Faculty and Postdoc, Medical, Biomedical and Health Sciences

Assessment of human fetal heart hemodynamics during prenatal development

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BACKGROUND

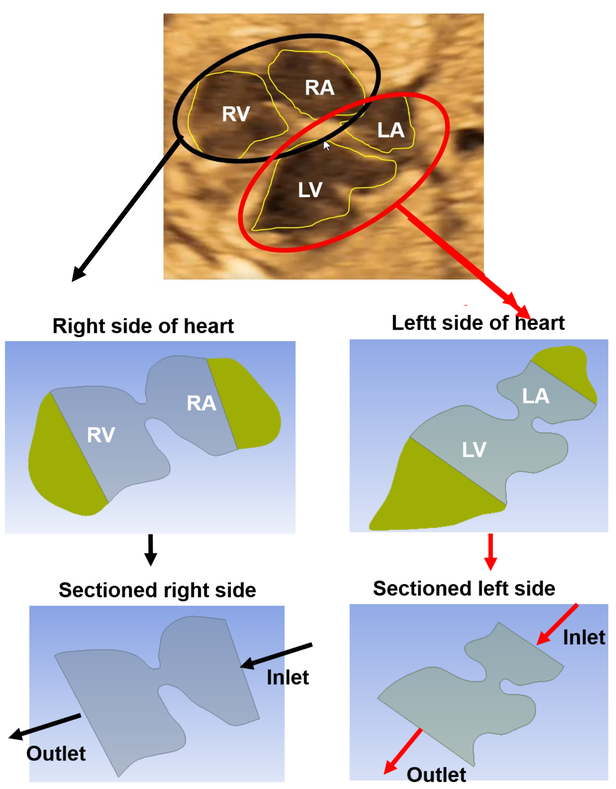
- The hemodynamic forces and wall shear stresses (WSS) play an important role during the fetal heart development.
- Abnormal levels of flow-driven shear stress can deteriorate the proper functioning of the cells responsible for the growth and remodeling of the heart and lead to congenital heart defects (CHDs).
- Hypoplastic left heart syndrome (HLHS) is a critical CHD with severely underdeveloped left ventricle and responsible for 25-40% of all neonatal cardiac deaths.
- The comparison of healthy and HLHS fetal hearts is important to understand the embryonic development of HLHS.

OBJECTIVE

- To characterize the main differences between the healthy and defective fetal hearts in terms of morphological growth, flow behavior, and WSS levels which will help to understand the mechanobiological development of the human fetal hearts.

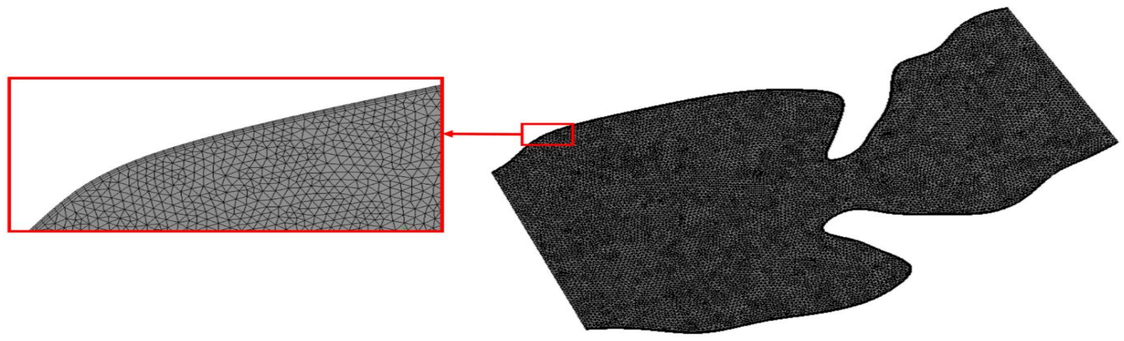
METHODS

- Generation of model geometry and defining boundary conditions:

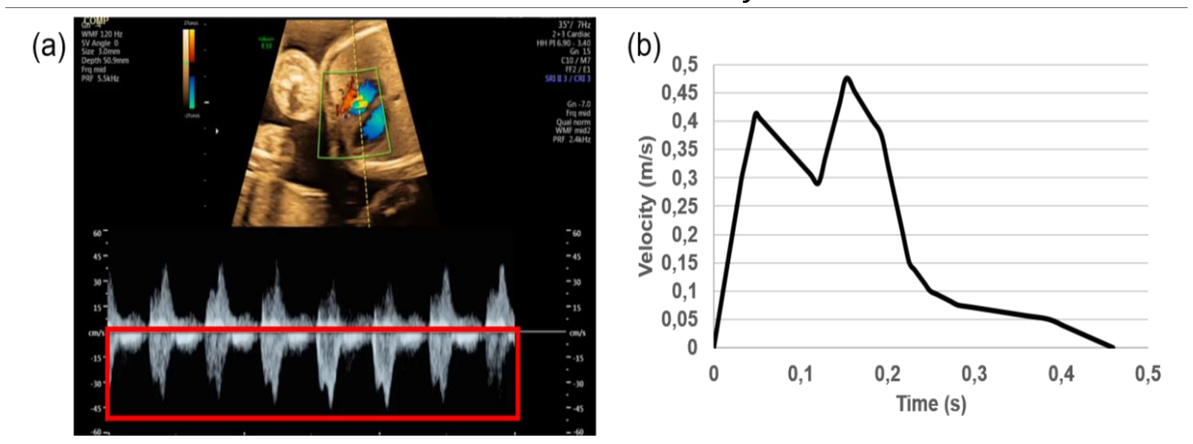


- Medical images are used to determine the borders of the fetal heart chambers.
- Left and right sides of healthy and defective hearts are investigated separately.
- About half of the chambers is removed to apply the inlet and outlet boundary conditions.
- Inlet flow conditions are determined using Doppler ultrasound velocity measurements.
- Computational fluid dynamics (CFD) simulations are performed using ANSYS Fluent solver for obtaining the flow field inside the heart.
- Flow velocities, pressures, WSS levels, and heart chamber areas are compared for the healthy and HLHS hearts.

- Meshing the generated model geometries for the CFD simulations:

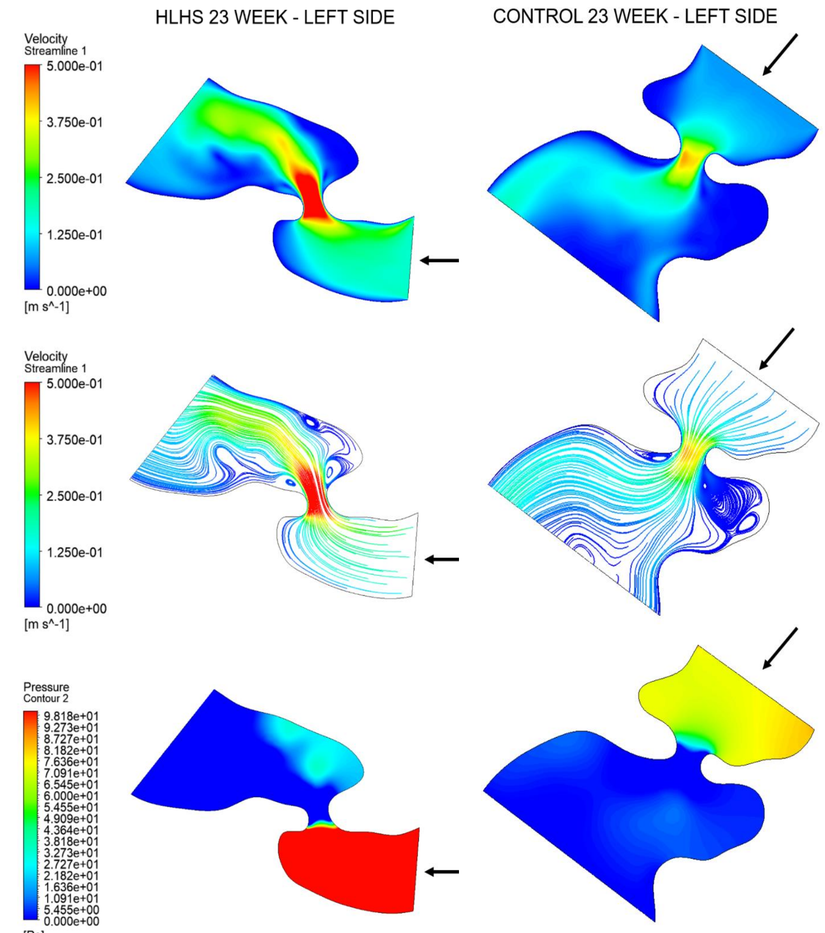


A sample mesh used to solve the governing flow equations in the CFD analysis. The mesh density is increased near the walls in order to improve the solution accuracy.



