Neonatology Hemodynamics Clinical Research (NHCR) Fellowship

APPENDIX A: Echocardiography protocols:

A) First Study (Complete protocol):

During echocardiography, always note: weight, age of patient, systemic blood pressure at the time of echocardiography. Record echocardiography with ECG recording. Scale of Nyquist velocity needs to be adapted in consideration of expected blood velocities. As such, a lower scale (40 to 60 cm/s) needs to be used in the context of: screening for ventricular septal defect in the immediate neonatal life (due to higher pulmonary pressures), coronary flow, venous flow, atrial septal defect shunting evaluation.

In all the views, appreciate the subjective contraction of each portion of the left and right ventricles, looking at segmental decrease in contraction. For Tissue Doppler Imaging, acquire images at high frame rates (150 fps) and record multiples beats (5 per loop).

Views and comprehensive first study:

1) **Parasternal long axis view (PLA):** The septum is nearly horizontal, and deviates less than 30° from the horizontal plane. The aortic valve and mitral valve are each displayed, as is the proximal aorta. The ventricular septum should be seen 2/3 to the apex.

    a. 2D image at the level of mitral and aortic valve, aortic root and cusps. Aortic valve, aortic root and ascending aorta measurements – 2D anatomy, Color Doppler on mitral valve, aortic valve
    b. Sweep posterior at the level of RV inflow (tricuspid valve) – 2D anatomy and Color Doppler on tricuspid valve
    c. Sweep anterior at the level of RV outflow tract (pulmonary valve and pulmonary artery) – 2D anatomy - Color Doppler on pulmonary valve, as well as pulmonary artery – PW Doppler at pulmonary valve leaflets attachment and in MPA
    d. Continuous wave (CW) Doppler interrogation of valvar insufficiency at tricuspid and pulmonary level if present and if aligned appropriately. Measure peak TR gradient, early diastolic and end diastolic PI gradient.
    e. Sweep from posterior to anterior to establish atrio-ventricular and ventriculo-arterial connections
    f. M-mode of left and right ventricle at the level of tip of mitral valve with line of interrogation perpendicular to interventricular septum for measurement of shortening fraction (SF) and measurements of LV / RV / Septum / Posterior wall thickness (only valid in normal biventricular anatomy), measurement of R-R interval.
    g. M-mode at the closure of aortic valve and with line of interrogation perpendicular to aorta for: Left atrial on aorta ratio (detection of signs of LV overload, or small aortic valve). Evaluation of LV ejection time from opening to closure of aortic valve.

h. Color Doppler of all interventricular septum for detection of VSDs (visualize up to the apex). Sweep in every plane from posterior (tricuspid valve level) to anterior (pulmonary valve level) – lower Nyquist in early neonatal period due to low blood velocity in the context of higher pulmonary pressures in the first few days of life. With decrease pulmonary pressures in time, higher possible Nyquist. If VSD detected and aligned with jet: CW Doppler interrogation through the VSD for gradient velocity
i. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

2. Parasternal short axis view (PSA)

a. 2D anatomy sweep from the aortic level to the apex
b. 2D anatomy image of the aortic valve: confirmation of the tricuspid opening of the aortic valve – Fusion of leaflets may not be obvious and the valve need to be seen opening in a tri-leaflet manner
c. 2D anatomy and zoom on left coronary artery (LCA) opening and right coronary artery opening. Delimitation of coronary system anatomy including division with circumflex coronary from LCA. Color Doppler of LCA and RCA with demonstration of flow during diastole with low Nyquist velocity. Measurements of coronary if dilation.
d. 2D capture of the RV-LV interaction at the mid-papillary level. Evaluation of septal curvature at the end of systole. Septal curvature was described and validated for the end of systole. Clinically, septal curvature is often appreciated throughout the cardiac cycle: diastole and systole. Measurement of eccentricity index.
e. Confirmation of 2 LV papillary muscles (anterolateral and posteromedial).
f. M-mode can be taken at mid-papillary level for quantification of SF (if not done in the PLA)
g. Color Doppler of the septum from aortic valve area to the apex (lower Nyquist in early neonatal period, highest Nyquist possible for visualization of flow) to rule out VSD. Consider CW Doppler across detected VSD if aligned with jet.
h. 2D and Color Doppler at the tricuspid valve and CW Doppler interrogation if regurgitation present for estimation of RV pressure
i. 2D and Color Doppler at the pulmonary valve and branched pulmonary arteries and CW Doppler interrogation if insufficiency present.
    i. Sometimes, LPA and RPA bifurcation requires a different incidence - upper on the chest in PSA. Measure in 2D the left and right pulmonary arteries (LPA and RPA) at their maximum diameter. Look at flow with color Doppler. Interrogation of flow by PW and CW Doppler in MPA, LPA and RPA.
j. This is not the ideal view to look at the atrial septum, although it can be appreciated partly in this view. At the left atrial level, color Doppler with low Nyquist velocity could demonstrate pulmonary veins. However, the best views for pulmonary veins remain often in the suprasternal area. If pulmonary veins are visualized, confirmation of their introduction at the left

atrium needs to be done with PW Doppler at insertion for each pulmonary vein.

k. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

3. Apical view: 4 chambers, 5 chambers, LV 2 chambers

a. 2D anatomy sweep from posterior to anterior (posterior wall to pulmonary arteries) – appreciation of caliber of the coronary sinus (if dilated, look for bilateral SVC).
b. 2D evaluation of mitral and tricuspid valve with measurements (often requires two different views for their maximal size)
c. Color Doppler of mitral valve
d. Color Doppler of tricuspid valve
e. CW Doppler interrogation of tricuspid regurgitation with appropriate alignment
f. Pulsed wave (PW) Doppler at inlet of LV and RV (transmitral and transtricuspid flow)
    i. E and A waves of LV and RV inlet (tip of Mitral and Tricuspid valve)
    ii. Use of CW Doppler if acceleration (obstruction or regurgitation) in order to calculate mean and peak velocities
g. Color Doppler of septum from anterior to posterior for perimembranous and muscular VSDs (same concept applies for Nyquist velocity in the context of similar LV and RV afterload in the early life). Visualize the apex for apical VSD.
h. Left sided pulmonary veins and right superior pulmonary vein can sometimes be seen entering the left atrium in the apical 4 chamber view by color Doppler.
i. 5 Chamber view with anatomy demonstrating LV outflow tract (LVOT) with aortic valve and ascending aorta.
    i. Color Doppler of flow through LVOT. PW Doppler at subaortic outlet for signs of subaortic obstruction, CW Doppler in Ascending Aorta past the valve for signs of acceleration of flow. PW in ascending aorta past the aortic valve for VTI calculation.
    ii. Sweep anteriorly and 2D visualization of RV outflow tract (RVOT)
    iii. Color Doppler of RVOT with PW Doppler at subpulmonic area and CW/PW Doppler past the pulmonary valve in MPA.
    iv. Evaluation for pulmonary insufficiency and interrogation by CW Doppler.
    v. Sweep of septum in 5 chamber view from anterior to posterior for VSD detection. If VSD detected, CW Doppler gradient interrogation for gradient velocity
j. In evaluation of function:
    i. Ejection fraction by biplane Simpson's method using 4 chambers view and 2 chambers LV view.
    ii. Tissue Doppler imaging (TDI) with interrogation at MV annulus at LV free wall, MV annulus at septal wall and tricuspid annulus at RV

free wall; calculation of e', a', E/e', MPI (myocardial performance index or Tei index) of LV and RV, TAPSE (tricuspid annular plain systolic excursion).

k. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).
    i. In the context of pericardial fluid, inflow of mitral and tricuspid valve need to be interrogated by PW Doppler in a compressed time matter for signs of tamponade (evaluate for fluctuation in time of the velocity of inflow). If suspicion of tamponade, PW Doppler interrogation of SVC and IVC needs to be done in the subcostal view for retrograde flow assessment.

4. Subcostal view: long axis and short axis (SCL and SCS)

a. SCL view – coronal cut:
    i. SCL for situs evaluation (inferior vena cava (IVC) to the right and posterior compared to the descending aorta). Sweep to ensure connection of IVC to right atrium with cross-section of spine.
    ii. Visualization of a line in the IVC (in cross-section) at connection with the right atrium, or an umbilical arterial line in the descending aorta in cross-section.
    iii. Atrial septal 2D evaluation
    iv. Atrial septum color Doppler evaluation and measurement (consider PW Doppler interrogation if acceleration of shunt flow across atrial septal defect or patent foramen ovale; consider M-Mode with color Doppler to evaluate shunting direction of inter-atrial shunt)
    v. 2D scanning anatomy of SCL axis without color Doppler (establishing atrio-ventricular and ventriculo-arterial connections)
    vi. 2D scanning with color of SCL axis from posterior to anterior
    vii. 2D scanning of interventricular septum with color Doppler for detection of VSD with special interest at apex for apical VSD that can be missed easily
    viii. Evaluation of RV and RVOT in 2D motion for qualitative function looking at each segment from RV (inlet, midcavity, apex and RVOT) segmental contraction, especially in the context of pulmonary hypertension (some patients might have segmental wall dysfunction).
    ix. Evaluation by color Doppler of flow in LVOT to Aorta and in RVOT to pulmonary artery with no acceleration. Evaluation for pulmonary insufficiency and interrogation by CW Doppler.
    x. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).
b. SCS view – sagital cut:
    i. Evaluation of IVC connection to right atrium, visualization of line position
    ii. Color Doppler in IVC at RA junction with low Nyquist velocity

iii. Color Doppler of subhepatic veins with low Nyquist and PW Doppler of hepatic veins – evaluation of retrograde flow in the subhepatic veins as a sign of abnormal RV diastolic function
iv. 2D visualization of descending aorta (DesAo)
v. Color Doppler of DesAo with PW Doppler for evaluation of diastolic extension of flow (ex: such as in coarctation) or retrograde DesAo flow (steal effect from a significant patent ductus, steal from significant atrial insufficiency, aorto-ventricular tunnel, pulmonary to aortic window, etc.). Note that the Doppler sampling is done at diaphragmatic level with minimal angle of insonation.
vi. Some have advocated for evaluation of celiac flow by color Doppler in this view and with PW Doppler interrogation (peak, mean, end diastolic velocity) as a marker of intestinal steal during evaluation of PDA significance.
vii. 2D sweep of anatomy in SCS view from IVC/SVC to apex (establishing atrio-ventricular and ventriculo-arterial connections); although this is not the typical view to appreciate LV-RV interaction in terms of septal curvature, some might appreciate indirect signs of RV overload with bowing of septum to LV side. Validated evaluation of septal curvature was described only in the PSA view.
viii. Visualization of SVC to RA with 2D clip and color Doppler in bicaval view (showing IVC and right SVC junctions to right atrium)
ix. Color Doppler at junction of SVC and RA to rule out ASD of the sinus venosus defect type. Right superior pulmonary vein can be often seen in this area and a PW Doppler should be sampled.
x. Atrial septal scanning in SCS view with evaluation of rim size of ASD or PFO in 2D; evaluation of color Doppler with shunt direction through inter-atrial communication if present (low Nyquist velocity)
xi. Color Doppler of mitral valve, septum for VSD, LVOT and RVOT
xii. 2D evaluation of RVOT for subpulmonary RVOT narrowing and malalignment of muscular outlet septum
xiii. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

