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Fundamentals of Quantification in Cardiac MRI

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List of Abbreviations

- bSSF = balanced steady-state free precession
- CO = cardiac output
- ECV = extracellular volume
- ED = end-diastole
- EDV = end-diastolic volume
- EF = ejection fraction
- ES = end-systole
- ESV = end-systolic volume
- GRE = gradient echo
- HR = heart rate
- LV = left ventricle
- LVOT = left ventricular outflow tract
- RV = right ventricle
- Qp:Qs = shunt fraction
- ROI = region of interest
- RVOT = right ventricular outflow tract
- SV = stroke volume
- TE = echo time
- TR = repetition time
- VENC = velocity-encoding gradient

Selected Formulas

- **Stroke volume (SV):** volume of blood pumped from the ventricle per beat.

$$SV = EDV - ESV$$

Unit: mL

- **Ejection fraction (EF):** volume of blood pumped from the ventricle per beat.

$$EF = \frac{EDV - ESV}{EDV} = \frac{SV}{EDV}$$

Unit: percentage (%)

- **Cardiac output (CO):** amount of blood the heart pumps through the circulatory system per minute.

$$CO = HR \times SV$$

Unit: L/min

- **Regurgitant fraction:** percentage of blood that regurgitates back through a valve per beat.

$$\text{Regurgitant fraction} = \frac{\text{Regurgitant volume}}{\text{Forward volume}}$$

Unit: percentage (%)

- **Shunt fraction (Qp:Qs):** ratio of blood flows through the pulmonic and systemic circulation.

$$Qp{:}Qs = \frac{\text{Pulmonary arterial flow}}{\text{Aortic flow}}$$

Unit: none

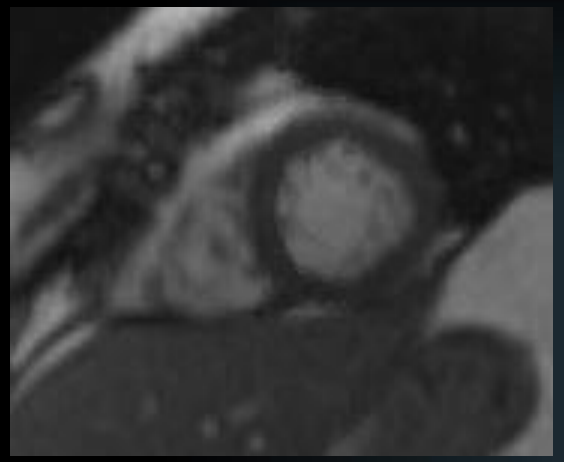
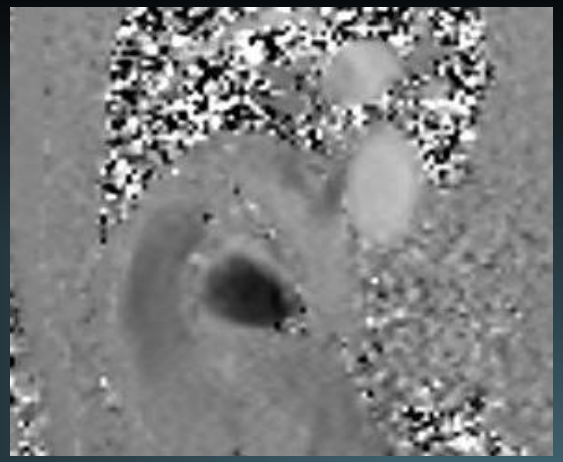
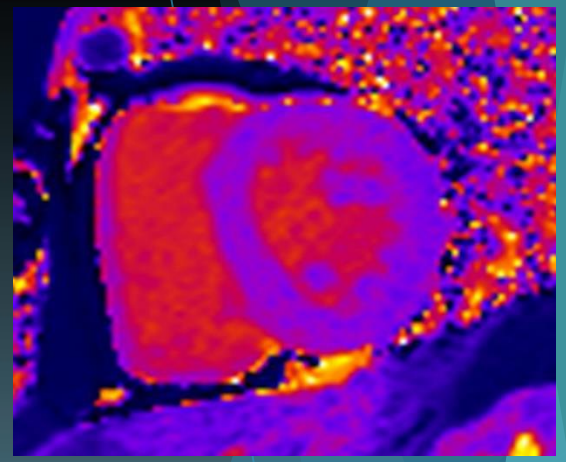
Learning Objectives

- To understand the basic principles of sequences commonly used in quantitative cardiac MRI.
- To understand the principles of parameter quantification in clinical scenarios.
- To understand and identify common pitfalls at cardiac MRI and learn appropriate troubleshooting techniques.

Background

- Cardiac MRI is considered the standard noninvasive modality for providing many structural and functional parameters.
- Quantitative information obtained at cardiac MRI has a significant impact on diagnosis, treatment, and prognostication of many cardiovascular diseases.
- Interpreting physicians must be familiar with basic quantification techniques to ensure accuracy and reliability of these results.

Outline

	Ventricular Volumes and Function	Quantification of Blood Flow	Quantitative Myocardial Tissue Characterization
Sequence	 Steady-state free precession imaging.	 Velocity-encoded phase-contrast imaging.	 Multiparametric mapping.
Calculated Parameters	• ESV and EDV • Stroke volume (SV) • Ejection fraction (EF) • Cardiac output (CO) • Myocardial thickness • Myocardial mass	• Peak velocity • Pressure gradient • Volumes • Flow	• Native and postcontrast T1 • ECV • T2 • T2* (“T2 star”)

Balanced Steady-State Free-Precession Imaging

- Rapid sequence utilizing very short repetition times (TRs) and echo times (TEs), allowing for rapid-filling k-space data within each cardiac phase.
  - Produce cine images over multiple heartbeats within a single breath hold.

- General parameter trade-offs:
  - Improved temporal resolution: increased number of phases acquired, more precise determination of end systole and diastole.
  - Lower section thickness or gap: increased number of sections covering heart, more precise mass and volume calculations.

Balanced Steady-State Free-Precession Imaging

- Bright-blood imaging sequences.
  - Weighting proportional to T2 or T1.
  - Not optimized for tissue characterization.

