabilities should be considered a requirement.

NOTICE AND DISCLAIMER

This report is made available by the collaborating organizations (the ASE, EAE, and AEPC) as a courtesy reference source for the members of those organizations. This report contains recommendations only and should not be used as the sole basis to make medical practice decisions or for disciplinary action against any employee. The statements

and recommendations contained in this report are primarily based on the opinions of experts, rather than on scientifically verified data. The ASE, EAE, and AEPC make no express or implied warranties regarding the completeness or accuracy of the information in this report, including the warranty of merchantability or fitness for a particular purpose. In no event shall the ASE, EAE, or AEPC be liable to you, your patients, or any other third parties for any decision made or action taken by you or such other parties in reliance on this information. Nor does your use of this information constitute the offering of medical advice by the collaborating organizations or create any physician-patient relationship between those organizations and your patients or anyone else.

REFERENCES

1. Kluckow M, Seri I, Evans N. Functional echocardiography: an emerging clinical tool for the neonatologist. *J Pediatr* 2007;150:125-30.
2. Kluckow M, Seri I, Evans N. Echocardiography and the neonatologist. *Pediatr Cardiol* 2008;29:1043-7.
3. Sehgal A, McNamara PJ. Does point-of-care functional echocardiography enhance cardiovascular care in the NICU? *J Perinatol* 2008;28:729-35.
4. Sehgal A, McNamara PJ. Does echocardiography facilitate determination of hemodynamic significance attributable to the ductus arteriosus? *Eur J Pediatr* 2009;168:907-14.
5. Evans N, Gournay V, Cabanas F, Kluckow M, Leone T, Groves A, McNamara P, Mertens L. Point-of-care ultrasound in the neonatal intensive care unit: international perspectives. *Seminars in fetal & neonatal medicine* 2011;16:61-8.
6. Rudolph AM. Myocardial growth before and after birth: clinical implications. *Acta Paediatr* 2000;89:129-33.
7. Brook WH, Connell S, Cannata J, Maloney JE, Walker AM. Ultrastructure of the myocardium during development from early fetal life to adult life in sheep. *J Anat* 1983;137:729-41.
8. Nadal-Ginard B, Mahdavi V. Molecular basis of cardiac performance. Plasticity of the myocardium generated through protein isoform switches. *J Clin Invest* 1989;84:1693-700.
9. Teitel D. Developmental aspects of cardiac performance. In: Shaddy R, Wernovsky G, editors. *Pediatric heart failure*. London: Taylor & Francis; 2005. pp. 31-63.
10. Rudolph AM. *Congenital diseases of the heart: clinical-physiological considerations*. 3rd ed. Chichester, United Kingdom: Wiley-Blackwell; 2009.
11. Kluckow M. Low systemic blood flow and pathophysiology of the preterm transitional circulation. *Early Hum Dev* 2005;81:429-37.
12. Kiserud T. Physiology of the fetal circulation. *Semin Fetal Neonatal Med* 2005;10:493-503.
13. Evans N. Assessment and support of the preterm circulation. *Early Hum Dev* 2006;82:803-10.
14. Hawkins J, Van Hare GF, Schmidt KG, Rudolph AM. Effects of increasing afterload on left ventricular output in fetal lambs. *Circ Res* 1989;65:127-34.
15. Kiserud T, Acharya G. The fetal circulation. *Prenat Diagn* 2004;24:1049-59.
16. Klopfenstein HS, Rudolph AM. Postnatal changes in the circulation and responses to volume loading in sheep. *Circ Res* 1978;42:839-45.
17. Reed KL, Sahn DJ, Marx GR, Anderson CF, Shenker L. Cardiac Doppler flows during fetal arrhythmias: physiologic consequences. *Obstet Gynecol* 1987;70:1-6.
18. Rudolph AM. Circulation in the normal fetus and cardiovascular adaptations to birth. In: Yagel S, Silverman NH, Gembruch U, editors. *Fetal cardiology*. New York: Informa Healthcare; 2008. pp. 131-52.
