EACVI

Society for Cardiovascular Magnetic Resonance

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Deep Learning Synthetic Strain MRI

A novel technique for the analysis of myocardial function

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NHS
Guy's and St Thomas'
NHS Foundation Trust

No disclosure

Physical definition of strain

- **Strain** is a dimensionless number, describing the relative length change of an object within a certain direction. With Lagrangian strain, the length change is described relative to its initial length. Natural strain represents the instantaneous length change relative to the object length at the immediately preceding time instance.

- **The rate** by which a deformation occurs is named strain rate and it is expressed in seconds

Voigt JU et al. JACC Cardiovasc imaging 2019

- TDI based strain rate is commonly given as natural strain rate, while strain is frequently converted into **Lagrangian strain**.

- **Feature tracking software in CMR** and echocardiography use commonly Lagrangian strain and strain rate.

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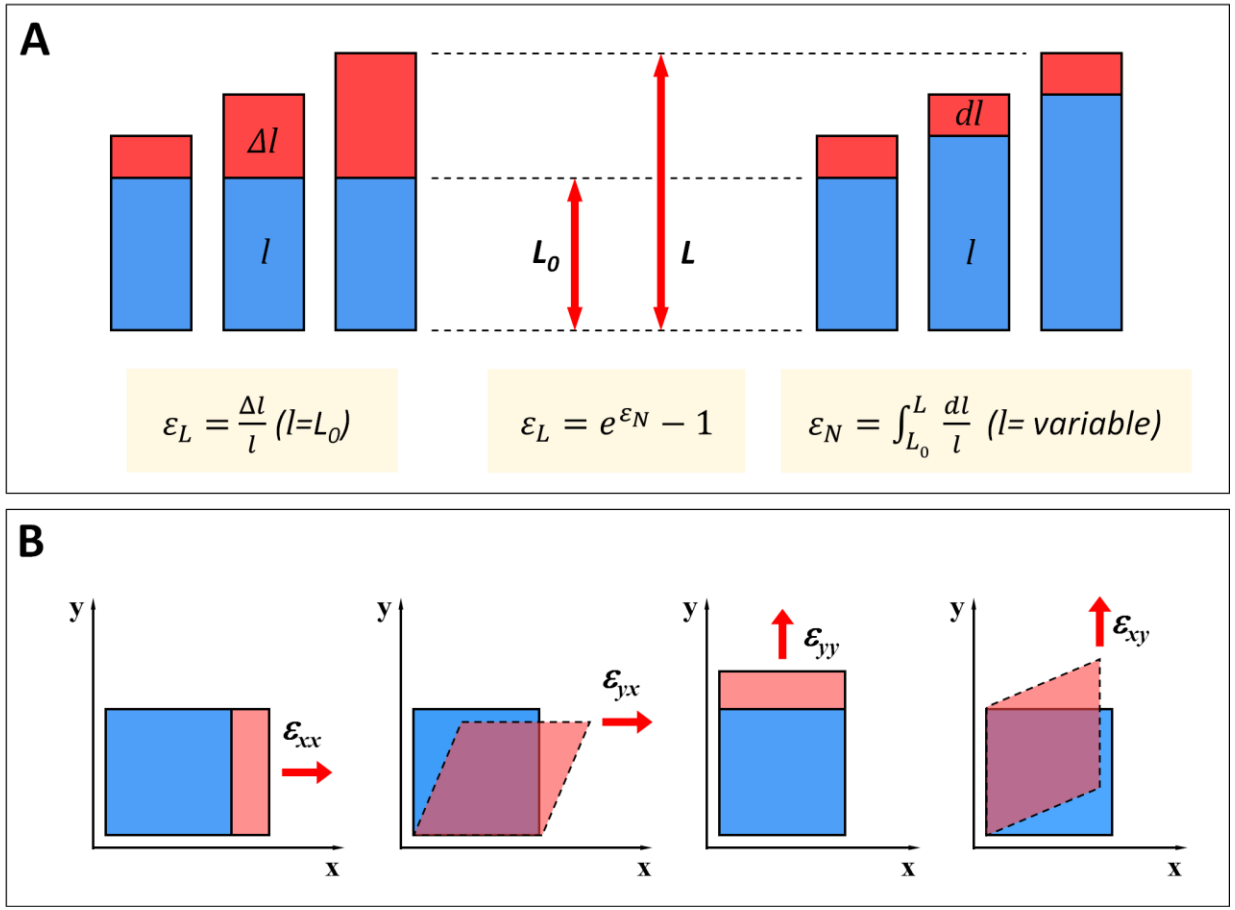
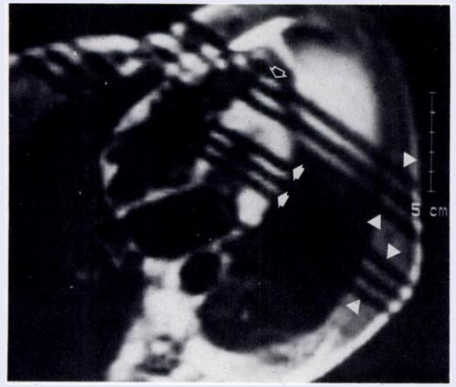
In a two-dimensional (2D) object, deformation can be described by two normal (orthogonal) strains. In addition, deforming forces which act antiparallel in different layers result in a shear of the object. The complete description of a three-dimensional (3D) deformation requires **3 normal strains and up to 6 shear strain components (xy, xz, yx, yz, zx and zy).**



Voigt JU et al. JACC Cardiovasc imaging 2019



Not a new technique: 1988

Cardiac Radiology

Elias A. Zerhouni, MD • David M. Parish, MD • Walter J. Rogers, PhD • Andrew Yang, MD • Edward P. Shapiro, MD

Human Heart: Tagging with MR Imaging—A Method for Noninvasive Assessment of Myocardial Motion[1]

First strain was an MRI technique

And Ten years later…..

Real-Time Strain Rate Imaging of the Left Ventricle by Ultrasound

JASE 1998

Andreas Heimdal, MSc, Asbjørn Støylen, MD, Hans Torp, DrTechn, and Terje Skjærpe, PhD,
Trondheim, Norway

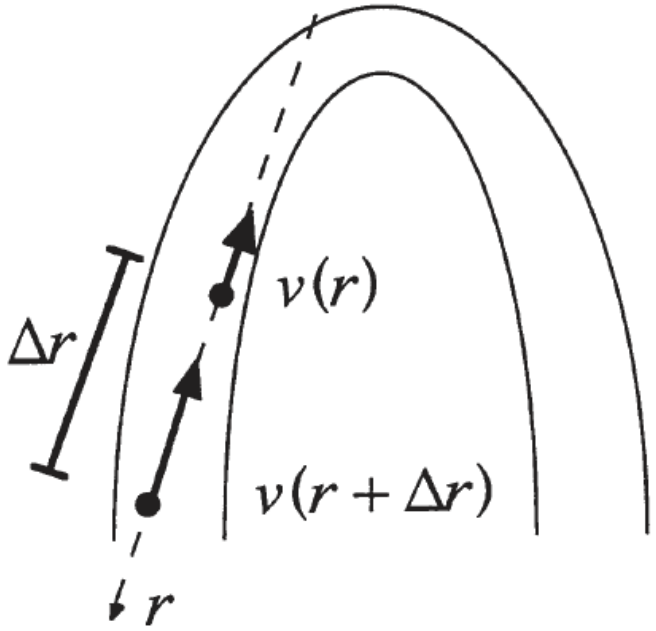


Figure 2 Illustration of estimation of strain rate of tissue segment Δr from tissue velocity. Size of Δr is exaggerated for clarity. *Dashed line* indicates one of the ultrasound beams, and r is the position along the ultrasound beam axis.