5. Modified Parasternal Short axis view (mPSA) or PDA view

a. View of PDA in 2D with connection from pulmonary to aortic side; measurements of PDA (prioritize 2D anatomy measurements of the narrowest point)
b. Color Doppler of PDA: shunt direction
c. CW Doppler of PDA: quantification of shunt gradient velocities
d. M-Mode with Color Doppler for shunt directionality

6. Suprasternal view short and long axis (SSS and SSL)

a. SSS view:
    i. Visualization of 2D anatomy with confirmation of left sided-arch and appropriate vessel branching to the right
    ii. Visualization of RPA course and Color Doppler for acceleration
    iii. Color Doppler of SVC to right atrium and innominate bridge

iv. Evaluation for possibility of left-sided SVC (especially in the context of a dilated coronary sinus) – rule out coarctation if presence of left SVC to coronary sinus.
v. Very anterior sweep for pulmonary veins evaluation ("crab view"): PW Doppler of the 4 pulmonary veins at their connection with the left atrium to rule out partial or total anomalous pulmonary venous return

b. SSL view
i. Visualization of 2D anatomy and measurements of aorta at Ascending Aorta, Transverse Aorta, Isthmus and Descending Aorta. Look for a posterior shelf at the descending aorta.
ii. Color Doppler for acceleration of flow and rule out coarctation; CW in the descending Aorta
1. Note that the PDA may be seen in many views, including this one
iii. PW Doppler in the distal descending Aorta, past the ductus for distal coarctation and flow pattern
iv. Second sweep in the neck in SSL for confirmation of right branching and left sided arch; rule out double arch

Middle cerebral artery:

- Some groups have used the PW Doppler profile and calculation of resistive index and pulsatility index, as well as pattern of diastolic flow in the middle cerebral artery as an indicator of PDA significance.

Special note on LV and RV cardiac output and SVC flow measurements by echocardiography:

It has been advocated by some studies and some group publishing on TNE to evaluate left and right cardiac output, as well as, SVC flow using echocardiography. When done systematically by an experienced sonographer, cardiac output estimation may be of interest. However, due to the extrapolation of a valvular surface area from a 2D measurement subject to inter-observer and intra-observer variability, this measurement can often be erroneous. Currently, the principle relies on measurement of the diameter of the respective outflow tract, with use of the velocity time integral (VTI = area under the curve during one systolic heartbeat of the PW Doppler tracing) of the respective outflow tract). The LVOT is measured in PLA and the PW Doppler envelope is measured in the apical 5 chamber view. The RVOT is measured in the PSA with the PW Doppler envelope interrogated in the same view. The cross-sectional area (CSA) of the outflow tracts is calculated with Pi/4 x Diameter^2. The cardiac output (CO) is extrapolated with VTI x CSA x Heart rate and is indexed by dividing by weight of the patient. CO is expressed in mL/Kg/min. The left ventricular cardiac output (LVO) is expressed in ml/kg/min. Normal values range from 170 to 450 ml/kg/min in neonates for LVO. Normal values range from 230 to 750 ml/kg/min in neonates for RV cardiac output.

The SVC flow is calculated with similar measurements. SVC measurements fluctuate with breathing. SVC is visualized in subcostal view at the bicaval view. The PW Doppler is

measured at the junction of the SVC and the right atrium. The average velocity is then calculated using the VTI of the curve. The 2D measurement of SVC is from the suprasternal short axis or high parasternal long axis view. Three to five 2D measurements should be done. SVC Flow is calculated with VTI x (Pi/4 x mean SVC diameter^2) x Heart rate / Body weight. A value below 40 ml/kg/min was associated with an increased risk of intra-ventricular haemorrhage and worst developmental outcomes in preterm infants.

B) <u>PDA Protocol:</u>

During echocardiography, always note: weight, age of patient, systemic blood pressure at the time of echocardiography. Record echocardiography with ECG recording. Scale of Nyquist velocity needs to be adapted in consideration of expected blood velocities.

In all the views, appreciate the subjective contraction of each portion of the left and right ventricles, looking at segmental decrease in contraction. For Tissue Doppler Imaging, acquire images at high frame rates (150 fps) and record multiples beats (5 per loop).

Specific markers of PDA significance:

- Size of PDA (by color and 2D, at its narrowest point)
- Color flow in PDA
- CW Doppler of PDA in Ductal view and gradient assessment
- LA/Ao ratio by M-mode (Normal if less than 1.4); signs of left sided volume overload (large left atrium, large left ventricle leading to mitral regurgitation and/or aortic insufficiency)
- LA/LPA ratio (Normal if less than 1)
- E/A Ratio of mitral valve inflow (more than 1.0)
- Retrograde flow in abdominal aorta during diastole (PW of Descending Aorta)
- Retrograde or absent flow in celiac/SMA
- Absent flow in the SMA (or resistive index more than 0.8 consistent with hsPDA)
- LV Output : RV Output ratio

Importance during assessment of PDA for closure or post-closure:

- Ensure no coarctation / RVOT or LVOT obstruction pre-closure
- Ensure no residual PDA, no obstruction in aorta or pulmonary artery post-ligation
- Assessment of function post-ligation is essential

