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From bench to bedside: Hemodynamic analysis using 4D flow MRI

Hyungkyu Huh

Daegu Gyeongbuk Medical Innovation Foundation (K-Medi Hub), Korea

The clinical utility of four-dimensional flow magnetic resonance imaging (4D flow MRI) is rapidly expanding in the diagnosis of cardiac and vascular conditions. This growth has been made possible by significant technological advancements in MR hardware and the development of AI-based fast image acquisition and reconstruction techniques, which have streamlined workflows and made clinical application more feasible. By moving beyond a qualitative assessment of anatomy, 4D flow MRI provides a comprehensive, four-dimensional perspective on blood flow dynamics, thereby enhancing the diagnostic value for cardiovascular diseases.

The 4D flow MRI methodology can derive a variety of sophisticated hemodynamic parameters based on the time-resolved 3D velocity field, such as pulse wave velocity, vortex formation, and turbulent kinetic energy. These parameters are critical for understanding complex cardiovascular phenomena and are expected to provide crucial, patient-specific insights into abnormal flow patterns, serving as a valuable complement to conventional CMR. However, the development of such parameters requires well-controlled validation before they can be considered clinically applicable. Furthermore, imaging protocols must be meticulously optimized based on the specific hemodynamic parameters being investigated.

This presentation will introduce in-vitro experiments using a dedicated phantom model to establish baseline accuracy and validate the theoretical foundation of a proposed parameter. Subsequently, in-vivo human and animal studies will be discussed, which serve to bridge the gap between idealized laboratory conditions and the complexities of real-world physiological and pathological states. The presentation will also detail imaging protocols and gating strategies designed to ensure data accuracy and mitigate common artifacts. We will conclude with a review of recent research and clinical applications, highlighting the path forward for translating these advanced hemodynamic diagnostic methods into viable, routine clinical tools.

Keywords: *4D flow MRI, Hemodynamic parameters, Cardiovascular diseases*