- Performed before or after contrast material is injected.
  - Performing examination after injecting contrast material increases blood pool signal intensity, but any pathologic myocardial enhancement may be seen.

- Prone to various artifacts that are more pronounced at 3 T.
  - Off-resonance, susceptibility, chemical shift.
  - May be overcome with GRE sequences.

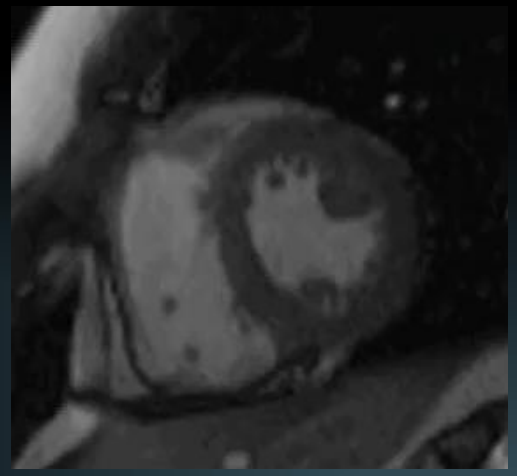
Ventricular Volume and Function

- Typically performed using a short-axis bSSFP image stack that covers entire ventricles from base to apex.
- RV analysis has also been described using four-chamber plane stacks.
  - May be useful in congenital heart disease cases.
- LV and RV analysis can be performed in the same set of images.
- Before quantification:
  - Ensure adequate coverage of the ventricles.
  - Evaluate for artifacts (ie, motion, susceptibility).

Ventricular Volume and Function

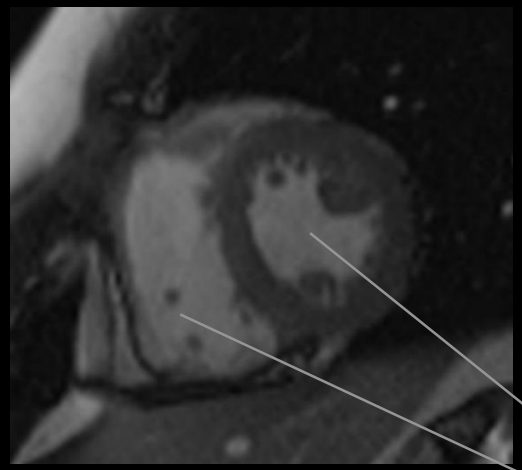
Step 1: Determine end-systolic (ES) and end-diastolic (ED) phases.

Largest ventricular blood pool

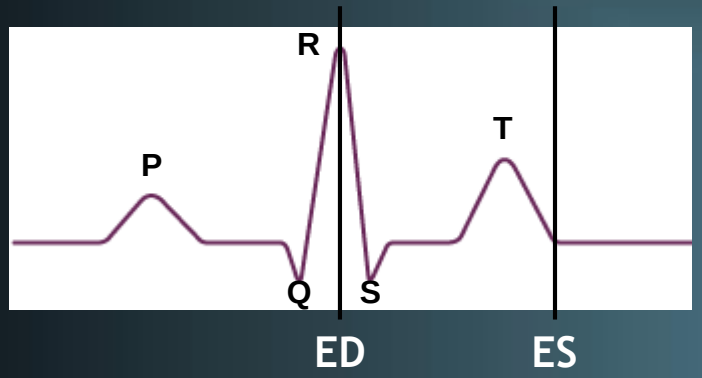


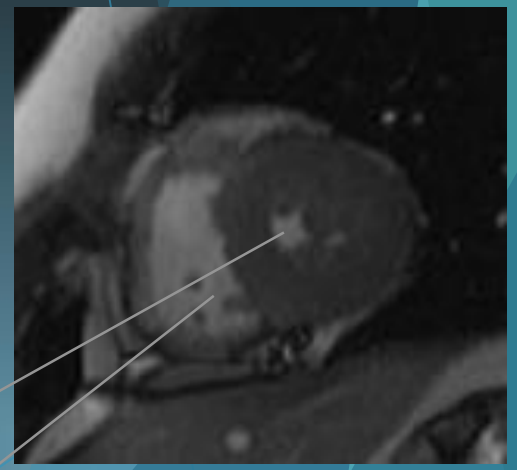
Short-axis bSSFP cine image (mid section).

Smallest ventricular blood pool



Short-axis ED-phase image.





Short-axis ES-phase image.

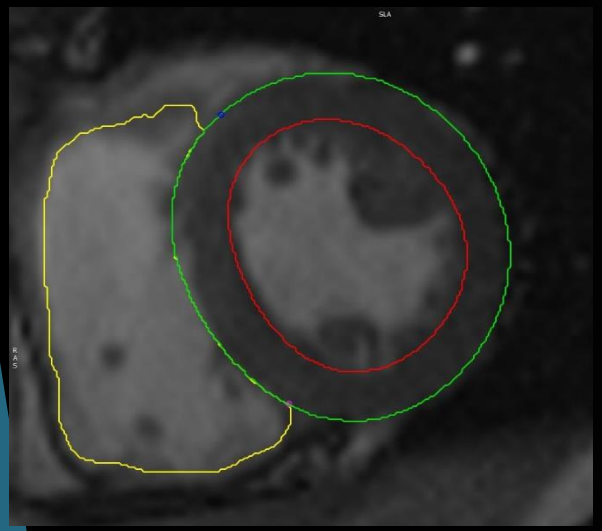
Tip: LV and RV may have different ED and ES phases.

Tip: Multiple sections need review to determine ED and ES phases.

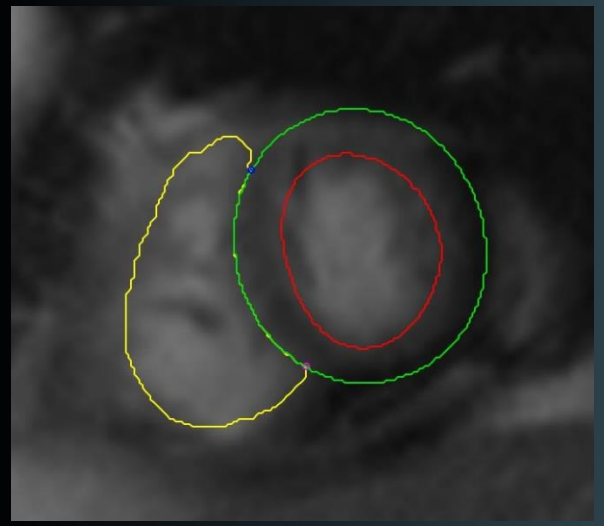
Ventricular Volume and Function

Step 2: Contour LV and RV endocardial and epicardial contours at each section position for ED and ES.