<u>Views for PDA protocol:</u> *This protocol must be applied after first study done by cardiology and after ruling out the possibility of a ductal-dependent cardiac defect. One must be cautious in the context of a closed ductus to ensure that there is no underlying coarctation. The PDA protocol is to follow premature newborns when there is suspicion of a hemodynamically significant ductus, or as part of a treatment with NSAIDs or surrounding ligation (pre and post-OR).*

a) **Parasternal long axis view (PLA):** The septum is nearly horizontal, and deviates less than 30° from the horizontal plane. The aortic valve and mitral valve are each

displayed, as is the proximal aorta. The ventricular septum should be seen 2/3 to the apex.

a. 2D image at the level of mitral and aortic valve, aortic root and cusps. – 2D anatomy, Color Doppler on mitral valve, aortic valve
b. Sweep posterior at the level of RV inflow (tricuspid valve) – 2D anatomy and Color Doppler on tricuspid valve
c. Sweep anterior at the level of RV outflow tract (pulmonary valve and pulmonary artery) – 2D anatomy - Color Doppler on pulmonary valve, as well as pulmonary artery – PW Doppler at pulmonary valve leaflets attachment and in MPA. PDA might be viewed by color in this incidence.
d. Continuous wave (CW) Doppler interrogation of valvar insufficiency at tricuspid and pulmonary level if present and if aligned appropriately. Measure peak TR gradient, early diastolic and end diastolic PI gradient.
e. M-mode of left and right ventricle at the level of tip of mitral valve with line of interrogation perpendicular to interventricular septum for measurement of shortening fraction (SF) and measurements of LV / RV / Septum / Posterior wall thickness (only valid in normal biventricular anatomy), measurement of R-R interval.
f. M-mode at the closure of aortic valve and with line of interrogation perpendicular to aorta for: Left atrial on aorta ratio (detection of signs of LV overload, or small aortic valve). Evaluation of LV ejection time from opening to closure of aortic valve.
g. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

7. Parasternal short axis view (PSA)

a. 2D anatomy sweep from the aortic level to the apex
b. 2D capture of the RV-LV interaction at the mid-papillary level. Evaluation of septal curvature at the end of systole. Clinically, septal curvature is often appreciated throughout the cardiac cycle: diastole and systole.
c. M-mode can be taken at mid-papillary level for quantification of SF (if not done in the PLA)
d. Color Doppler of the septum from aortic valve area to the apex
e. 2D and Color Doppler at the tricuspid valve and CW Doppler interrogation if regurgitation present for estimation of RV pressure
f. 2D and Color Doppler at the pulmonary valve and branched pulmonary arteries and CW Doppler interrogation if insufficiency present. PDA might be viewed by color in this incidence. 2D measurement of RPA and LPA for ratio PDA to LPA. Color Doppler and CW/PW of both RPA and LPA (post-ligation, need to rule out obstruction of a pulmonary artery).
g. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

8. Modified Parasternal Short axis view (mPSA) or PDA view

a. View of PDA in 2D with connection from pulmonary to aortic side; measurements of PDA (prioritize 2D anatomy measurements of the narrowest point)
b. Color Doppler of PDA: shunt direction

c. CW Doppler of PDA: quantification of shunt gradient velocities
d. M-Mode with Color Doppler for shunt directionality

9. Apical view: 4 chambers, 5 chambers, LV 2 chambers

a. 2D anatomy sweep from posterior to anterior (posterior wall to pulmonary arteries)
b. 2D evaluation of mitral and tricuspid valve
c. Color Doppler of mitral valve
d. Color Doppler of tricuspid valve
e. CW Doppler interrogation of tricuspid regurgitation with appropriate alignment
f. Pulsed wave (PW) Doppler at inlet of LV and RV (transmitral and transtricuspid flow)
    i. E and A waves of LV and RV inlet (tip of Mitral and Tricuspid valve)
g. Color Doppler of septum from anterior to posterior
h. 5 Chamber view with anatomy demonstrating LV outflow tract (LVOT) with aortic valve and ascending aorta.
    i. Color Doppler of flow through LVOT. PW in ascending aorta past the aortic valve for VTI calculation.
    ii. Sweep anteriorly and 2D visualization of RV outflow tract (RVOT). Color Doppler of RVOT with PW Doppler past the pulmonary valve in MPA.
i. Ejection fraction by biplane Simpson's method using 4 chambers view and 2 chambers LV view.
j. Tissue Doppler imaging (TDI) with interrogation at MV annulus at LV free wall, calculation of e', a', E/e', MPI (myocardial performance index or Tei index) of LV
k. TAPSE (tricuspid annular plain systolic excursion).
l. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

10. Subcostal view: long axis and short axis (SCL and SCS)

a. SCL view – coronal cut:
    i. Atrial septal 2D evaluation
    ii. Atrial septum color Doppler evaluation
    iii. 2D scanning anatomy of SCL axis with and without color Doppler.
b. SCS view – sagital cut:
    i. Evaluation of IVC connection to right atrium, visualization of line position
    ii. 2D visualization of descending aorta (DesAo)
    iii. Color Doppler of DesAo with PW Doppler for evaluation of diastolic extension of flow (ex: such as in coarctation) or retrograde DesAo flow (steal effect from a significant patent ductus, steal from significant atrial insufficiency, aorto-ventricular tunnel, pulmonary to aortic window, etc.). Note that the Doppler sampling is done at diaphragmatic level with minimal angle of insonation.