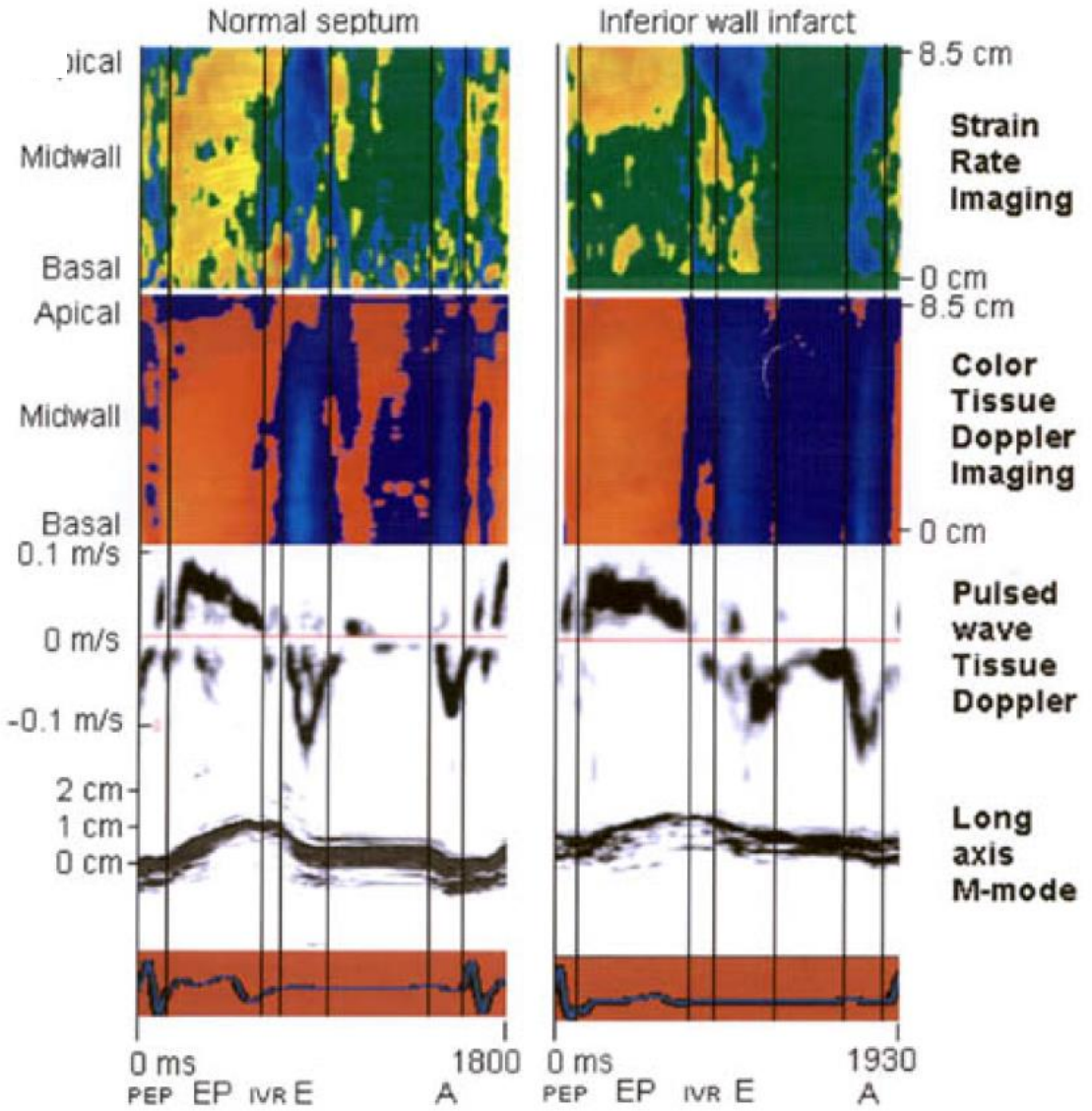
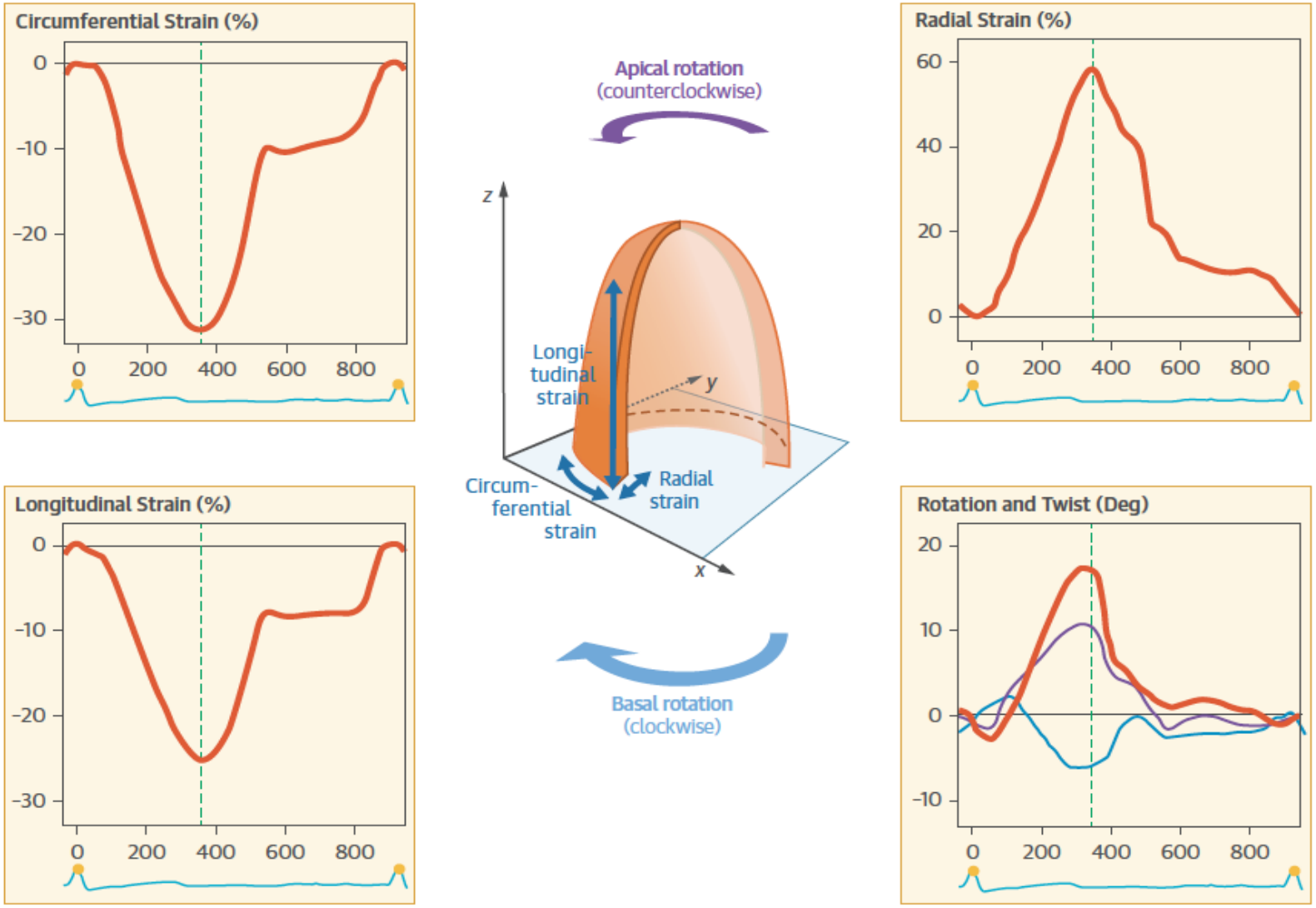
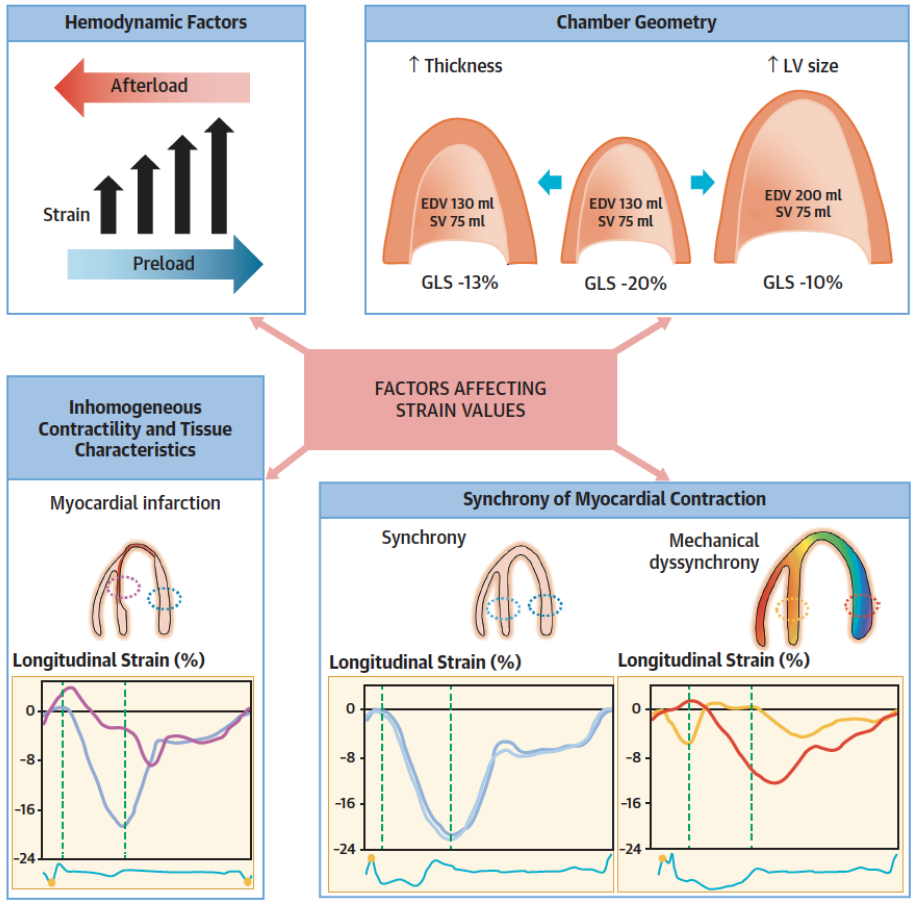


FIGURE 1 **Components of Myocardial Deformation**



The **center panel** shows the 3 normal strains (longitudinal, circumferential, and radial), which are oriented along the axes of the left ventricle. The **outer panels** show typical strain curves of the respective components. The **lower right panel** shows that rotation, which is defined as looking from the left ventricular apex to its base. Apical minus basal rotation equals left ventricular twist. **Dashed green lines** indicate aortic valve closure.

CENTRAL ILLUSTRATION Factors Affecting Strain Values



Voigt, J.-U. et al. J Am Coll Cardiol Img. 2019;12(9):1849-63.

Strain values are significantly influenced by loading conditions, chamber geometry, conduction delays, and tissue characteristics. The strain curves illustrate typical findings: **blue** indicates normal segments, **purple** indicates infarcted segment, **yellow** indicates early activated (septal) segment, **red** indicates late activated (lateral) segment. **Dashed green lines** indicate aortic valve opening and closure. EDV = end-diastolic volume; GLS = global longitudinal strain; SV = stroke volume.