19. Johnson P, Maxwell DJ, Tynan MJ, Allan LD. Intracardiac pressures in the human fetus. *Heart* 2000;84:59-63.
20. Harada K, Ogawa M, Tanaka T. Right ventricular pre-ejection myocardial velocity and myocardial acceleration in normal fetuses assessed by Doppler tissue imaging. *J Am Soc Echocardiogr* 2005;18:370-4.
21. Younoszai AK, Saudek DE, Emery SP, Thomas JD. Evaluation of myocardial mechanics in the fetus by velocity vector imaging. *J Am Soc Echocardiogr* 2008;21:470-4.
22. Blackburn S. Placental, fetal, and transitional circulation revisited. *J Perinat Neonatal Nurs* 2006;20:290-4.
23. Baschat A, Gembruch U. Development of fetal cardiac and extracardiac Doppler flows in early gestation. In: Yagel S, Silverman NH, Gembruch U, editors. *Fetal cardiology*. New York: Informa Healthcare; 2008. pp. 153-71.
24. Osborn DA. Diagnosis and treatment of preterm transitional circulatory compromise. *Early Hum Dev* 2005;81:413-22.
25. Mertens L, Helbing W, Sieverding L, Daniels O. Guidelines from the Association for European Paediatric Cardiology: standards for training in paediatric echocardiography. *Cardiol Young* 2005;15:441-2.
26. Sanders SP, Colan SD, Cordes TM, Donofrio MT, Ensing GJ, Geva T, et al. ACCF/AHA/AAP recommendations for training in pediatric cardiology. Task Force 2: pediatric training guidelines for noninvasive cardiac imaging endorsed by the American Society of Echocardiography and the Society of Pediatric Echocardiography. *J Am Coll Cardiol* 2005;46:1384-8.
27. Lai WW, Geva T, Shirali GS, Frommelt PC, Humes RA, Brook MM, et al. Guidelines and standards for performance of a pediatric echocardiogram: a report from the Task Force of the Pediatric Council of the American Society of Echocardiography. *J Am Soc Echocardiogr* 2006;19:1413-30.
28. Lai WW, Mertens LL, Cohen MS, Geva T. *Echocardiography in pediatric and congenital heart disease: from fetus to adult*. Chichester, United Kingdom: Wiley-Blackwell; 2009.
29. Lopez L, Colan SD, Frommelt PC, Ensing GJ, Kendall K, Younoszai AK, et al. Recommendations for quantification methods during the performance of a pediatric echocardiogram: a report from the Pediatric Measurements Writing Group of the American Society of Echocardiography Pediatric and Congenital Heart Disease Council. *J Am Soc Echocardiogr* 2010;23:465-95.
30. Zecca E, Romagnoli C, Vento G, De Carolis MP, De Rosa G, Tortorolo G. Left ventricle dimensions in preterm infants during the first month of life. *Eur J Pediatr* 2001;160:227-30.
31. Skelton R, Gill AB, Parsons JM. Reference ranges for cardiac dimensions and blood flow velocity in preterm infants. *Heart (Br Card Soc)* 1998;80:281-5.
32. Nagasawa H. Novel regression equations of left ventricular dimensions in infants less than 1 year of age and premature neonates obtained from echocardiographic examination. *Cardiol Young* 2010;20:526-31.
33. Kampmann C, Wiethoff CM, Wenzel A, Stolz G, Betancor M, Wippermann CF, et al. Normal values of M mode echocardiographic measurements of more than 2000 healthy infants and children in central Europe. *Heart (Br Card Soc)* 2000;83:667-72.
34. Kimball TR, Ralston MA, Khoury P, Crump RG, Cho FS, Reuter JH. Effect of ligation of patent ductus arteriosus on left ventricular performance and its determinants in premature neonates. *J Am Coll Cardiol* 1996;27:193-7.