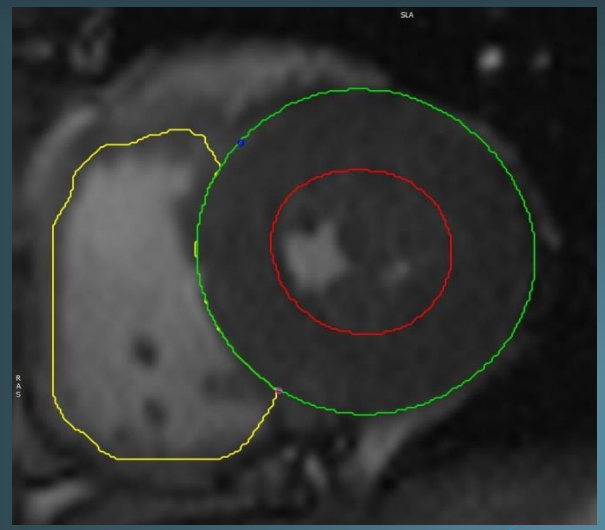
- Endocardial contours: used in volume calculations (LV and RV).
- Epicardial contours: necessary for mass calculations (LV only).



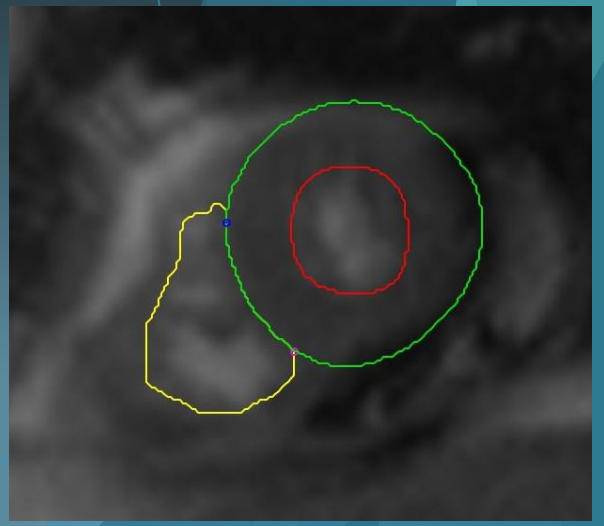
Short-axis ED mid section image.



Short-axis ED apical section image.



Short-axis ES mid section image.



Short-axis ES apical section image.

Yellow contour = RV endocardial, red contour = LV endocardial, green contour = LV epicardial.

Ventricular Volume and Function

Tips for selecting and contouring LV basal sections:

- Contour to the basal section where myocardium surrounds at least 50% of blood volume.
- Basal-most LV section at ED may include only left atrium without LV blood volume at ES.
- Include LV outflow tract (LVOT) in LV blood volume.
- At the LVOT, endocardial and epicardial contours abut one another if no myocardium is visible.

Tips for selecting and contouring RV basal sections:

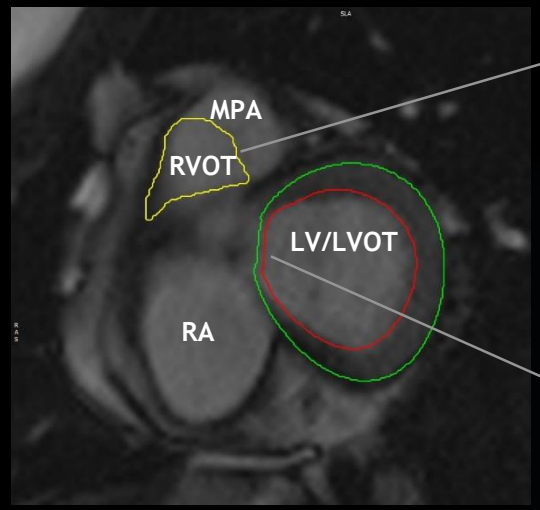
- Basal-most RV section at ED may include only right atrium without RV blood volume at ES.
- Include RV outflow tract (RVOT) in RV blood volume.
- Basal RV contours may have a more irregular shape (ie, comma shape) compared to LV.

Apical section tip:

- When the most apical section contains only a circle of myocardium without a visible blood pool, an epicardial contour without an endocardial contour should be drawn.

Tip: Cross-reference with long-axis views to confirm location on short-axis images (assume consistent breath holds among sequences).

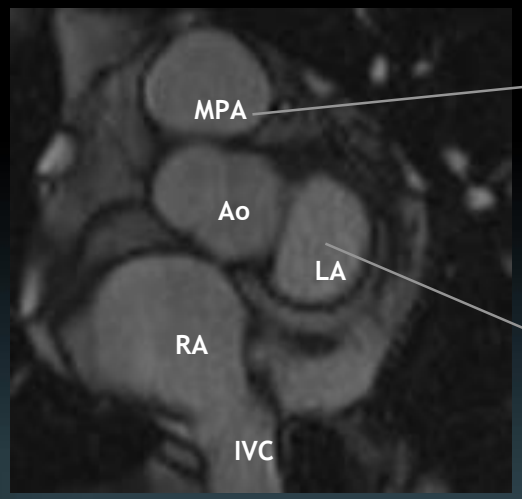
Ventricular Volume and Function



Basal-most LV short-axis section image.

RV contour includes RVOT.