TABLE 2 Clinical Application of Myocardial Strain by Cardiac Disease

Disease	Factors Affecting Strain	Clinical Application (Ref. #)
Cardiotoxicity	Globally impaired contractility	Detection of subclinical cardiac dysfunction after cancer treatment (20,56,88) Predict cardiotoxicity (56) Identify patients with high risk for clinical cardiac events (cardiac death, heart failure) after anthracycline therapy (89)
Ischemic disease	Regional inhomogeneity in contractility	Improved detection of coronary artery disease (24,90) Detection of induced ischemia in stress tests (24) Predict outcome and LV remodeling after acute myocardial infarction (91,92) Predict outcome (heart failure hospitalization and all-cause mortality) in patients with chronic ischemic cardiomyopathy (93) Identify patients with risk of arrhythmias (mechanical dispersion) (54)
Valvular heart diseases	Preload, afterload, chamber geometry (remodeling), contractility, myocardial fibrosis	Predict outcome (cardiac death, heart failure, reoperation) and long-term LV dysfunction after valve procedure (35,94,95)
Cardiomyopathy	Chamber geometry, myocardial deposits, myocardial fibrosis, reduced contractility, regionally inhomogeneous function	
Cardiac resynchronization therapy	Inhomogeneous timing of contraction, inhomogeneous regional remodeling	
Pulmonary hypertension	Afterload, chamber geometry	
Congenital heart disease (left-to-right shunt, tetralogy of Fallot)	Preload, afterload, chamber geometry	
Atrial fibrillation	Chamber geometry, atrial myocardial fibrosis	

CRT = cardiac resynchronization therapy; EF = ejection fraction; HCM = hypertrophic cardiom
fraction; LV = left ventricular.

FIGURE 5 Predictive Value of Global Longitudinal Strain

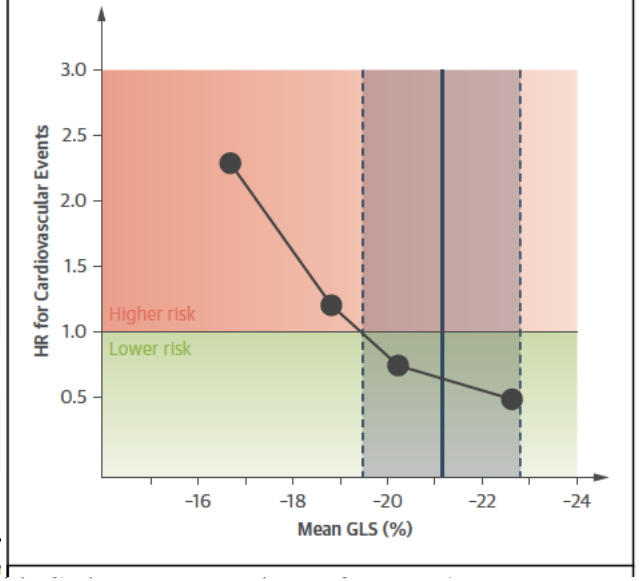


TABLE 1 Comparison of Different Imaging Techniques for Assessing Myocardial Deformation

Imaging Modality	Measurement Method	Strengths	Weaknesses	Ref. #
Echocardiography				
TDI	Measures myocardial velocity gradients (strain rate), which are then integrated to deformation values (strain)	• Very good temporal resolution • Very fast qualitative function assessment of a single region • Direct display of measured data without regularization algorithms (no "cosmetics")	• The deformation component to be measured must be aligned with the ultrasound beam • A comprehensive LV assessment is cumbersome • Dedicated image acquisitions needed • Apparently more noise than in STE	(3,4)
2D-STE	Tracks features (speckles) in the myocardium	• Regional and global strain measurements possible • Semi- or fully automatic tracking • No dedicated image acquisitions needed • Apparently less noise than in TDI	• Lower temporal resolution than TDI • Dependent on image quality • Intervendor differences • Strong influence of post-processing (regularization) algorithms ("cosmetics")	(4,6,26,71)
3D STE	Tracks features (speckles) in the myocardium	• Measures deformation in any direction • No geometric assumptions • No need for multiple plane acquisition • Assessment of LV rotational deformation • Area strain measurement	• Very low temporal and spatial resolution • Limited by low image quality • Intervendor differences • No standardization • Low feasibility • Added clinical value unclear	(4,5,8,9)
Alternative strain assessment techniques	MAPSE/LV length Manual tracings of LV lengths at systole and diastole	• Less image quality dependent • No additional post-processing software is needed	• Data are limited to longitudinal shortening only • Clinical data on these approaches are limited	(70,87)

CMR				
Feature tracking	Tracks features (mainly endocardial contour details) along the myocardial wall Different image analysis approaches (optical flow, nonrigid, elastic algorithm, and so on)	• Regional and global strain measurements • No additional image acquisition	• Lower temporal resolution than echocardiographic STE • High variability of regional measurements • Intervendor differences	(8,10–12)
Tagging	Imposes and follows planes of saturated myocardial magnetization	• Accurate regional strain measurements	• Additional acquisition time • Low temporal resolution • Demanding processing • Fading tags (depends on magnetic field strength) • No standards for measuring • Research tool	(13)
Other	Specific acquisition sequences (DENSE, SENC, HARP, and so on)	• Regional and global strain measurements • Fast-SENC with short acquisition time	• Additional acquisitions • Low signal-to-noise ratio • No standardization • Demanding processing • Research tool	(13)

Voigt JU et al. JACC Cardiovasc imaging 2019

Strain weaknesses

- Multiple vendors, multiple softwares
- Values variety between vendors
- Manual ROI and correction still frequently needed
- Specific weaknesses of each technique

What would be the ideal solution for MRI cardiac strain?

Results

Robust and reliable.
Quantitative and visually confirmable.
Separates normal from disease.

Acquisition

Little or no additional scan time.

Analysis

Automated. Little or no need for human intervention.

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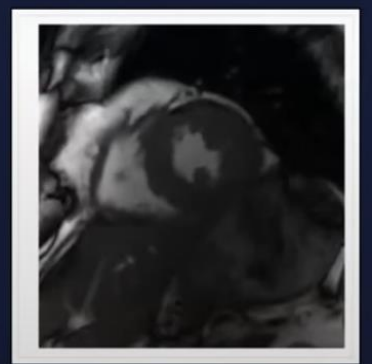
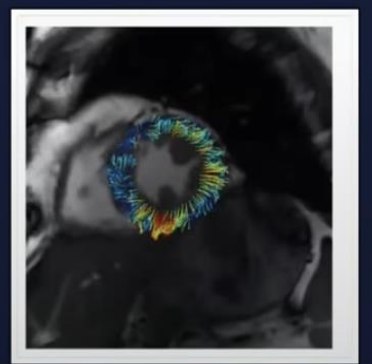
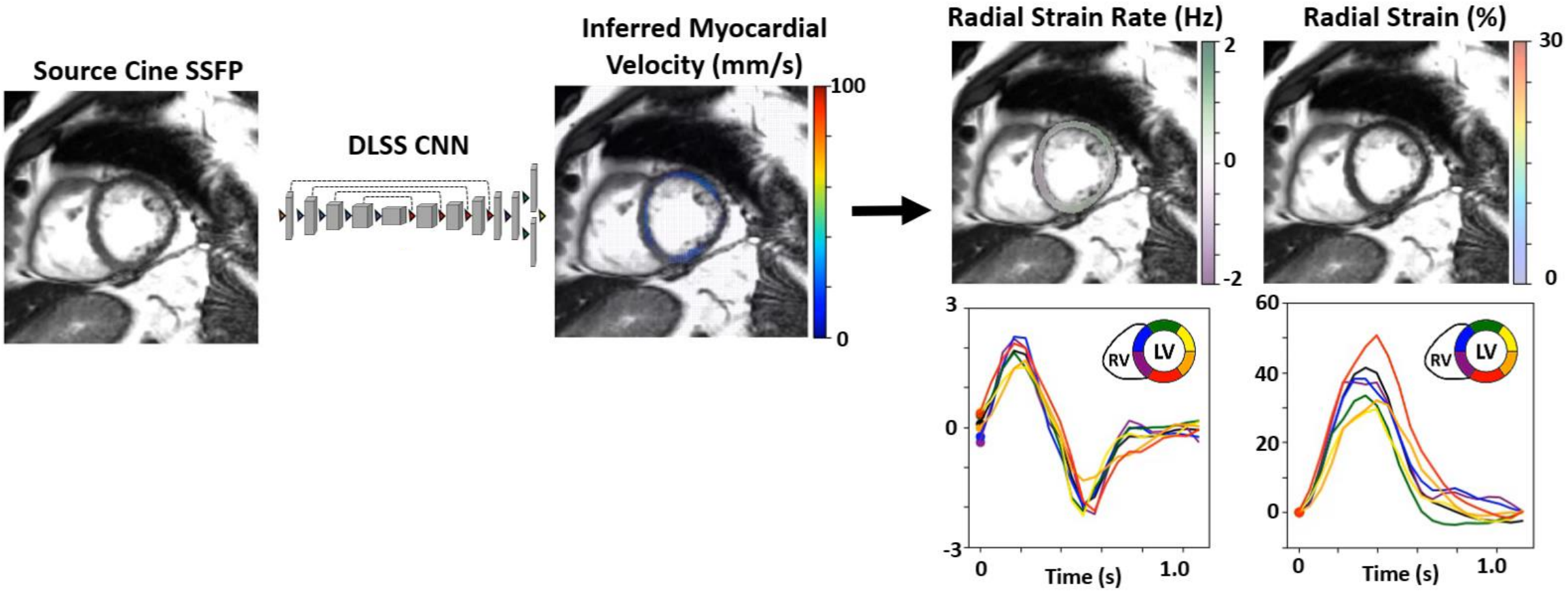
Deep Learning Synthetic Strain (DLSS)

Can we teach a deep learning algorithm using 4D Flow myocardial velocities?!?