iv. Some have advocated for evaluation of celiac flow by color Doppler in this view and with PW Doppler interrogation (peak, mean, end diastolic velocity) as a marker of intestinal steal during evaluation of PDA significance.
v. 2D sweep of anatomy in SCS view from IVC/SVC to apex (establishing atrio-ventricular and ventriculo-arterial connections) + Color Doppler
vi. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

11. Suprasternal view short and long axis (SSS and SSL)

a. SSL view
   i. Visualization of 2D anatomy of Ascending Aorta, Transverse Aorta, Isthmus and Descending Aorta. Look for a posterior shelf at the descending aorta.
   ii. Color Doppler for acceleration of flow and rule out coarctation (in the context of a post-ligation study, need to rule out aortic obstruction); CW in the descending Aorta
      1. Note that the PDA may be seen in many views, including this one
   iii. PW Doppler in the distal descending Aorta, past the ductus for distal coarctation and flow pattern

12. RV and LV cardiac output calculations

Middle cerebral artery:

- Some groups have used the PW Doppler profile and calculation of resistive index and pulsatility index, as well as pattern of diastolic flow in the middle cerebral artery as an indicator of PDA significance.

C) <u>Heart function protocol</u>

During echocardiography, always note: weight, age of patient, systemic blood pressure at the time of echocardiography. Record echocardiography with ECG recording. Scale of Nyquist velocity needs to be adapted in consideration of expected blood velocities. In all the views, appreciate the subjective contraction of each portion of the left and right ventricles, looking at segmental decrease in contraction. For Tissue Doppler Imaging, acquire images at high frame rates (150 fps) and record multiples beats (5 per loop).

Goal of the heart function protocol

- Assessment of myocardial performance (RV and LV)
- Assessment of pulmonary pressures and shunts (at ductal and atrial level), such as in the context of shock or HIE
- Assessment of cardiac output (RV and LV)
- Rule out anatomic obstruction causing disturbed function
- Rule out cardiac tamponade

<u>Views and comprehensive first study:</u>

2) **Parasternal long axis view (PLA):** The septum is nearly horizontal, and deviates less than 30° from the horizontal plane. The aortic valve and mitral valve are each displayed, as is the proximal aorta. The ventricular septum should be seen 2/3 to the apex.

    j. 2D image at the level of mitral and aortic valve, aortic root and cusps. 2D anatomy, Color Doppler on mitral valve, aortic valve
    k. Sweep posterior at the level of RV inflow (tricuspid valve) – 2D anatomy and Color Doppler on tricuspid valve
    l. Sweep anterior at the level of RV outflow tract (pulmonary valve and pulmonary artery) – 2D anatomy - Color Doppler on pulmonary valve, as well as pulmonary artery – PW Doppler at pulmonary valve leaflets attachment and in MPA
    m. Continuous wave (CW) Doppler interrogation of valvar insufficiency at tricuspid and pulmonary level if present and if aligned appropriately. Measure peak TR gradient, early diastolic and end diastolic PI gradient.
    n. Sweep from posterior to anterior to establish atrio-ventricular and ventriculo-arterial connections
    o. M-mode of left and right ventricle at the level of tip of mitral valve with line of interrogation perpendicular to interventricular septum for measurement of shortening fraction (SF) and measurements of LV / RV / Septum / Posterior wall thickness (only valid in normal biventricular anatomy), measurement of R-R interval.
    p. M-mode at the closure of aortic valve and with line of interrogation perpendicular to aorta for: Left atrial on aorta ratio (detection of signs of LV overload, or small aortic valve). Evaluation of LV ejection time from opening to closure of aortic valve.
    q. Color Doppler of all interventricular septum
    r. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

13. Parasternal short axis view (PSA)

    a. 2D anatomy sweep from the aortic level to the apex
    b. 2D anatomy image of the aortic valve
    c. 2D capture of the RV-LV interaction at the mid-papillary level. Evaluation of septal curvature at the end of systole. Septal curvature was described and validated for the end of systole. Clinically, septal curvature is often appreciated throughout the cardiac cycle: diastole and systole. Measurement of eccentricity index.
    d. M-mode can be taken at mid-papillary level for quantification of SF (if not done in the PLA)
    e. Color Doppler of the septum from aortic valve area to the apex
    f. 2D and Color Doppler at the tricuspid valve and CW Doppler interrogation if regurgitation present for estimation of RV pressure
    g. 2D and Color Doppler at the pulmonary valve and branched pulmonary arteries and CW Doppler interrogation if insufficiency present.

i. Sometimes, LPA and RPA bifurcation requires a different incidence - upper on the chest in PSA. Look at flow with color Doppler. Interrogation of flow by PW and CW Doppler in MPA, LPA and RPA.

h. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

14. Apical view: 4 chambers, 5 chambers, LV 2 chambers

a. 2D anatomy sweep from posterior to anterior (posterior wall to pulmonary arteries)
b. 2D evaluation of mitral and tricuspid valve with measurements (often requires two different views for their maximal size)
c. Color Doppler of mitral valve
d. Color Doppler of tricuspid valve
e. CW Doppler interrogation of tricuspid regurgitation with appropriate alignment
f. Pulsed wave (PW) Doppler at inlet of LV and RV (transmitral and transtricuspid flow)
    i. E and A waves of LV and RV inlet (tip of Mitral and Tricuspid valve)
    ii. Use of CW Doppler if acceleration (obstruction or regurgitation) in order to calculate mean and peak velocities
g. Color Doppler of septum from anterior to posterior
h. 5 Chamber view with anatomy demonstrating LV outflow tract (LVOT) with aortic valve and ascending aorta.
    i. Color Doppler of flow through LVOT. PW Doppler at subaortic outlet for signs of subaortic obstruction, CW Doppler in Ascending Aorta past the valve for signs of acceleration of flow. PW in ascending aorta past the aortic valve for VTI calculation.
    ii. Sweep anteriorly and 2D visualization of RV outflow tract (RVOT)
    iii. Color Doppler of RVOT with PW Doppler at subpulmonic area and CW/PW Doppler past the pulmonary valve in MPA.
    iv. Evaluation for pulmonary insufficiency and interrogation by CW Doppler.
i. In evaluation of function:
    i. Ejection fraction by biplane Simpson's method using 4 chambers view and 2 chambers LV view.
    ii. Tissue Doppler imaging (TDI) with interrogation at MV annulus at LV free wall, MV annulus at septal wall and tricuspid annulus at RV free wall; calculation of e', a', E/e', MPI (myocardial performance index or Tei index) of LV and RV
    iii. TAPSE (tricuspid annular plain systolic excursion).
j. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).
    i. In the context of pericardial fluid, inflow of mitral and tricuspid valve need to be interrogated by PW Doppler in a compressed time matter for signs of tamponade (evaluate for fluctuation in time of the

velocity of inflow). If suspicion of tamponade, PW Doppler interrogation of SVC and IVC needs to be done in the subcostal view for retrograde flow assessment.

15. Subcostal view: long axis and short axis (SCL and SCS)

a. SCL view – coronal cut:
   i. 2D Sweep to ensure connection of IVC to right atrium with cross-section of spine.
   ii. Atrial septal 2D evaluation
   iii. Atrial septum color Doppler evaluation and measurement (consider PW Doppler interrogation if acceleration of shunt flow across atrial septal defect or patent foramen ovale; consider M-Mode with color Doppler to evaluate shunting direction of inter-atrial shunt)
   iv. 2D scanning with color of SCL axis from posterior to anterior
   v. Evaluation of RV and RVOT in 2D motion for qualitative function looking at each segment from RV (inlet, midcavity, apex and RVOT) segmental contraction, especially in the context of pulmonary hypertension (some patients might have segmental wall dysfunction).
   vi. Evaluation by color Doppler of flow in LVOT to Aorta and in RVOT to pulmonary artery with no acceleration. Evaluation for pulmonary insufficiency and interrogation by CW Doppler.
   vii. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

b. SCS view – sagital cut:
   i. Color Doppler in IVC at RA junction with low Nyquist velocity
   ii. Color Doppler of subhepatic veins with low Nyquist and PW Doppler of hepatic veins – evaluation of retrograde flow in the subhepatic veins as a sign of abnormal RV diastolic function
   iii. 2D visualization of descending aorta (DesAo)
   iv. Color Doppler of DesAo with PW Doppler for evaluation of diastolic extension of flow. Note that the Doppler sampling is done at diaphragmatic level with minimal angle of insonation.
   v. 2D sweep of anatomy in SCS view from IVC/SVC to apex (establishing atrio-ventricular and ventriculo-arterial connections); although this is not the typical view to appreciate LV-RV interaction in terms of septal curvature, some might appreciate indirect signs of RV overload with bowing of septum to LV side. Validated evaluation of septal curvature was described only in the PSA view.
   vi. Visualization of SVC to RA with 2D clip and color Doppler in bicaval view (showing IVC and right SVC junctions to right atrium)
   vii. Atrial septal scanning in SCS view with evaluation of rim size of ASD or PFO in 2D; evaluation of color Doppler with shunt direction through inter-atrial communication if present (low Nyquist velocity)
   viii. Color Doppler of mitral valve, septum for VSD, LVOT and RVOT
   ix. 2D evaluation of RVOT

x. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

16. Modified Parasternal Short axis view (mPSA) or PDA view

a. View of PDA in 2D with connection from pulmonary to aortic side; measurements of PDA (prioritize 2D anatomy measurements of the narrowest point)
b. Color Doppler of PDA: shunt direction
c. CW Doppler of PDA: quantification of shunt gradient velocities
d. M-Mode with Color Doppler for shunt directionality

17. Suprasternal view short and long axis (SSS and SSL)

a. SSS view:
    i. Visualization of 2D anatomy
    ii. Color Doppler of SVC to right atrium and innominate bridge
    iii. Very anterior sweep for pulmonary veins evaluation ("crab view"): PW Doppler of the 4 pulmonary veins at their connection with the left atrium to rule out partial or total anomalous pulmonary venous return
b. SSL view
    i. Visualization of 2D anatomy of aorta at Ascending Aorta, Transverse Aorta, Isthmus and Descending Aorta. Look for a posterior shelf at the descending aorta.
    ii. Color Doppler for acceleration of flow and rule out coarctation; CW in the descending Aorta
        1. Note that the PDA may be seen in many views, including this one

LV and RVOT assessment

D) <u>Pulmonary Hypertension protocol:</u>

During echocardiography, always note: weight, age of patient, systemic blood pressure at the time of echocardiography. Record echocardiography with ECG recording. Scale of Nyquist velocity needs to be adapted in consideration of expected blood velocities. In all the views, appreciate the subjective contraction of each portion of the left and right ventricles, looking at segmental decrease in contraction. For Tissue Doppler Imaging, acquire images at high frame rates (150 fps) and record multiples beats (5 per loop).