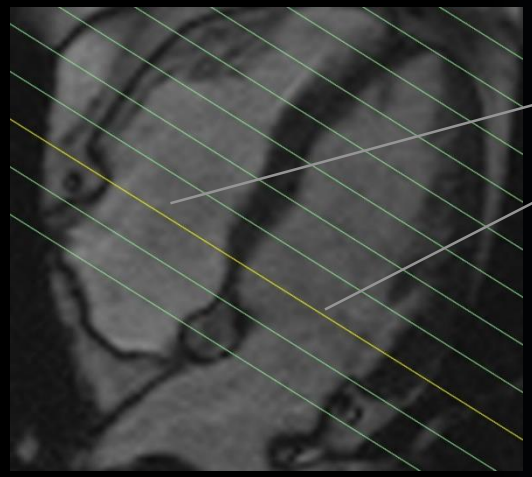
LV contours include LVOT extending up to aortic valve cusps.



Next atrial short-axis section image.

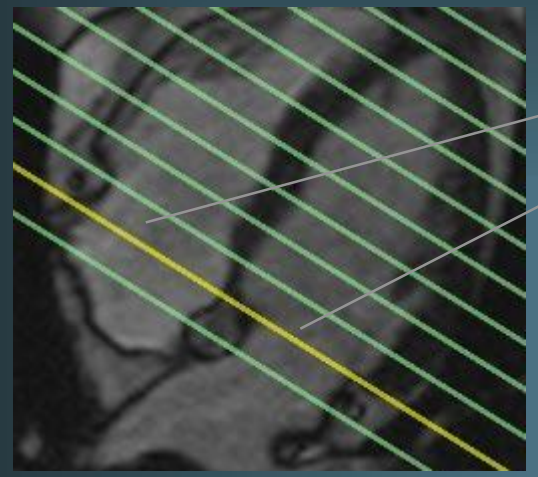
Level of the pulmonic valve with no RV visible.

Less than 50% of blood pool surrounded by myocardium.



ED four-chamber reference image.

Section includes portions of the RV and LV.



ED four-chamber reference image.

Section is at the level of the atria.

LEGEND

- Ao: aorta
- IVC: inferior vena cava
- LA: left atrium
- LV: left ventricle
- LVOT: left ventricle outflow tract
- MPA: main pulmonary artery
- RA: right atrium
- RV: right ventricle
- RVOT: right ventricle outflow tract

Yellow contour = RV endocardial, red contour = LV endocardial, green contour = LV epicardial.

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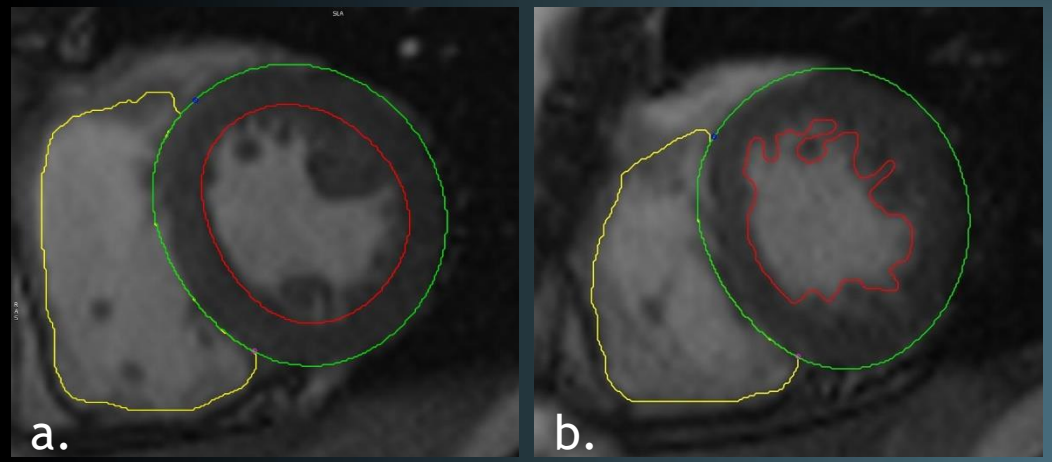
Ventricular Volume and Function

Include or exclude LV papillary muscles and trabeculations?

- Including or excluding these structures in LV endocardial contours affects volumes and mass measurements.
  - Combined papillary muscles and trabeculations account for up to 28% of LV mass.[1]
  - Effects exaggerated in highly trabeculated and hypertrophied ventricles.
- Structures should be treated similarly on ED and ES phases.
- Technique should be stated in report.
- Be aware of methodology used in reference standards.
- RV: routinely ignore trabeculations when contouring.



Yellow contour = RV endocardial, red = LV endocardial, green = LV epicardial.

Corresponding mid-ED short-axis sections:

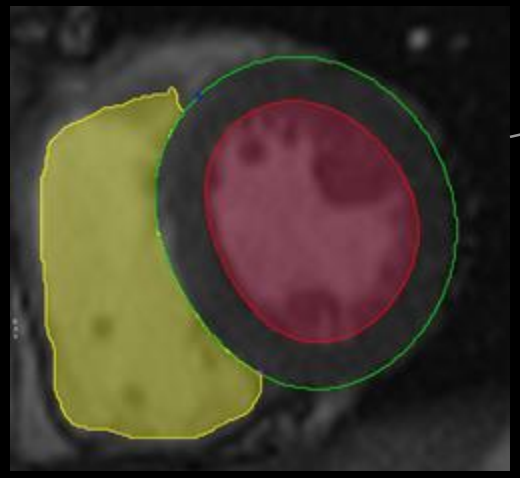
a. Contours with papillary muscles and trabeculations excluded.

b. Contours with papillary muscles and trabeculations included.

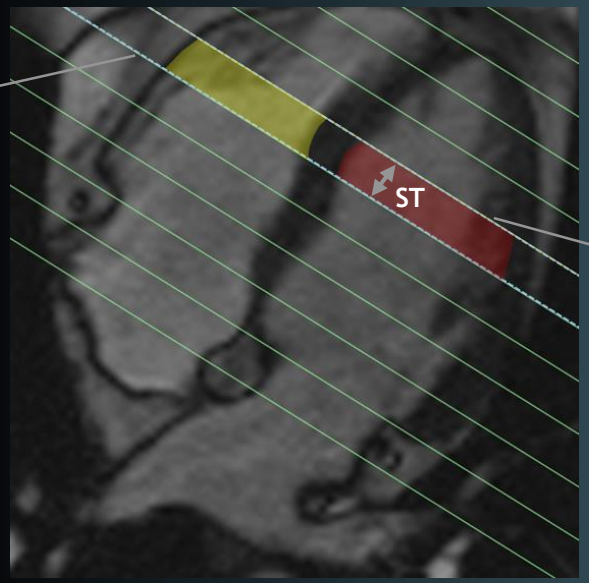
Ventricular Volume and Function

Step 3: Calculate endocardial end-diastolic volume (EDV) and end-systolic volume (ESV).