Deep Learning Synthetic Strain (DLSS) MRI



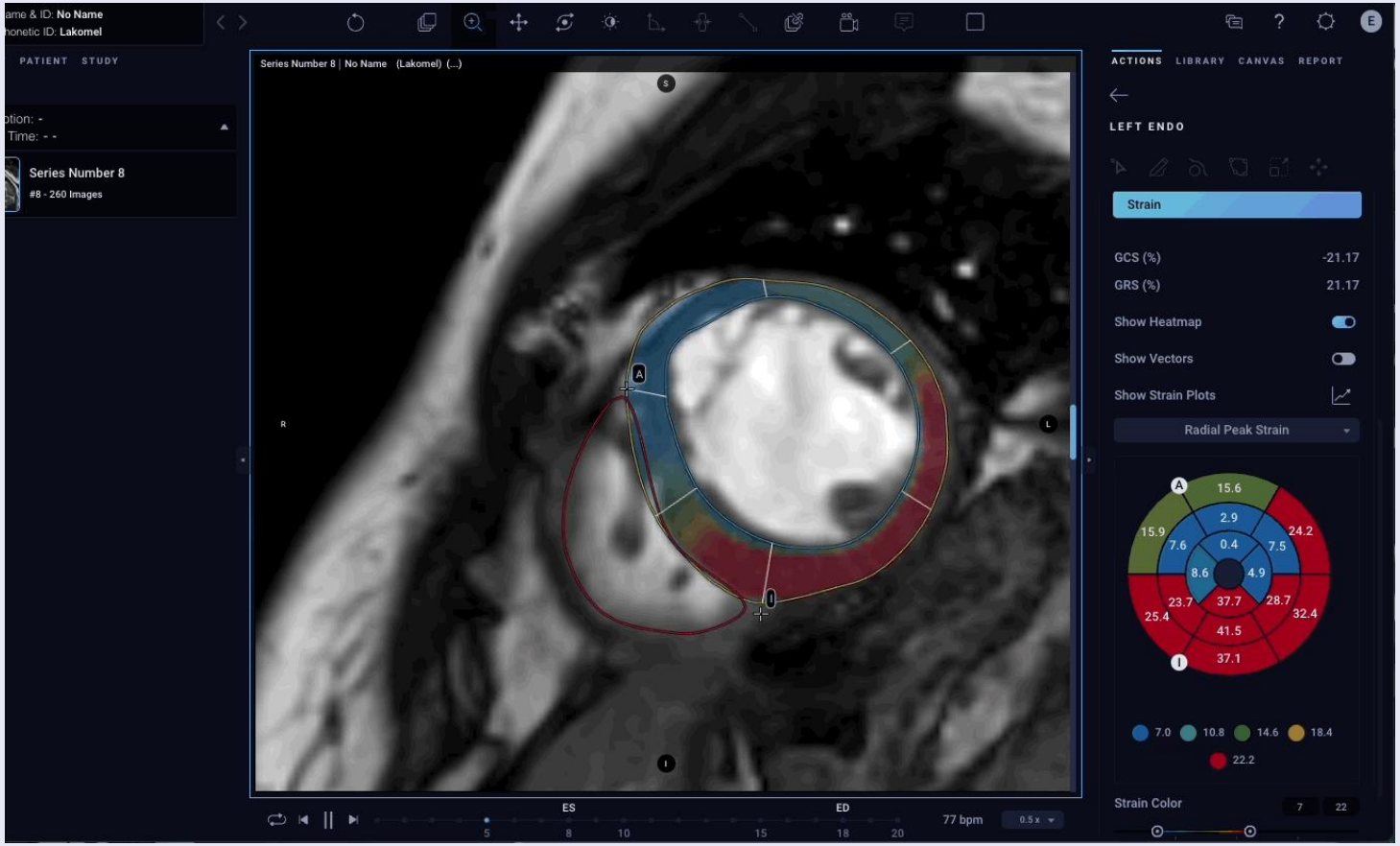
Strain AI

Powered by 4D Flow

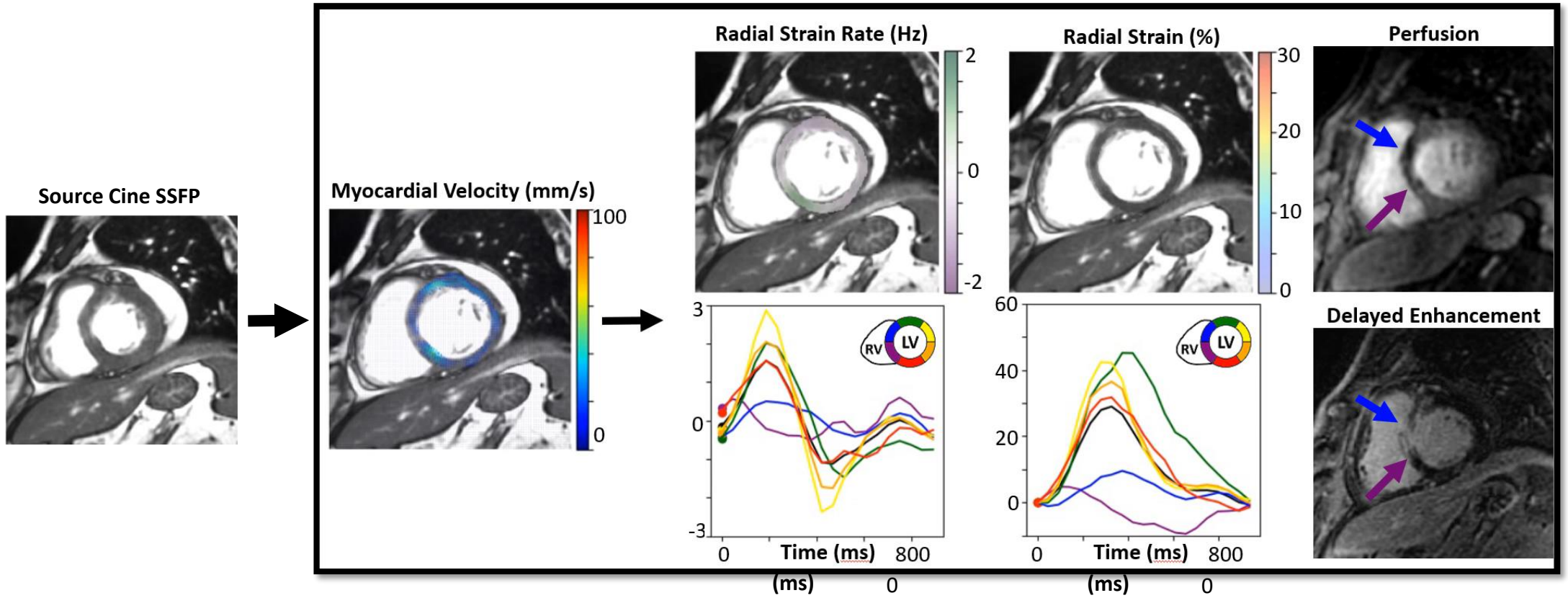
Zero click strain values powered by AI

Automated analysis of :

- Radial & Circumferential Strain
- Radial & Circumferential Strain Rate
- Time to Peak Radial & Circumferential
- Myocardial Velocity



Deep Learning Synthetic Strain (DLSS) MRI



LAD Occlusion and Infarct

UC San Diego Health

Deep-Learning Left Ventricular Mechanical Analysis – Sensing Bi-Ventricular Dysfunction in Tetralogy of Fallot

Students:

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Rahul Chandrupatla

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Alberst Hsiao, MD PhD

Institutions:

UC San Diego Health

Rady Children's Hospital

Inova Fairfax Hospital

Hospital Clinic Barcelona

Necker Enfants-Malades Hospital

Repaired tetralogy of Fallot (rTOF) patients develop both RV and LV dysfunction

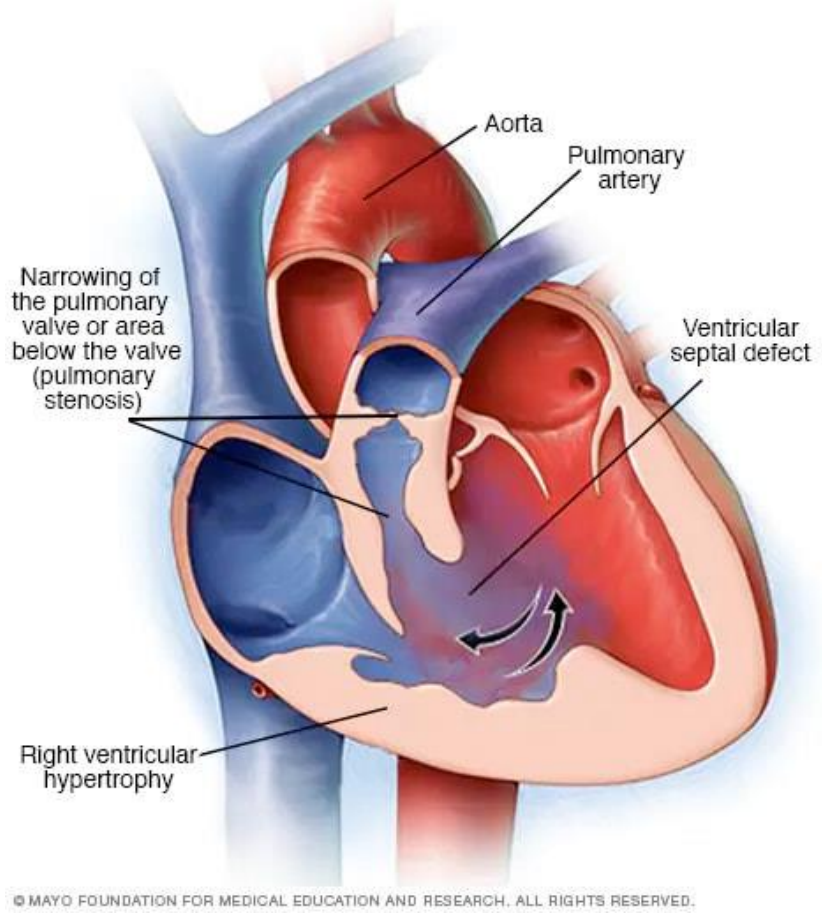
Tetralogy of Fallot

- Frequently develop RV dysfunction secondary to pulmonary valvular regurgitation
- Followed with cardiac MRI

Right Ventricular Pulmonary Valve Replacement Criteria

- RV volumes, pulmonary regurgitation fraction, RV ejection fraction, symptoms: …still debating…

Left Ventricular dysfunction occurs in ~20% of patients



LV dysfunction in rTOF is assessed with LV ejection fraction

Left Ventricular Pulmonary Valve Replacement Criteria

- LV dysfunction is commonly evaluated with LV ejection fraction (%)
- LVEF < 55% is a criteria for PVR

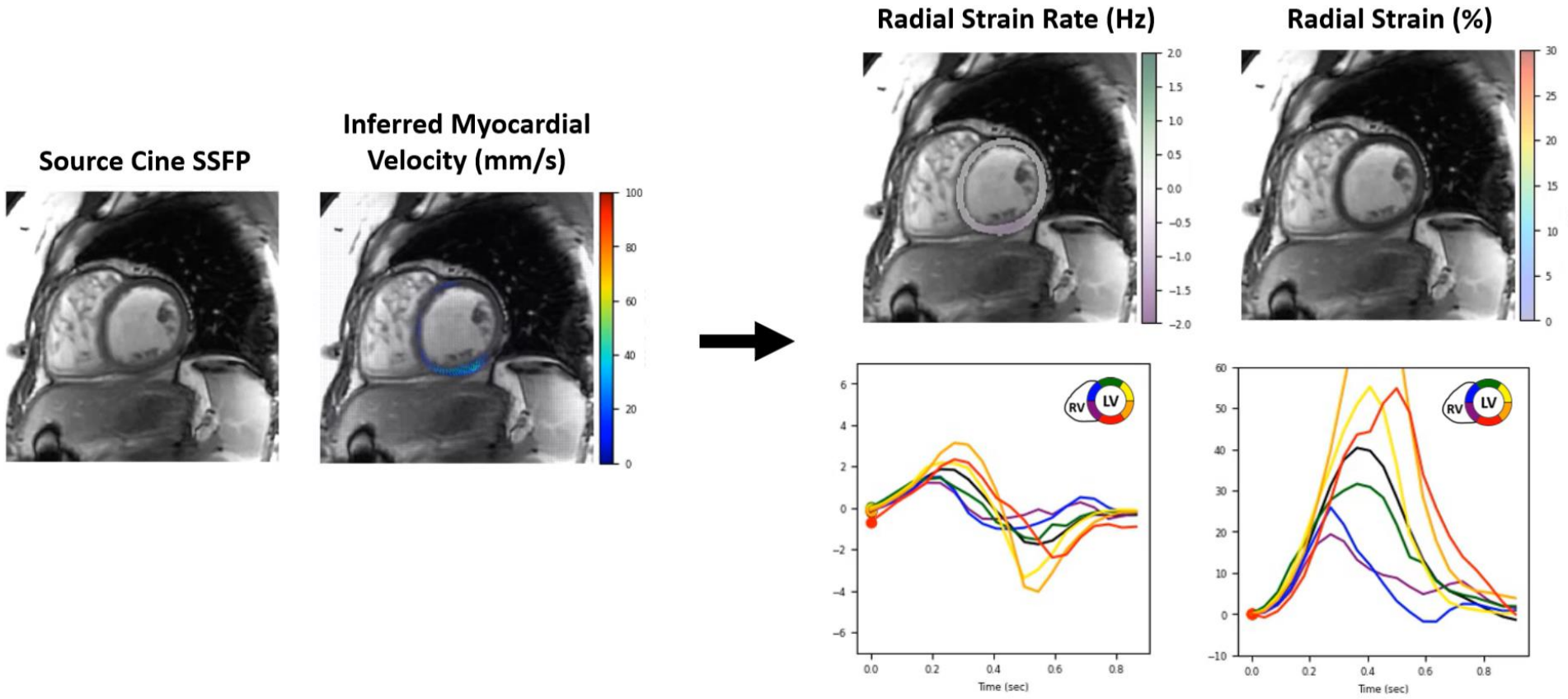
Limitations of Ejection Fraction:

- LVEF is insensitive and only decreases after years of adverse ventricular remodeling.
- Fails to account for regional variations and biventricular interactions

Hypothesis

Regional measures of LV strain and dyssynchrony may sensitively detect LV dysfunction in repaired tetralogy of Fallot

Deep learning synthetic strain (DLSS) provides automated measurements of strain and dyssynchrony



CMR exams for patients with rTOF were retrospectively collected from five international institutions

Institution	Patients
UC San Diego Health, *San Diego, CA*	34
Rady Children's Hospital, *San Diego, CA*	79
Necker-Enfants Malades Hospital, *Paris, France*	39
Hospital Clínic de Barcelona, *Barcelona, Spain*	19
Inova Fairfax Hospital, *Fairfax, Virginia*	27
Total	**198**

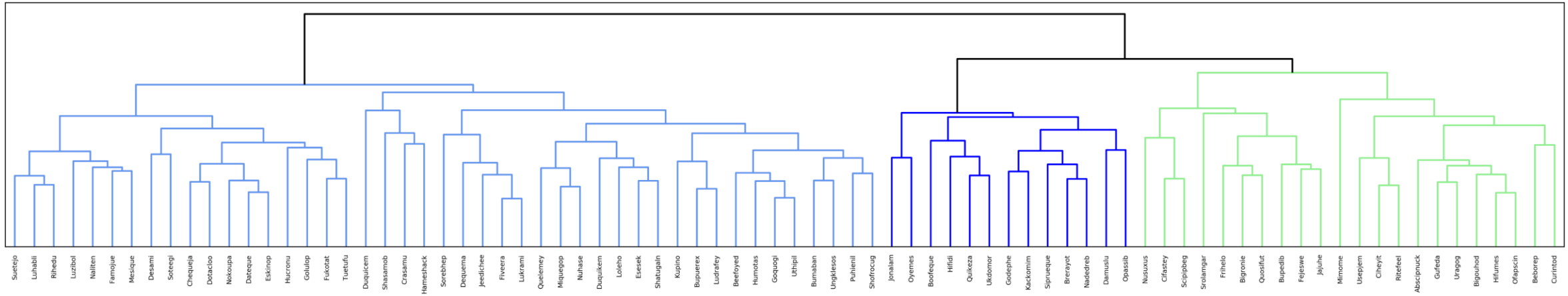


Figure 2: Hierarchical clustering of tetralogy of Fallot and normal cohorts into strain phenotypes using normalized segmental DLSS measurements. We discovered multiple distinct phenotypes from the regional measures of contraction strength and timing.