<u>Goals of PH protocol:</u>

- Assessment of pulmonary pressures and right ventricular function
- Prior to the start of medications affecting the pulmonary vascular bed (e.g. iNO, milrinone, sildenafil, bosentan, prostacyclin analogs), such as in the context of PPHN
    - To assess response to therapy (e.g. iNO)
- For screening of PH in patients with bronchopulmonary dysplasia (not initial study)
- For follow-up evaluations of patients with congenital diaphragmatic hernia

Views to acquire on a PH protocol:

3) **Parasternal long axis view (PLA):** The septum is nearly horizontal, and deviates less than 30° from the horizontal plane. The aortic valve and mitral valve are each displayed, as is the proximal aorta. The ventricular septum should be seen 2/3 to the apex.

    s. 2D image at the level of mitral and aortic valve, aortic root and cusps. Aortic valve, aortic root and ascending aorta – 2D anatomy, Color Doppler on mitral valve, aortic valve
    t. Sweep posterior at the level of RV inflow (tricuspid valve) – 2D anatomy and Color Doppler on tricuspid valve
    u. Sweep anterior at the level of RV outflow tract (pulmonary valve and pulmonary artery) – 2D anatomy - Color Doppler on pulmonary valve, as well as pulmonary artery – PW Doppler at pulmonary valve leaflets attachment and in MPA
    v. Continuous wave (CW) Doppler interrogation of valvar insufficiency at tricuspid and pulmonary level if present and if aligned appropriately. Measure peak TR gradient, early diastolic and end diastolic PI gradient.
    w. Sweep from posterior to anterior; subjective assessment of RV function
    x. M-mode of left and right ventricle at the level of tip of mitral valve with line of interrogation perpendicular to interventricular septum for measurement of shortening fraction (SF) and measurements of LV / RV / Septum / Posterior wall thickness (only valid in normal biventricular anatomy), measurement of R-R interval.
    y. M-mode at the closure of aortic valve and with line of interrogation perpendicular to aorta for: Left atrial on aorta ratio (detection of signs of LV overload, or small aortic valve). Evaluation of LV ejection time from opening to closure of aortic valve.
    z. Color Doppler of all interventricular septum for detection of VSDs (visualize up to the apex). Sweep in every plane from posterior (tricuspid valve level) to anterior (pulmonary valve level) – lower Nyquist in early neonatal period due to low blood velocity in the context of higher pulmonary pressures in the first few days of life. With decrease pulmonary pressures in time, higher possible Nyquist. If VSD detected and aligned with jet: CW Doppler interrogation through the VSD for gradient velocity
    aa. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

18. Parasternal short axis view (PSA)

    a. 2D anatomy sweep from the aortic level to the apex
    b. 2D capture of the RV-LV interaction at the mid-papillary level. Evaluation of septal curvature at the end of systole. Septal curvature was described and validated for the end of systole. Clinically, septal curvature is often appreciated throughout the cardiac cycle: diastole and systole. Measurement of eccentricity index.
    c. M-mode can be taken at mid-papillary level for quantification of SF (if not done in the PLA)

d. Color Doppler of the septum from aortic valve area to the apex. Consider CW Doppler across detected VSD if aligned with jet.
e. 2D and Color Doppler at the tricuspid valve and CW Doppler interrogation if regurgitation present for estimation of RV pressure
f. 2D and Color Doppler at the pulmonary valve and branched pulmonary arteries and CW Doppler interrogation if insufficiency present.
    i. Sometimes, LPA and RPA bifurcation requires a different incidence - upper on the chest in PSA. Measure in 2D the left and right pulmonary arteries (LPA and RPA) at their maximum diameter. Look at flow with color Doppler. Interrogation of flow by PW and CW Doppler in MPA, LPA and RPA.
g. This is not the ideal view to look at the atrial septum, although it can be appreciated partly in this view. At the left atrial level, color Doppler with low Nyquist velocity could demonstrate pulmonary veins. However, the best views for pulmonary veins remain often in the suprasternal area. If pulmonary veins are visualized, confirmation of their introduction at the left atrium needs to be done with PW Doppler at insertion for each pulmonary vein.
h. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

19. Apical view: 4 chambers, 5 chambers, LV 2 chambers

a. 2D anatomy sweep from posterior to anterior (posterior wall to pulmonary arteries)
b. 2D evaluation of mitral and tricuspid valve
c. Color Doppler of mitral valve
d. Color Doppler of tricuspid valve
e. CW Doppler interrogation of tricuspid regurgitation with appropriate alignment
f. Pulsed wave (PW) Doppler at inlet of LV and RV (transmitral and transtricuspid flow)
    i. E and A waves of LV and RV inlet (tip of Mitral and Tricuspid valve)
g. Color Doppler of septum from anterior to posterior
h. Left sided pulmonary veins and right superior pulmonary vein can sometimes be seen entering the left atrium in the apical 4 chamber view by color Doppler.
i. 5 Chamber view with anatomy demonstrating LV outflow tract (LVOT) with aortic valve and ascending aorta.
    i. Color Doppler of flow through LVOT. PW in ascending aorta past the aortic valve for VTI calculation.
    ii. Sweep anteriorly and 2D visualization of RV outflow tract (RVOT)
    iii. Color Doppler of RVOT with PW Doppler past the pulmonary valve in MPA
    iv. Evaluation for pulmonary insufficiency and interrogation by CW Doppler.
j. In evaluation of function:

i. Ejection fraction by biplane Simpson's method using 4 chambers view and 2 chambers LV view.
ii. Tissue Doppler imaging (TDI) with interrogation at MV annulus at LV free wall, MV annulus at septal wall and tricuspid annulus at RV free wall; calculation of e', a', E/e', MPI (myocardial performance index or Tei index) of LV and RV
iii. TAPSE (tricuspid annular plain systolic excursion).

k. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

20. Subcostal view: long axis and short axis (SCL and SCS)

a. SCL view – coronal cut:
   i. Sweep to ensure connection of IVC to right atrium with cross-section of spine.
   ii. Atrial septal 2D evaluation
   iii. Atrial septum color Doppler evaluation and measurement (consider PW Doppler interrogation if acceleration of shunt flow across atrial septal defect or patent foramen ovale; consider M-Mode with color Doppler to evaluate shunting direction of inter-atrial shunt)
   iv. 2D scanning anatomy of SCL axis without color Doppler (establishing atrio-ventricular and ventriculo-arterial connections)
   v. 2D scanning with color of SCL axis from posterior to anterior
   vi. Evaluation of RV and RVOT in 2D motion for qualitative function looking at each segment from RV (inlet, midcavity, apex and RVOT) segmental contraction, especially in the context of pulmonary hypertension (some patients might have segmental wall dysfunction).
   vii. Evaluation by color Doppler of flow in LVOT to Aorta and in RVOT to pulmonary artery with no acceleration. Evaluation for pulmonary insufficiency and interrogation by CW Doppler.
   viii. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

b. SCS view – sagital cut:
   i. Evaluation of IVC connection to right atrium
   ii. Color Doppler in IVC at RA junction with low Nyquist velocity
   iii. Color Doppler of subhepatic veins with low Nyquist and PW Doppler of hepatic veins – evaluation of retrograde flow in the subhepatic veins as a sign of abnormal RV diastolic function
   iv. 2D visualization of descending aorta (DesAo)
   v. Color Doppler of DesAo with PW. Note that the Doppler sampling is done at diaphragmatic level with minimal angle of insonation.
   vi. 2D sweep of anatomy in SCS view from IVC/SVC to apex (establishing atrio-ventricular and ventriculo-arterial connections); although this is not the typical view to appreciate LV-RV interaction in terms of septal curvature, some might appreciate indirect signs of RV overload with bowing of septum to LV side. Validated evaluation of septal curvature was described only in the PSA view.

vii. Visualization of SVC to RA with 2D clip and color Doppler in bicaval view (showing IVC and right SVC junctions to right atrium)
viii. Atrial septal scanning in SCS view with evaluation of rim size of ASD or PFO in 2D; evaluation of color Doppler with shunt direction through inter-atrial communication if present (low Nyquist velocity)
ix. Color Doppler of mitral valve, septum for VSD, LVOT and RVOT
x. 2D evaluation of RVOT
xi. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

21. Modified Parasternal Short axis view (mPSA) or PDA view

a. View of PDA in 2D with connection from pulmonary to aortic side; measurements of PDA (prioritize 2D anatomy measurements of the narrowest point)
b. Color Doppler of PDA: shunt direction
c. CW Doppler of PDA: quantification of shunt gradient velocities
d. M-Mode with Color Doppler for shunt directionality

22. Suprasternal view short and long axis (SSS and SSL)

a. SSS view:
    i. Visualization of 2D anatomy
    ii. Visualization of RPA course and Color Doppler for acceleration
    iii. Very anterior sweep for pulmonary veins evaluation ("crab view"): PW Doppler of the 4 pulmonary veins at their connection with the left atrium to rule out partial or total anomalous pulmonary venous return
b. SSL view
    i. Visualization of 2D anatomy of aorta at Ascending Aorta, Transverse Aorta, Isthmus and Descending Aorta.
    ii. Color Doppler of Aorta; CW in the descending Aorta
        1. Note that the PDA may be seen in many views, including this one

Calculation of RV and LV cardiac output

E) <u>Line placements / ECMO Cannulas</u>

Point of care ultrasound for the evaluation of line placements:

Subcostal view: long axis and short axis (SCL and SCS)

a. SCL view – coronal cut:
    i. Sweep to ensure connection of IVC to right atrium with cross-section of spine.
    ii. Visualization of a line in the IVC (in cross-section) at connection with the right atrium, or an umbilical arterial line in the descending aorta in cross-section.
    iii. Atrial septum evaluation with sweep to ensure to passage of line to the left atrium.

iv. 2D scanning with and without color of SCL axis from posterior to anterior
v. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

b. SCS view – sagital cut:
i. Evaluation of IVC connection to right atrium, visualization of line position
ii. Color Doppler in IVC at RA junction with low Nyquist velocity
iii. 2D visualization of descending aorta (DesAo) and presence of aortic line
iv. Color Doppler of DesAo with PW
v. 2D sweep of anatomy in SCS
vi. Visualization of SVC to RA with 2D clip and color Doppler in bicaval view (showing IVC and right SVC junctions to right atrium) – ensure line from IVC not going to SVC or left atrium via inter-atrial communication
vii. Atrial septal scanning in SCS view with evaluation of rim size of ASD or PFO in 2D; evaluation of color Doppler with shunt direction through inter-atrial communication if present (low Nyquist velocity)
viii. Evaluation of pericardial fluid and measurement at end of diastole (largest filling of ventricle).

c. In the context of pericardial fluid, in Apical 4 chambers view: inflow of mitral and tricuspid valve need to be interrogated by PW Doppler in a compressed time matter for signs of tamponade (evaluate for fluctuation in time of the velocity of inflow). If suspicion of tamponade, PW Doppler interrogation of SVC and IVC needs to be done in the subcostal view for retrograde flow assessment.