35. McNamara PJ, Stewart L, Shivananda SP, Stephens D, Sehgal A. Patent ductus arteriosus ligation is associated with impaired left ventricular systolic performance in premature infants weighing less than 1000 g. *J Thorac Cardiovasc Surg* 2010;140:150-7.
36. Colan SD, Parness IA, Spevak PJ, Sanders SP. Developmental modulation of myocardial mechanics: age- and growth-related alterations in afterload and contractility. *J Am Coll Cardiol* 1992;19:619-29.
37. Rowland DG, Gutgesell HP. Noninvasive assessment of myocardial contractility, preload, and afterload in healthy newborn infants. *Am J Cardiol* 1995;75:818-21.
38. Colan SD, Borow KM, Neumann A. Left ventricular end-systolic wall stress-velocity of fiber shortening relation: a load-independent index of myocardial contractility. *J Am Coll Cardiol* 1984;4:715-24.
39. Toyono M, Harada K, Takahashi Y, Takada G. Maturation changes in left ventricular contractile state. *Int J Cardiol* 1998;64:247-52.
40. Pena JL, da Silva MG, Alves JM Jr, Salemi VM, Mady C, Baltabaeva A, et al. Sequential changes of longitudinal and radial myocardial

- deformation indices in the healthy neonate heart. *J Am Soc Echocardiogr* 2010;23:294-300.
41. Pena JL, da Silva MG, Faria SC, Salemi VM, Mady C, Baltabaeva A, et al. Quantification of regional left and right ventricular deformation indices in healthy neonates by using strain rate and strain imaging. *J Am Soc Echocardiogr* 2009;22:369-75.
 42. Nagueh SF, Appleton CP, Gillebert TC, Marino PN, Oh JK, Smiseth OA, et al. Recommendations for the evaluation of left ventricular diastolic function by echocardiography. *J Am Soc Echocardiogr* 2009;22:107-33.
 43. Lester SJ, Tajik AJ, Nishimura RA, Oh JK, Khandheria BK, Seward JB. Unlocking the mysteries of diastolic function: deciphering the Rosetta stone 10 years later. *J Am Coll Cardiol* 2008;51:679-89.
 44. Harada K, Shiota T, Takahashi Y, Tamura M, Toyono M, Takada G. Doppler echocardiographic evaluation of left ventricular output and left ventricular diastolic filling changes in the first day of life. *Pediatr Res* 1994;35:506-9.
 45. Riggs TW, Rodriguez R, Snider AR, Batton D. Doppler echocardiographic evaluation of right and left ventricular diastolic function in normal neonates. *J Am Coll Cardiol* 1989;13:700-5.
 46. Schmitz L, Koch H, Bein G, Brockmeier K. Left ventricular diastolic function in infants, children, and adolescents. Reference values and analysis of morphologic and physiologic determinants of echocardiographic Doppler flow signals during growth and maturation. *J Am Coll Cardiol* 1998;32:1441-8.
 47. Schmitz L, Stiller B, Pees C, Koch H, Xanthopoulos A, Lange P. Doppler-derived parameters of diastolic left ventricular function in preterm infants with a birth weight <1500 g: reference values and differences to term infants. *Early Hum Dev* 2004;76:101-14.
 48. Harada K, Takahashi Y, Tamura M, Orino T, Takada G. Serial echocardiographic and Doppler evaluation of left ventricular systolic performance and diastolic filling in premature infants. *Early Hum Dev* 1999;54:169-80.
 49. Ito T, Harada K, Takada G. Changes in pulmonary venous flow patterns in patients with ventricular septal defect. *Pediatr Cardiol* 2002;23:491-5.
 50. Mori K, Nakagawa R, Nii M, Edagawa T, Takehara Y, Inoue M, et al. Pulsed wave Doppler tissue echocardiography assessment of the long axis function of the right and left ventricles during the early neonatal period. *Heart (Br Card Soc)* 2004;90:175-80.