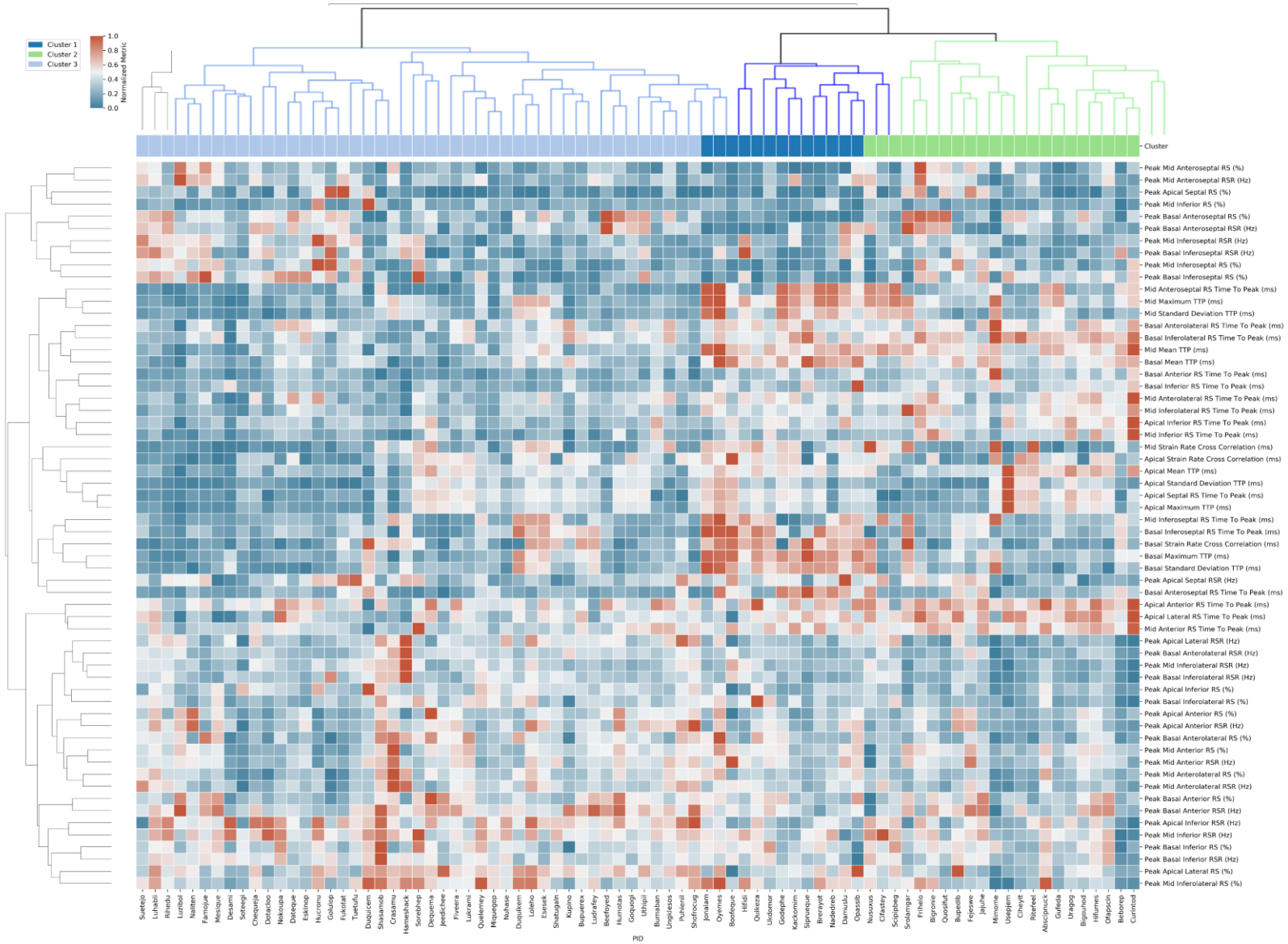
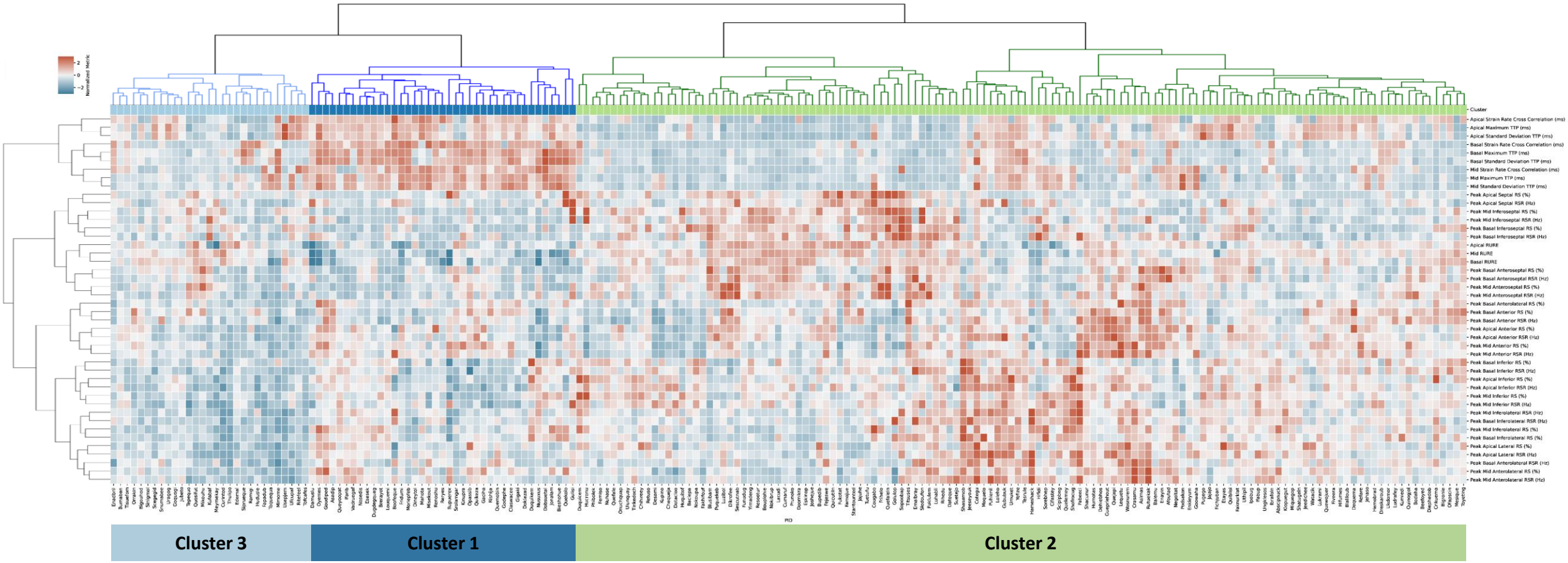


Figure 2: Hierarchical clustering of tetralogy of Fallot and normal cohorts into strain phenotypes using normalized segmental DLSS measurements. Patient phonetic IDs are shown on the x-axis with color codes used to distinguish each phenotypic cluster. We discovered multiple distinct phenotypes from the regional measures of contraction strength and timing.