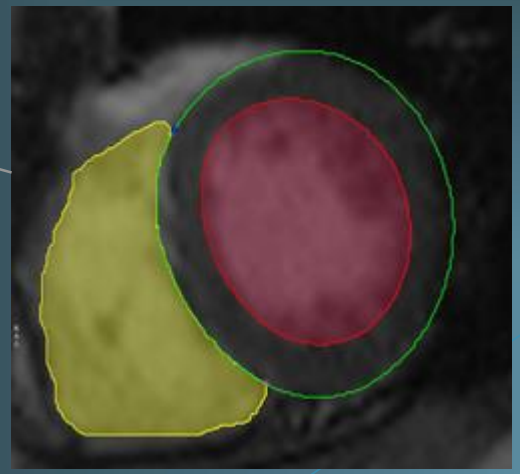
- Total volumes calculated using Simpson's Rule technique.
- Volume of each section calculated by cross-sectional area within endocardial contour multiplied by section thickness and intersection gap (predetermined scanner parameter).
- Individual section volumes added to compute total ventricular volume.



Short-axis steady-state free-precession (SSFP) image.



Four-chamber reference SSFP image.



Short-axis SSFP image.

LEGEND

Yellow line: RV endocardial contour
Yellow shade: RV endocardial cross-sectional area (CSA)
Green line: LV epicardial contour
Red line: LV endocardial contour
Red shade: LV endocardial cross-sectional area
ST: section thickness and intersection gap

Ventricular Volume and Function

Step 4: Calculate stroke volume (SV), ejection fraction (EF), and cardiac output (CO).

- Ventricular parameters normalized to the patient's body surface area to allow comparison to published data.

$$CO = HR \times SV$$

$$SV = EDV - ESV$$

$$EF = \frac{EDV - ESV}{EDV}$$

Volumetric Analysis	LV	RV
ED Volume (mL)	122	140
ES Volume (mL)	50	72
Cardiac output (L/min)	6.12	5.78
Stroke Volume (mL)	72	68
Ejection fraction (%)	59	49

Representative volume/function output

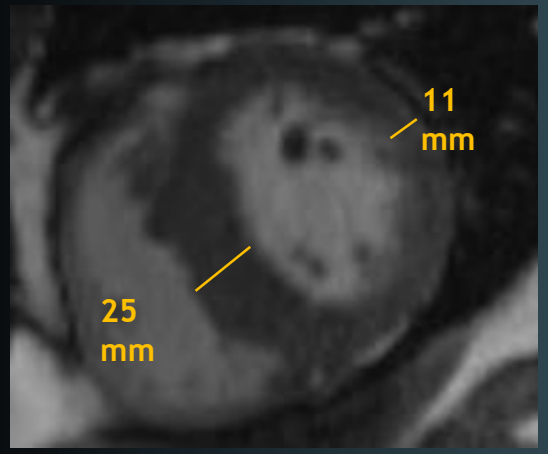
Tip: In the absence of intra- or extracardiac shunts or significant valvular regurgitation, LV and RV SVs should be nearly equal (closed-circuit system).

Myocardial Thickness

- Report measurements in end diastole.

- Measure myocardial thickness on images obtained orthogonal to the chamber.
  - Typically made on short-axis images.
  - Measurements made on oblique axis through the ventricle may overestimate thickness.

Case example: Hypertrophic cardiomyopathy.



Short-axis bSSFP image.

Asymmetric hypertrophy of the basal septum (25 mm) compared to the anterolateral wall thickness (11 mm), meeting criteria for hypertrophic cardiomyopathy.[2]

Myocardial Mass

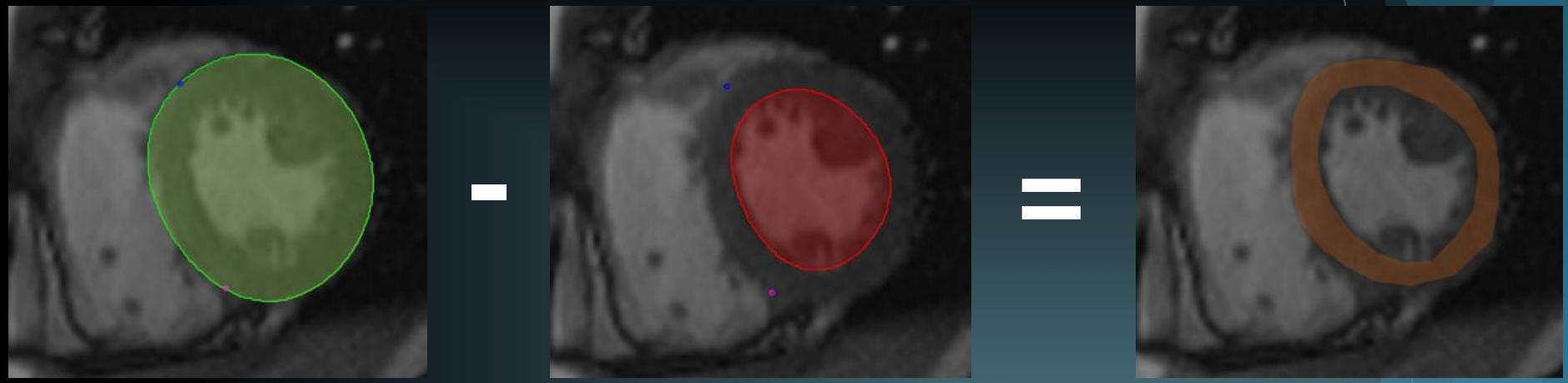
Step 1: Copy ES and ED phases and LV endocardial and epicardial contours from previous ventricular volume and function calculation.