 51. Frommelt PC, Ballweg JA, Whitstone BN, Frommelt MA. Usefulness of Doppler tissue imaging analysis of tricuspid annular motion for determination of right ventricular function in normal infants and children. *Am J Cardiol* 2002;89:610-3.
 52. Eidem BW, Tei C, O'Leary PW, Cetta F, Seward JB. Nongeometric quantitative assessment of right and left ventricular function: myocardial performance index in normal children and patients with Ebstein anomaly. *J Am Soc Echocardiogr* 1998;11:849-56.
 53. Cheung MM, Smallhorn JF, Redington AN, Vogel M. The effects of changes in loading conditions and modulation of inotropic state on the myocardial performance index: comparison with conductance catheter measurements. *Eur Heart J* 2004;25:2238-42.
 54. Mertens LL, Friedberg MK. Imaging the right ventricle—current state of the art. *Nature Rev Cardiol* 2010;7:551-63.
 55. Koestenberger M, Ravekes W, Everett AD, Stueger HP, Heinzl B, Gamillscheg A, et al. Right ventricular function in infants, children and adolescents: reference values of the tricuspid annular plane systolic excursion (TAPSE) in 640 healthy patients and calculation of z score values. *J Am Soc Echocardiogr* 2009;22:715-9.
 56. Groves AM, Kuschel CA, Knight DB, Skinner JR. Does retrograde diastolic flow in the descending aorta signify impaired systemic perfusion in preterm infants? *Pediatr Res* 2008;63:89-94.
 57. Ensing G, Seward J, Darragh R, Caldwell R. Feasibility of generating hemodynamic pressure curves from noninvasive Doppler echocardiographic signals. *J Am Coll Cardiol* 1994;23:434-42.
 58. Masuyama T, Kodama K, Kitabatake A, Sato H, Nanto S, Inoue M. Continuous-wave Doppler echocardiographic detection of pulmonary regurgitation and its application to noninvasive estimation of pulmonary artery pressure. *Circulation* 1986;74:484-92.
 59. Kluckow M, Evans N. Superior vena cava flow in newborn infants: a novel marker of systemic blood flow. *Arch Dis Child Fetal Neonatal Ed* 2000;82:F182-7.
 60. Cheitlin MD, Alpert JS, Armstrong WF, Aurigemma GP, Beller GA, Bierman FZ, et al. ACC/AHA guidelines for the clinical application of echocardiography: executive summary. A report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Committee on Clinical Application of Echocardiography). Developed in collaboration with the American Society of Echocardiography. *J Am Coll Cardiol* 1997;29:862-79.
 61. Riggs TW, Snider AR. Respiratory influence on right and left ventricular diastolic function in normal children. *Am J Cardiol* 1989;63:858-61.
 62. Reller MD, Rice MJ, McDonald RW. Review of studies evaluating ductal patency in the premature infant. *J Pediatr* 1993;122:S59-62.
 63. Wyllie J. Treatment of patent ductus arteriosus. *Semin Neonatol* 2003;8:425-32.
 64. Szymankiewicz M, Hodgman JE, Siassi B, Gadzinowski J. Mechanics of breathing after surgical ligation of patent ductus arteriosus in newborns with respiratory distress syndrome. *Biol Neonate* 2004;85:32-6.
 65. Rojas MA, Gonzalez A, Bancalari E, Claure N, Poole C, Silva-Neto G. Changing trends in the epidemiology and pathogenesis of neonatal chronic lung disease. *J Pediatr* 1995;126:605-10.
 66. van de Bor M, Verloove-Vanhorick SP, Brand R, Ruys JH. Patent ductus arteriosus in a cohort of 1338 preterm infants: a collaborative study. *Paediatr Perinat Epidemiol* 1988;2:328-36.
 67. Baptista MJ, Correia-Pinto J, Areias JC, Guimaraes H. Patent ductus arteriosus in neonatal intensive care [article in Portuguese]. *Rev Port Cardiol* 1999;18:1095-100.