Patients exhibit multiple distinct phenotypes of regional LV mechanics



Phenotypic Cluster Characteristics: Segmental DLSS Metrics

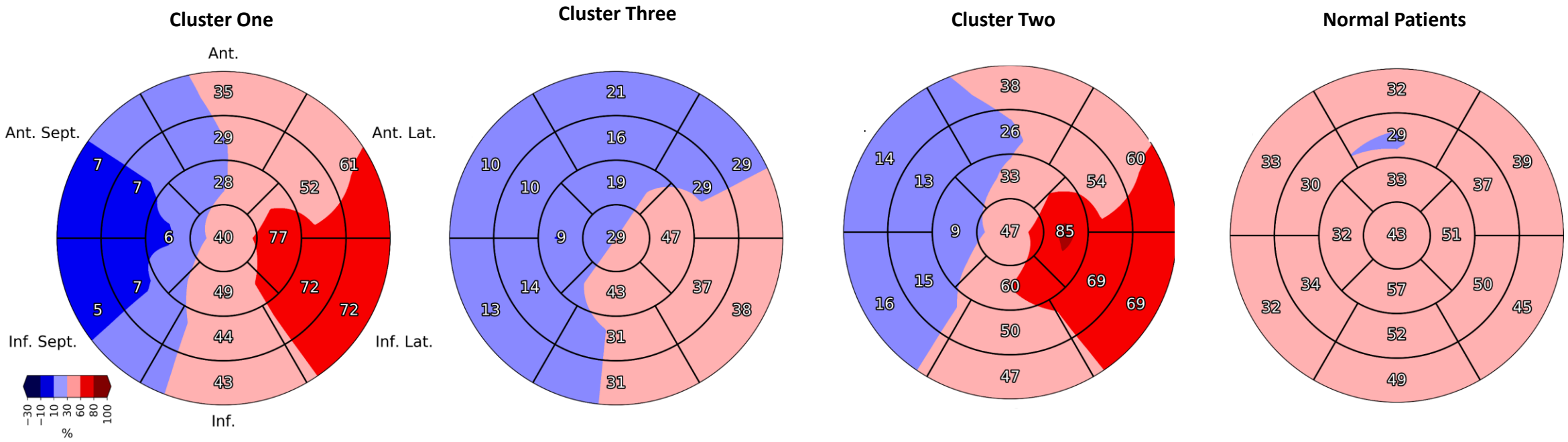
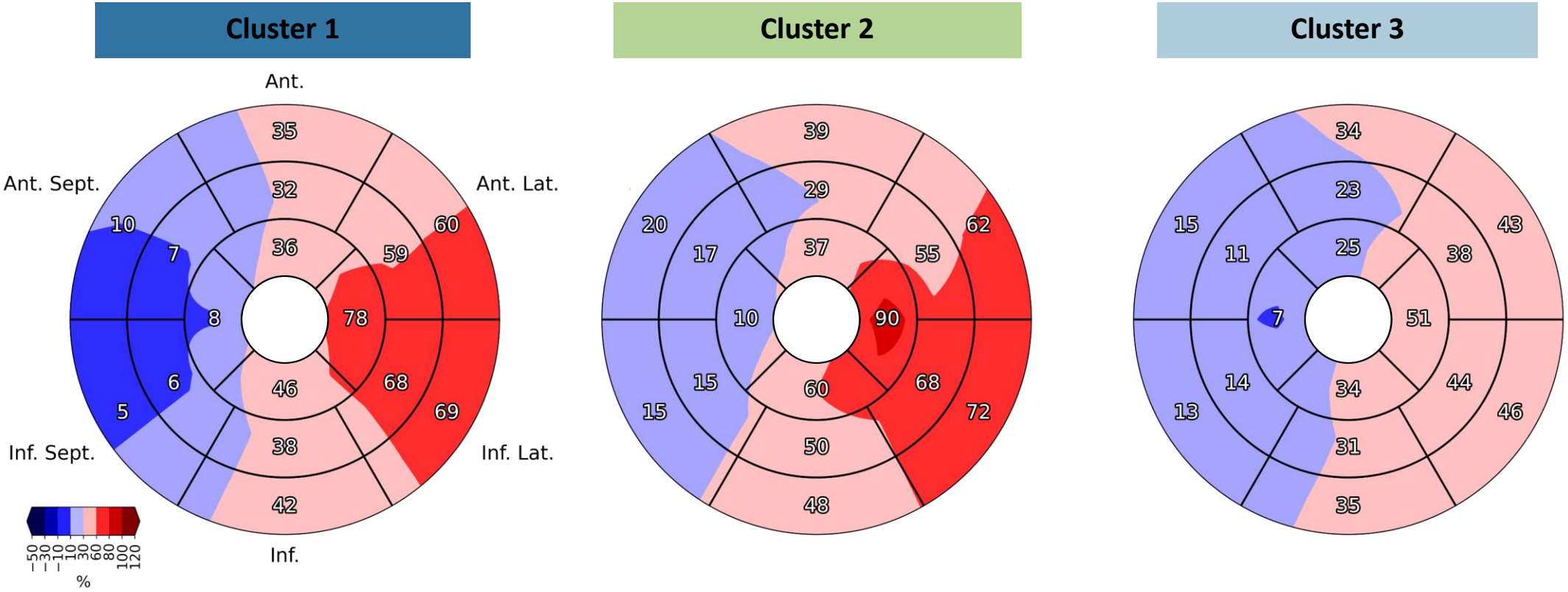
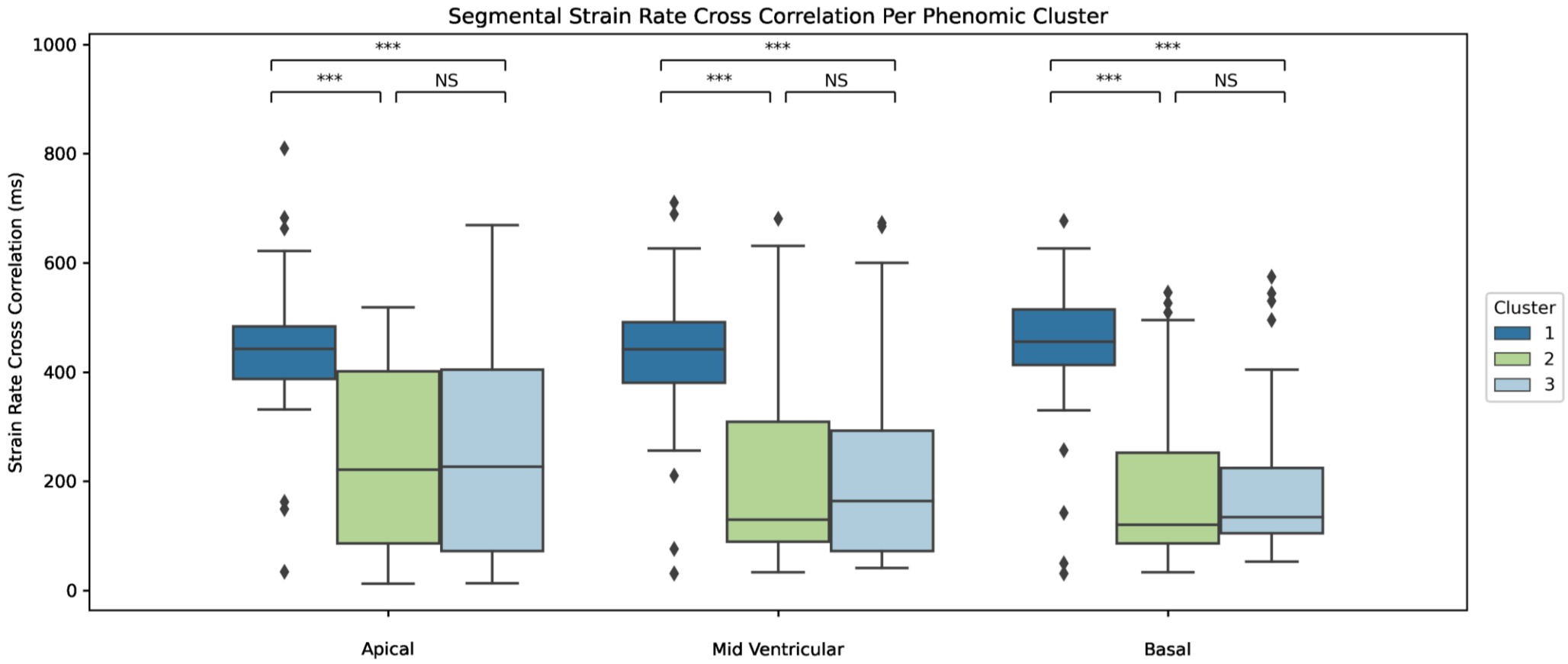


Figure 3a: AHA 17-segment bulls-eye plots of the mean peak radial strain for phenotypic cluster one, two, three, and normal patients. Relative to the normal patients, cluster one demonstrates significantly decreased strains in the anteroseptal and inferoseptal segments, with compensation in the lateral wall. In contrast, cluster three demonstrates decreased septal and anterior radial strains without adequate compensation in the lateral wall. Cluster two demonstrates well compensated TOF patients with moderately decreased septal strains with adequate compensation in the lateral segments.

Segmental Peak Radial Strain (%) Per Phenotypic Cluster



Cluster 1 is characterized by increased LV dyssynchrony



P-values are calculated using a two-sided *t*-test. **** = p<0.001; NS = not statistically significant.*

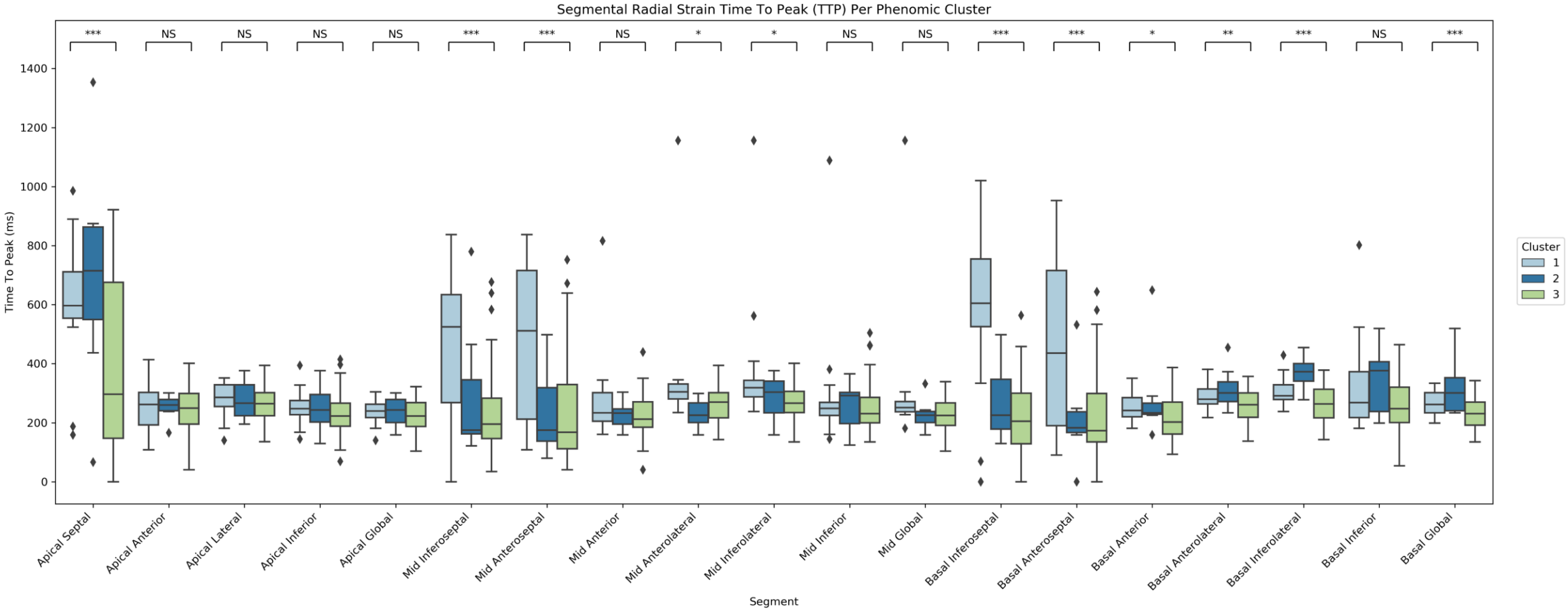
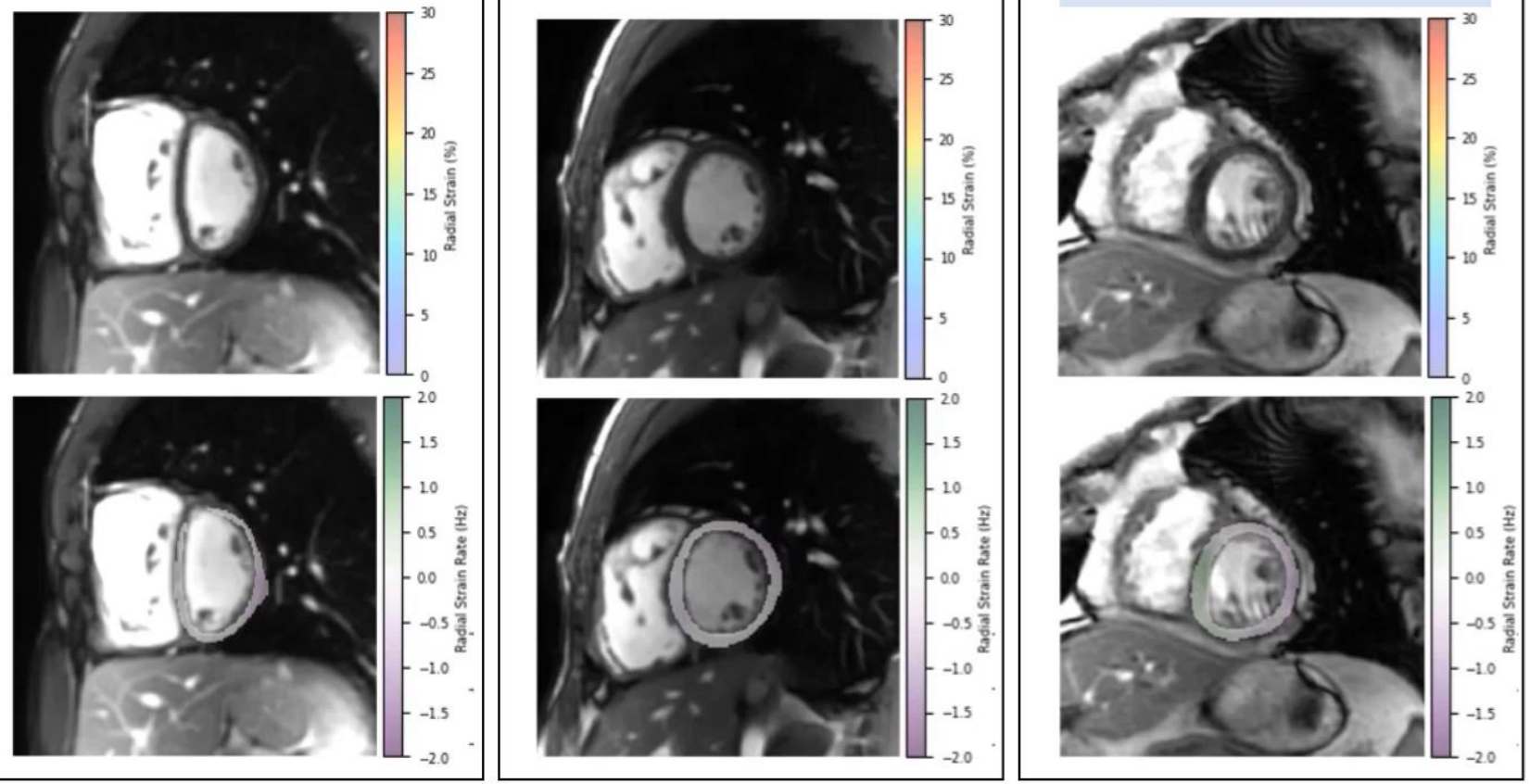