- For mass calculations, some may choose only to draw epicardial contours only in ED.
- Drawing epicardial contours in both ED and ES and comparing masses adds an additional internal validation measure (conservation of mass).

Myocardial Mass

Step 2: Calculate ED and ES endocardial and epicardial volumes.

- Total volumes calculated using Simpson's Rule technique as demonstrated previously.
- Decide to include or exclude papillary muscles and trabeculations.



Short-axis mid section epicardial cross-sectional area.

Short-axis mid section endocardial cross-sectional area.

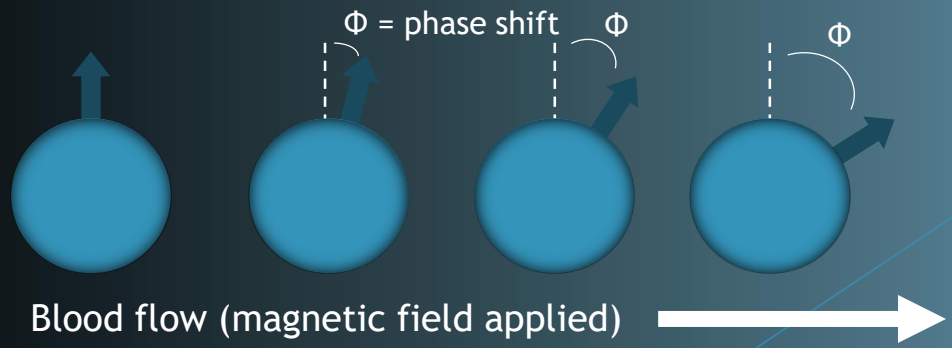
Short-axis mid section myocardial cross-sectional area.

Step 3: Subtract endocardial from epicardial volume to obtain myocardial volume.

Step 4: Calculate myocardial mass by multiplying myocardial volume by known specific density (1.05 g/mL).

Velocity-encoded Phase-Contrast Imaging

- Spoiled gradient-echo sequence in which induced phase shifts in moving protons are directly proportional to their velocity along the direction of the gradient.
- Images are generated according to net phase shift (between +180° and -180°).
  - Flow appears with high or low signal intensity depending on direction. Static protons appear gray.
- Velocity-encoding gradient (VENC) defined corresponding to maximal phase shift.
- Peak velocity can be calculated according to the degree of phase shift.
- Magnitude image is also reconstructed from the same data assisting in anatomic localization.

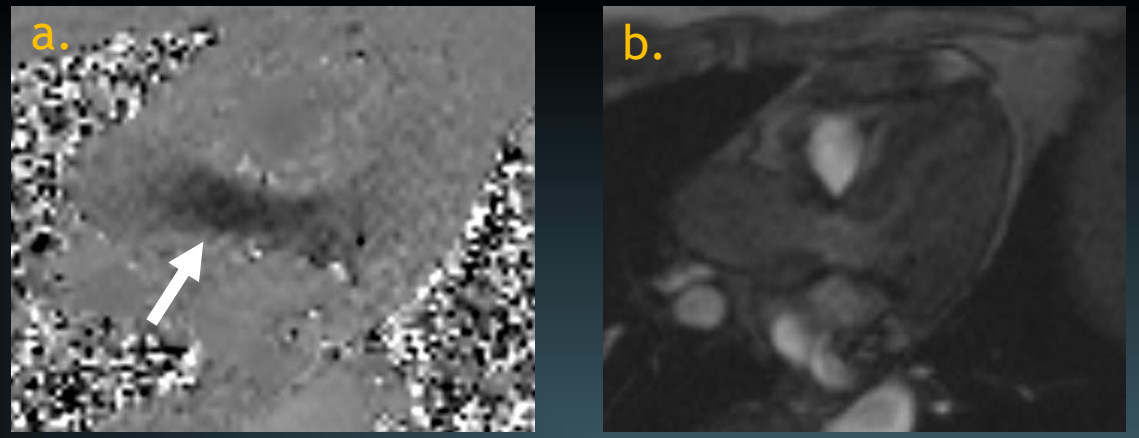


Velocity-encoded Phase-Contrast Imaging

- Phase-contrast images depict in-plane or through-plane velocities with respect to flow direction.

In-plane

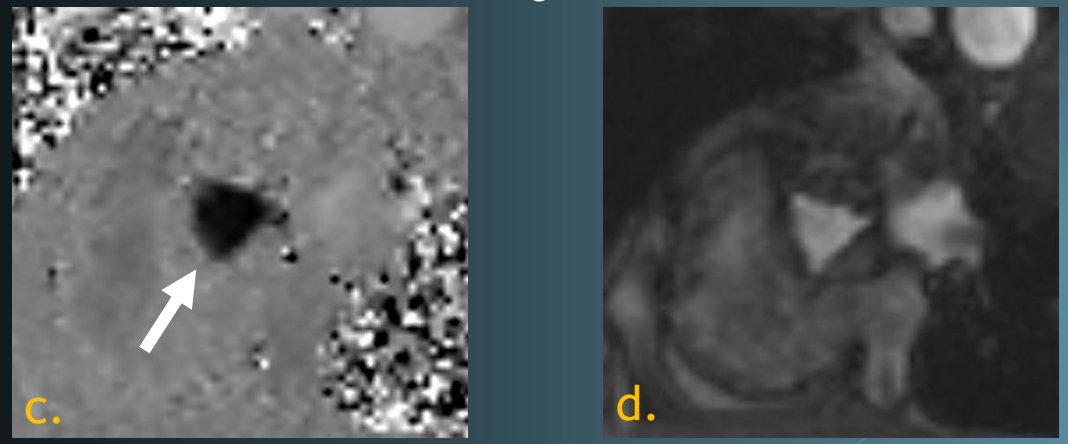
- Depicts velocity parallel to the direction of blood flow.
- Useful to depict site of and measuring peak velocity.
- Unable to help calculate flow parameters accurately.



In-plane LVOT systolic phase (a) and magnitude (b) phase-contrast images.

Through-plane

- Depicts velocity orthogonal to the direction of blood flow.
- Necessary for accurate calculation of flow parameters.



Through-plane systolic phase (c) and magnitude (d) phase-contrast MR images at the level of the aortic valve.