 68. Jim WT, Chiu NC, Chen MR, Hung HY, Kao HA, Hsu CH, et al. Cerebral hemodynamic change and intraventricular hemorrhage in very low birth weight infants with patent ductus arteriosus. *Ultrasound Med Biol* 2005;31:197-202.
 69. McNamara PJ, Sehgal A. Towards rational management of the patent ductus arteriosus: the need for disease staging. *Arch Dis Child Fetal Neonatal Ed* 2007;92:F424-7.
 70. Hankins GD, Koen S, Gei AF, Lopez SM, Van Hook JW, Anderson GD. Neonatal organ system injury in acute birth asphyxia sufficient to result in neonatal encephalopathy. *Obstet Gynecol* 2002;99:688-91.
 71. Perlman JM, Tack ED, Martin T, Shackelford G, Amon E. Acute systemic organ injury in term infants after asphyxia. *Am J Dis Child* 1989;143:617-20.
 72. Rajakumar PS, Vishnu Bhat B, Sridhar MG, Balachander J, Konar BC, Narayanan P, et al. Electrocardiographic and echocardiographic changes in perinatal asphyxia. *Indian J Pediatr* 2009;76:261-4.
 73. Flores-Nava G, Echevarria-Ybarguengoitia JL, Navarro-Barron JL, Garcia-Alonso A. Transient myocardial ischemia in newborn babies with perinatal asphyxia (hypoxic cardiomyopathy) [article in Spanish]. *Bol Med Hosp Infant Mex* 1990;47:809-14.
 74. Rowe RD, Hoffman T. Transient myocardial ischemia of the newborn infant: a form of severe cardiorespiratory distress in full-term infants. *J Pediatr* 1972;81:243-50.
 75. Kanik E, Ozer EA, Bakiler AR, Aydinlioglu H, Dorak C, Dogrusoz B, et al. Assessment of myocardial dysfunction in neonates with hypoxic-ischemic encephalopathy: is it a significant predictor of mortality? *J Matern Fetal Neonatal Med* 2009;22:239-42.
 76. Barberi I, Calabro MP, Cordaro S, Gitto E, Sottile A, Prudente D, et al. Myocardial ischaemia in neonates with perinatal asphyxia. Electrocardiographic, echocardiographic and enzymatic correlations. *Eur J Pediatr* 1999;158:742-7.
 77. Wei Y, Xu J, Xu T, Fan J, Tao S. Left ventricular systolic function of newborns with asphyxia evaluated by tissue Doppler imaging. *Pediatr Cardiol* 2009;30:741-6.
 78. Azzopardi DV, Strohm B, Edwards AD, Dyet L, Halliday HL, Juszczak E, et al. Moderate hypothermia to treat perinatal asphyxial encephalopathy. *N Engl J Med* 2009;361:1349-58.
 79. Battin MR, Thoresen M, Robinson E, Polin RA, Edwards AD, Gunn AJ. Does head cooling with mild systemic hypothermia affect requirement for blood pressure support? *Pediatrics* 2009;123:1031-6.

80. Eicher DJ, Wagner CL, Katikaneni LP, Hulsey TC, Bass WT, Kaufman DA, et al. Moderate hypothermia in neonatal encephalopathy: safety outcomes. *Pediatr Neurol* 2005;32:18-24.
81. Gluckman PD, Wyatt JS, Azzopardi D, Ballard R, Edwards AD, Ferriero DM, et al. Selective head cooling with mild systemic hypothermia after neonatal encephalopathy: multicentre randomised trial. *Lancet* 2005;365:663-70.
82. Shankaran S, Laptook AR, Ehrenkranz RA, Tyson JE, McDonald SA, Donovan EF, et al. Whole-body hypothermia for neonates with hypoxic-ischemic encephalopathy. *N Engl J Med* 2005;353:1574-84.
83. Thoresen M, Whitelaw A. Cardiovascular changes during mild therapeutic hypothermia and rewarming in infants with hypoxic-ischemic encephalopathy. *Pediatrics* 2000;106:92-9.