Figure 3b: Segmental TTP measurements for each strain phenotypic cluster. Consistent with right ventricular volume overload and accompanying septal dyssynchrony, cluster 1 demonstrates statistically significant increases in TTP measurements in the inferoseptal and anteroseptal segments. Although there are outliers, clusters 2 and 3 demonstrate no evidence of dyssynchrony in the septal segments. ** = p<0.05; ** = p<0.01; *** = p<0.001; NS = not statistically significant.*

	Cluster 1 Patient	Cluster 2 Patient	Cluster 3 Patient
RVEDVi	167.0 mL/m2	114.0 mL/m2	53.9 mL/m2
LVEF%	49%	67%	48%
Max TTP	643.9 ms	293.0 ms	198.4 ms
SRCC	395.8 ms	87.6 ms	52.7 ms
Septal RS (%)	9.0%	22.0%	13.3%
Lateral RS (%)	85.6%	89.0 %	31.8%



	Cluster 1 (n=39)	Cluster 2 (n=130)	Cluster 3 (n=29)	p-value
Demographics				
Age (years)	22.0 ± 10.9	20.9 ± 11.7	30.5 ± 13.4	**<0.01**
Weight (kg)	117.7 ± 45.5	115.5 ± 50.8	101.4 ± 41.5	0.40
Height (cm)	103.9 ± 61.1	104.3 ± 54.3	135.9 ± 58.6	0.05
BSA (m2)	1.6 ± 0.5	1.6 ± 0.3	1.8 ± 0.3	0.07
Time Since Repair	19.9 ± 10.3	18.5 ± 10.2	26.4 ± 12.7	**<0.01**
Prior PVR (n)	2 (5.1%)	26 (20.0%)	9 (31.0%)	0.02
Time Since PVR	4.5 ± 4.5	6.6 ± 5.5	5.1 ± 5.6	0.74
Volume and Function				
RVEDVi (mL/m2)	153.0 ± 33.9	124.5 ± 31.1	130.5 ± 37.4	**<0.001**
RVESVi (mL/m2)	73.2 ± 19.1	62.9 ± 20.0	71.8 ± 26.5	0.02
RVSVi (mL/m2)	73.3 ± 15.9	62.3 ± 18.7	58.8 ± 15.9	**<0.01**
LVEDVi (mL/m2)	69.0 ± 27.3	58.4 ± 28.7	70.8 ± 26.8	0.03
LVESVi (mL/m2)	38.6 ± 8.7	37.0 ± 8.9	45.1 ± 15.1	**<0.01**
LVSVi (mL/m2)	42.7 ± 12.1	45.4 ± 11.8	37.5 ± 11.9	0.02
RVEF (%)	49.3 ± 6.2	51.1 ± 8.7	45.7 ± 7.2	0.01
LVEF (%)	56.0 ± 5.6	59.8 ± 5.9	52.6 ± 10.2	**<0.001**
Flow and Regurgitation				
Pulmonary RF (%)	38.8 ± 14.4	31.2 ± 19.1	24.6 ± 17.2	0.03

Note – Data is reported as the mean and standard deviation. *P*-values are calculated using a one-way ANOVA for continuous variables and a Pearson's chi-squared test for categorical variables. Significant values ($p<0.05$) are bolded.

Future directions

- Robustness and reproducibility
- Correlation to outcome
- Clinical application and validation of DLSS

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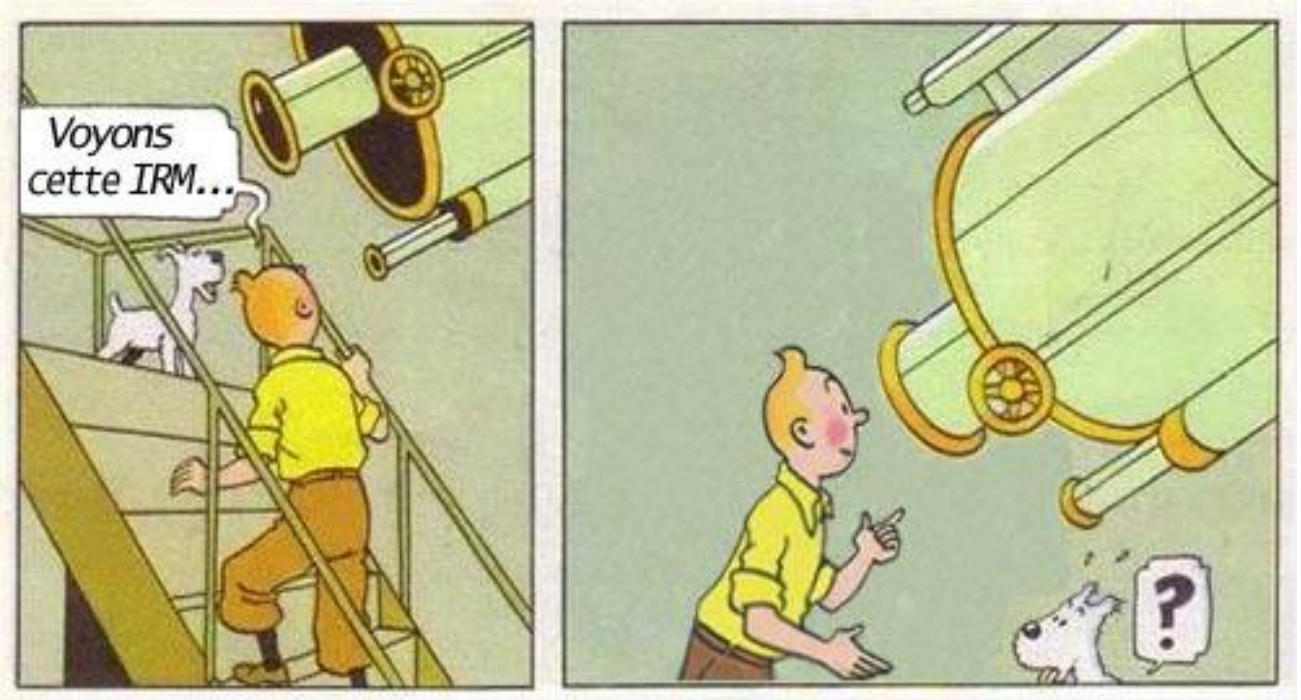
DLSS released today!



Merci pour votre attention…