Flow across the LVOT (a, b) and through the aortic valve (c, d) appears with low signal intensity on phase image (arrow in a and c). Corresponding anatomy is better delineated on magnitude images.

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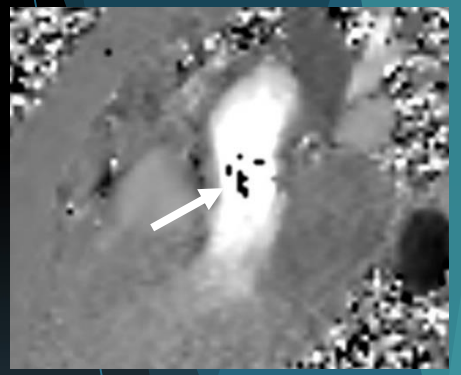
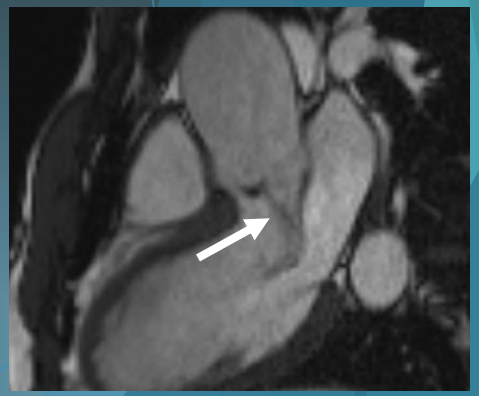
Peak Velocity and Gradient

- Prior to quantification:
  - Ensure proper VENC selection:
    - VENC set too low causes aliasing.
    - VENC set too high causes low velocities obscured by background noise.
    - **Tip:** Aliasing should be corrected at the time of scanning by increasing the VENC. Most postprocessing software packages have algorithms for decreasing artifact from aliasing.
  - Through-plane images are obtained at the level of and perpendicular to the direction of peak flow jet.
    - **Tip:** Cross-reference with in-plane phase-contrast or bSSFP images to ensure correct plane selection.
    - Phase-contrast images may underestimate flows with eccentric jets and helical flow.

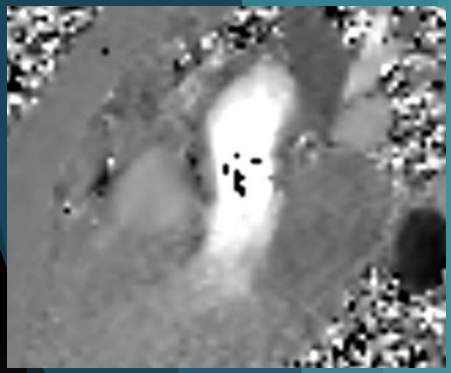


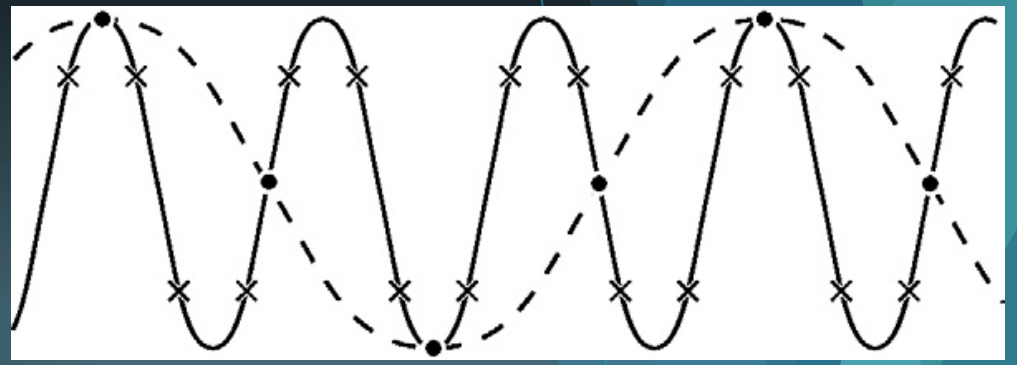
LVOT view in-plane phase-contrast image with aliasing artifact (arrow) due to inappropriately low VENC selection (150 cm/sec).



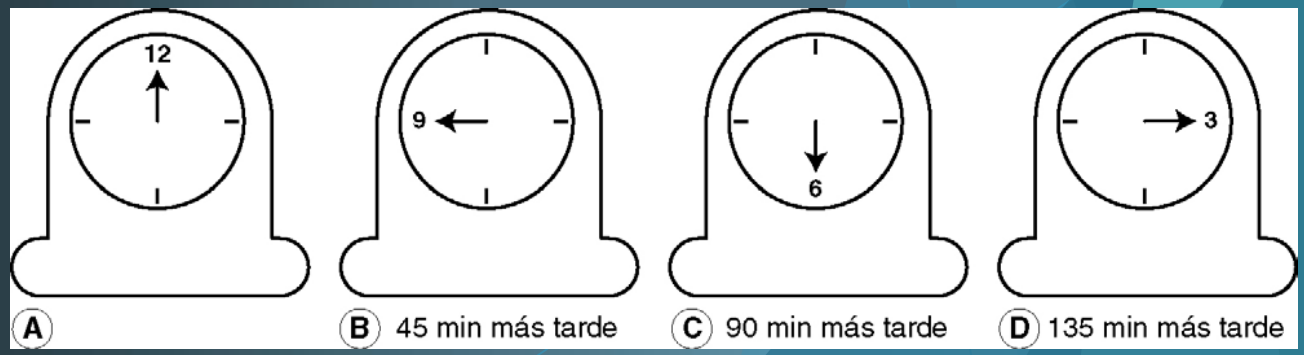
LVOT view three-chamber bSSFP image with an eccentric regurgitant jet (arrow) directed posteriorly toward the anterior mitral leaflet.