84. Dempsey EM, Al Hazzani F, Barrington KJ. Permissive hypotension in the extremely low birthweight infant with signs of good perfusion. *Arch Dis Child Fetal Neonatal Ed* 2009;94:F241-4.
85. Evans N. Which inotrope for which baby? *Arch Dis Child Fetal Neonatal Ed* 2006;91:F213-20.
86. Greisen G. Autoregulation of cerebral blood flow in newborn babies. *Early Hum Dev* 2005;81:423-8.
87. Tweed A, Cote J, Lou H, Gregory G, Wade J. Impairment of cerebral blood flow autoregulation in the newborn lamb by hypoxia. *Pediatr Res* 1986;20:516-9.
88. Tsuji M, duPlessis A, Taylor G, Crocker R, Volpe JJ. Near infrared spectroscopy detects cerebral ischemia during hypotension in piglets. *Pediatr Res* 1998;44:591-5.
89. Tyszczuk L, Meek J, Elwell C, Wyatt JS. Cerebral blood flow is independent of mean arterial blood pressure in preterm infants undergoing intensive care. *Pediatrics* 1998;102:337-41.
90. Goldstein RF, Thompson RJ Jr, Oehler JM, Brazy JE. Influence of acidosis, hypoxemia, and hypotension on neurodevelopmental outcome in very low birth weight infants. *Pediatrics* 1995;95:238-43.
91. Miall-Allen VM, de Vries LS, Whitelaw AG. Mean arterial blood pressure and neonatal cerebral lesions. *Arch Dis Child* 1987;62:1068-9.
92. Watkins AM, West CR, Cooke RW. Blood pressure and cerebral haemorrhage and ischaemia in very low birthweight infants. *Early Hum Dev* 1989;19:103-10.
93. Weindling AM, Wilkinson AR, Cook J, Calvert SA, Fok TF, Rochefort MJ. Perinatal events which precede periventricular haemorrhage and leukomalacia in the newborn. *Br J Obstet Gynaecol* 1985;92:1218-23.
94. Baud O, d'Allest AM, Lacaze-Masmonteil T, Zupan V, Nedelcoux H, Boithias C, et al. The early diagnosis of periventricular leukomalacia in premature infants with positive rolandic sharp waves on serial electroencephalography. *J Pediatr* 1998;132:813-7.
95. Bejar RF, Vaucher YE, Benirschke K, Berry CC. Postnatal white matter necrosis in preterm infants. *J Perinatol* 1992;12:3-8.
96. Cunningham S, Symon AG, Elton RA, Zhu C, McIntosh N. Intra-arterial blood pressure reference ranges, death and morbidity in very low birthweight infants during the first seven days of life. *Early Hum Dev* 1999;56:151-65.
97. de Vries LS, Regev R, Dubowitz LM, Whitelaw A, Aber VR. Perinatal risk factors for the development of extensive cystic leukomalacia. *Am J Dis Child* 1988;142:732-5.
98. D'Souza SW, Janakova H, Minors D, Suri R, Waterhouse J, Appleton G, et al. Blood pressure, heart rate, and skin temperature in preterm infants: associations with periventricular haemorrhage. *Arch Dis Child Fetal Neonatal Ed* 1995;72:F162-7.
99. Engle WD. Blood pressure in the very low birth weight neonate. *Early Hum Dev* 2001;62:97-130.
100. Gronlund JU, Korvenranta H, Kero P, Jalonen J, Valimaki IA. Elevated arterial blood pressure is associated with peri-intraventricular haemorrhage. *Eur J Pediatr* 1994;153:836-41.
101. Limperopoulos C, Bassan H, Kalish LA, Ringer SA, Eichenwald EC, Walter G, et al. Current definitions of hypotension do not predict abnormal cranial ultrasound findings in preterm infants. *Pediatrics* 2007;120:966-77.
102. Perlman JM. White matter injury in the preterm infant: an important determination of abnormal neurodevelopment outcome. *Early Hum Dev* 1998;53:99-120.