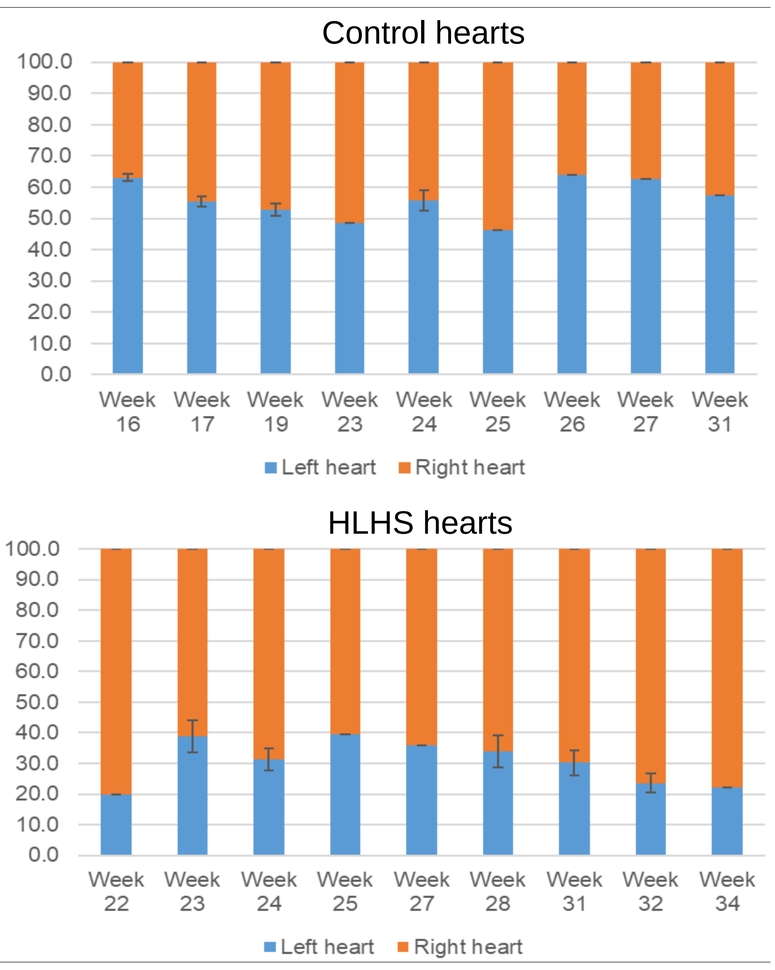
A sample Doppler ultrasound measurement in a human fetal heart.
(a) The red box shows the flow waveforms measured in the mitral valve.
(b) Mitral valve flow waveform as a function of time for one cardiac cycle.

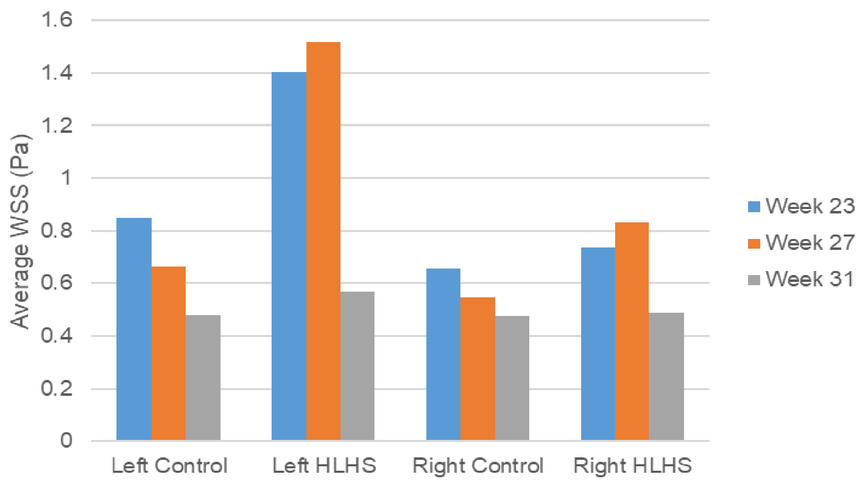
RESULTS



- The presented plots show the velocity and pressure contours at the instant of peak valve flow rates.
- High velocity flow jets are observed at the valve locations.
- HLHS hearts have higher peak flow rates in the valves compared to the control hearts.
- The turbulent activity in the left side of the heart is higher than the right side.
- The pressures drop significantly at the valve locations due to the reduced flow area.

- For the control hearts, there is a balance between the left and right sides of the heart which is preserved during the development.
- For the control hearts, the area ratio between the left and right sides of the heart is about 57.5% to 42.5%.
- HLHS significantly reduces the cross-sectional area of the left side of the heart.
- For the HLHS hearts, the area ratio between the left and right sides becomes about 30% to 70%.
- For the HLHS hearts, the left/right area ratio tends to decrease as the heart develops.





Comparison of WSS for the control and HLHS hearts

- The average wall shear stress (WSS) levels significantly increase in the left side of the HLHS hearts.
- WSS levels tend to scale down with increasing weeks of gestation.

CONCLUSION

- The presence of CHDs alters the biomechanical environment and hemodynamics in the fetal hearts.
- HLHS leads to a significant increase in the WSS levels, particularly in the left side of the fetal hearts.
- In HLHS hearts, the ratio of cross-sectional area between the left and right sides of the heart changes drastically due to the underdeveloped left side.