Redefining MRI:
From Image to Insight

ICMRI 2026
THE 14th INTERNATIONAL CONGRESS ON MRI
& 31st ANNUAL SCIENTIFIC MEETING OF KSMRM

AUGUST 27 - 28, 2026
Grand Walkerhill Seoul, Seoul, Korea
https://icmri.ksmrm.org/2026m

Cardiovascular 1

SY20-1

Engineer's View Point of 4D Flow MRI

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Four-dimensional (4D) Flow MRI sits at the intersection of fluid mechanics and medical imaging. To an engineer, it is best understood as a measurement instrument: a phase-contrast acquisition that encodes three-directional velocity throughout a three-dimensional volume across the cardiac cycle, effectively turning the MR scanner into a non-invasive, in-vivo velocimetry system conceptually analogous to laboratory particle image velocimetry (PIV). From this single acquisition, the full velocity field yields quantitative hemodynamic parameters—peak velocity, flow rate, regurgitant fraction, wall shear stress, kinetic energy, viscous energy loss, pressure gradient, and turbulent kinetic energy—that are difficult or impossible to obtain by any other modality.

This lecture takes the engineer's view and follows the full measurement chain that converts raw signal into a clinically meaningful number. (1) Acquisition: the trade-offs among spatial resolution, temporal resolution, scan time, and velocity-encoding (VENC) selection, and how aliasing, displacement, and noise enter the data. (2) Preprocessing: eddy-current and Maxwell-term correction, phase unwrapping, and noise masking, and their downstream impact on every derived quantity. (3) Segmentation and analysis-plane placement: the geometric definitions that decide whether a derived value is physically meaningful. (4) Quantification: the numerical operators—spatial gradients, surface and volume integration, and finite differences—used to compute shear stress, energy, and pressure, and why these results are inherently sensitive to resolution and noise.

A central engineering theme is reproducibility. Because derived parameters depend strongly on protocol, post-processing choices, and operator decisions, rigor in standardization, validation, and uncertainty quantification is what turns interesting numbers into trustworthy biomarkers. The talk reviews the validation strategies engineers rely on—in-vitro flow-phantom experiments, PIV cross-comparison, and computational fluid dynamics (CFD) as complementary ground truth—together with the standardization framework established by the 2023 international 4D Flow CMR Consensus Statement.

Finally, the lecture addresses automation. Manual post-processing remains the principal barrier to clinical scalability; robust, AI-assisted pipelines for automated vessel segmentation, plane placement, and quantitative reporting are required to deliver reproducible results within routine radiology workflows. It closes with an engineering outlook on coupling 4D Flow MRI with CFD, GPU-accelerated reconstruction, and deep-learning-based denoising and super-resolution—ultimately bridging the laboratory measurement mindset with patient-specific clinical decision making.

Keywords: *4D Flow MRI, Hemodynamics, Phase-contrast velocimetry, Wall shear stress, Image post-processing, Computational fluid dynamics*