103. Trounce JQ, Levene MI. Diagnosis and outcome of subcortical cystic leukomalacia. *Arch Dis Child* 1985;60:1041-4.
104. Walsh MC, Stork EK. Persistent pulmonary hypertension of the newborn. Rational therapy based on pathophysiology. *Clin Perinatol* 2001;28:609-27.
105. Walsh-Sukys MC. Persistent pulmonary hypertension of the newborn. The black box revisited. *Clin Perinatol* 1993;20:127-43.
106. McNamara PJ, Murthy P, Kantores C, Teixeira L, Engelberts D, van Vliet T, et al. Acute vasodilator effects of Rho-kinase inhibitors in neonatal rats with pulmonary hypertension unresponsive to nitric oxide. *Am J Physiol Lung Cell Mol Physiol* 2008;294:L205-13.
107. Hoffman SB, Massaro AN, Gingalewski C, Short BL. Predictors of survival in congenital diaphragmatic hernia patients requiring extracorporeal membrane oxygenation: CNMC 15-year experience. *J Perinatol* 2010;30:546-52.
108. Graziano JN. Cardiac anomalies in patients with congenital diaphragmatic hernia and their prognosis: a report from the Congenital Diaphragmatic Hernia Study Group. *J Pediatr Surg* 2005;40:1045-9.
109. Vogel M, McElhinney DB, Marcus E, Morash D, Jennings RW, Tworetzky W. Significance and outcome of left heart hypoplasia in fetal congenital diaphragmatic hernia. *Ultrasound Obstet Gynecol* 2010;35:310-7.
110. Cohen MS, Rychik J, Bush DM, Tian ZY, Howell LJ, Adzick NS, et al. Influence of congenital heart disease on survival in children with congenital diaphragmatic hernia. *J Pediatr* 2002;141:25-30.
111. Lin AE, Pober BR, Adatia I. Congenital diaphragmatic hernia and associated cardiovascular malformations: type, frequency, and impact on management. *Am J Med Genet C Semin Med Genet* 2007;145C:201-16.
112. Gray JE, Ringer SA. Common neonatal procedures. In: Cloherty JP, Stark AR, editors. *Manual of neonatal care*. 4th ed. Philadelphia: Lippincott-Raven; 1998.
113. Yao S. Major arterial and venous thrombosis. In: Cloherty JP, Stark AR, editors. *Manual of neonatal care*. 4th ed. Philadelphia: Lippincott-Raven; 1998.
114. Karapinar B, Cura A. Complications of central venous catheterization in critically ill children. *Pediatr Int* 2007;49:593-9.
115. Sheridan RL, Weber JM. Mechanical and infectious complications of central venous cannulation in children: lessons learned from a 10-year experience placing more than 1000 catheters. *J Burn Care Res* 2006;27:713-8.
116. Narang S, Roy J, Stevens TP, Butler-O'Hara M, Mullen CA, D'Angio CT. Risk factors for umbilical venous catheter-associated thrombosis in very low birth weight infants. *Pediatr Blood Cancer* 2009;52:75-9.
117. Tanke RB, van Megen R, Daniels O. Thrombus detection on central venous catheters in the neonatal intensive care unit. *Angiology* 1994;45:477-80.
118. Greenway A, Massicotte MP, Monagle P. Neonatal thrombosis and its treatment. *Blood Rev* 2004;18:75-84.
119. Ako J, Ikari Y, Hatori M, Hara K, Ouchi Y. Changing spectrum of infective endocarditis: review of 194 episodes over 20 years. *Circ J* 2003;67:3-7.
120. Pearlman SA, Higgins S, Eppes S, Bhat AM, Klein JD. Infective endocarditis in the premature neonate. *Clin Pediatr (Phila)* 1998;37:741-6.
121. Valente AM, Jain R, Scheurer M, Fowler VG Jr, Corey GR, Bengur AR, et al. Frequency of infective endocarditis among infants and children with *Staphylococcus aureus* bacteremia. *Pediatrics* 2005;115:e15-9.
122. Kim MJ, Chang HK, Lee MS, Han SJ, Oh JT. Internal jugular vein deformities after central venous catheterisation in neonates: evaluation by Doppler ultrasound. *J Paediatr Child Health* 2010;46:154-8.
123. Kuschel CA, Bach KP, Webster NJ, Page B, Groves AM, Battin MR. The reliability of 2D and colour Doppler ultrasound in localising longline position. *J Paediatr Child Health* 2008;44:483-7.
124. Dalton HJ, Rycus PT, Conrad SA. Update on extracorporeal life support 2004. *Semin Perinatol* 2005;29:24-33.

125. Barnacle AM, Smith LC, Hiorns MP. The role of imaging during extracorporeal membrane oxygenation in pediatric respiratory failure. *AJR Am J Roentgenol* 2006;186:58-66.
126. Irish MS, O'Toole SJ, Kapur P, Bambini DA, Azizkhan RG, Allen JE, et al. Cervical ECMO cannula placement in infants and children: recommendations for assessment of adequate positioning and function. *J Pediatr Surg* 1998;33:929-31.
127. Thomas TH, Price R, Ramaciotti C, Thompson M, Megison S, Lemler MS. Echocardiography, not chest radiography, for evaluation of cannula placement during pediatric extracorporeal membrane oxygenation. *Pediatr Crit Care Med* 2009;10:56-9.
128. Kuenzler KA, Arthur LG, Burchard AE, Lawless ST, Wolfson PJ, Murphy SG. Intraoperative ultrasound reduces ECMO catheter malposition requiring surgical correction. *J Pediatr Surg* 2002;37:691-4.
129. Fisher JC, Jefferson RA, Kuenzler KA, Stolar CJ, Arkovitz MS. Challenges to cannulation for extracorporeal support in neonates with right-sided congenital diaphragmatic hernia. *J Pediatr Surg* 2007;42:2123-8.
130. Nihoyannopoulos P, Fox K, Fraser A, Pinto F. EAE laboratory standards and accreditation. *Eur J Echocardiogr* 2007;8:80-7.
131. Intersocietal Commission for the Accreditation of Echocardiography Laboratories. Changes: the latest revisions to ICAEL standards. Available at: http://www.icael.org/icael/standards/ICAEL_2010_Standards. Accessed August 18, 2011.
132. Picard MH, Adams D, Bierig SM, Dent JM, Douglas PS, Gillam LD, et al. American Society of Echocardiography recommendations for quality echocardiography laboratory operations. *J Am Soc Echocardiogr* 2011;24:1-10.
133. Frommelt P, Gorentz J, Deatsman S, Organ D, Frommelt M, Mussatto K. Digital imaging, archiving, and structured reporting in pediatric echocardiography: impact on laboratory efficiency and physician communication. *J Am Soc Echocardiogr* 2008;21:935-40.
134. Casey F, Brown D, Craig BC, Rogers J, Mulholland HC. Diagnosis of neonatal congenital heart defects by remote consultation using a low-cost telemedicine link. *J Telemed Telecare* 1996;2:165-9.
135. Fisher JB, Alboliras ET, Berdusis K, Webb CL. Rapid identification of congenital heart disease by transmission of echocardiograms. *Am Heart J* 1996;131:1225-7.
136. Sable C, Roca T, Gold J, Gutierrez A, Gulotta E, Culpepper W. Live transmission of neonatal echocardiograms from underserved areas: accuracy, patient care, and cost. *Telemed J* 1999;5:339-47.
137. Sable C. Telemedicine applications in pediatric cardiology. *Minerva Pediatr* 2003;55:1-13.
138. Huang T, Moon-Grady AJ, Traugott C, Marcini J. The availability of telecardiology consultations and transfer patterns from a remote neonatal intensive care unit. *J Telemed Telecare* 2008;14:244-8.