LVOT view in-plane phase-contrast image with aliasing artifact (arrow) due to inappropriately low VENC selection (150 cm/sec).





aliasing
wagon-wheel (stroboscopic) **effect**



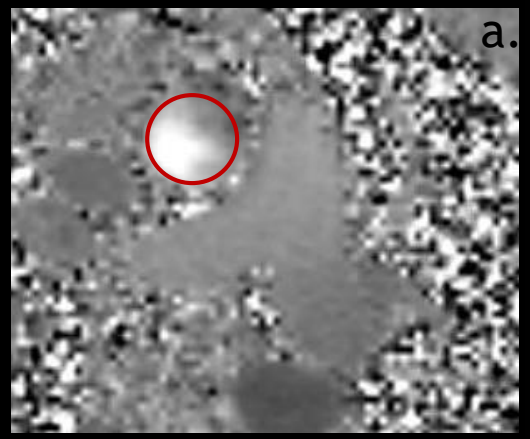
Thrush A, Hartshorne T. Ecografía Vacular. Cómo, por qué y cuándo. Tercera edición. Elsevier, Barcelona 2011.

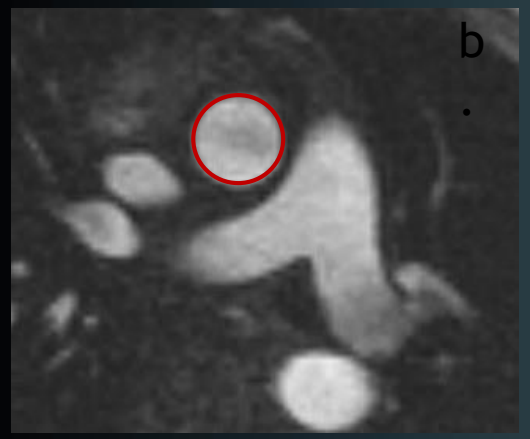
https://www.scienceabc.com/eyeopeners/wheels-appear-spinning-backwards-high-speeds.html

Peak Velocity and Gradient

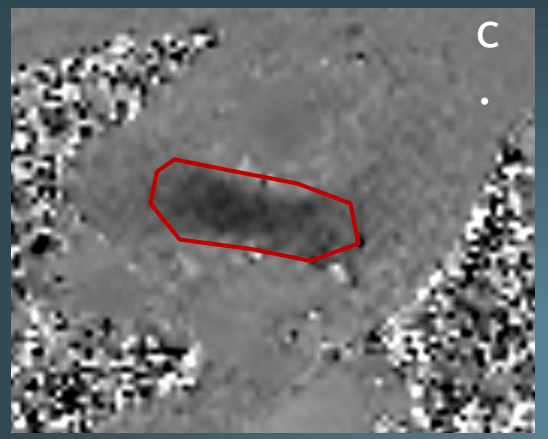
Step 1: Load both phase and magnitude images into postprocessing software.
Step 2: Draw ROI on through-plane or in-plane image in which margins of flow are best delineated.

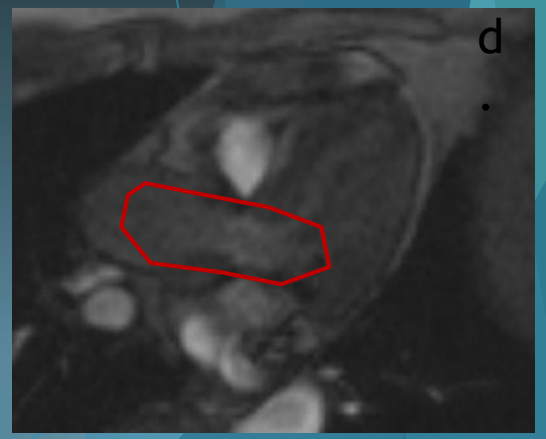
- **Tip:** Draw ROIs on magnitude images because of better anatomy depiction.
- Software propagates ROIs to all phases in series and phase images.
- Velocity and flow data obtained from phase images only.





Axial through-plane systolic phase (a) and magnitude (b) phase-contrast images above the level of the aortic valve show the ROI (red circle) around the aorta.





LVOT view in-plane systolic phase (c) and magnitude (d) phase-contrast images show the ROI (red oval) around the area of flow in the LVOT and proximal aorta.

Peak Velocity and Gradient

Step 3: Measurement of peak velocities for each phase according to phase shift (signal) on phase images.

- **Tip:** Software background correction may correct inaccuracies to the presence of phase offsets.

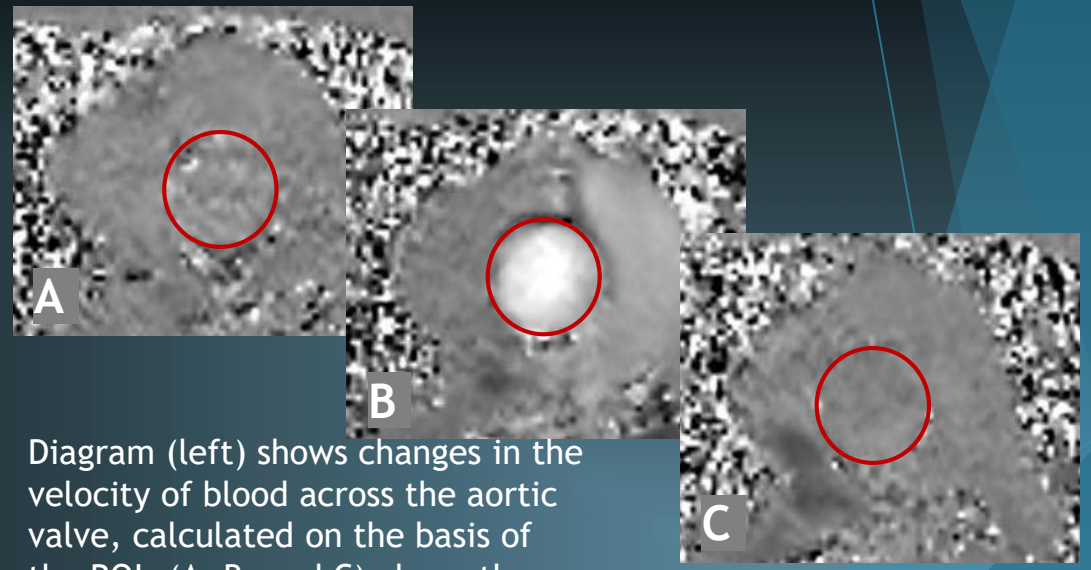
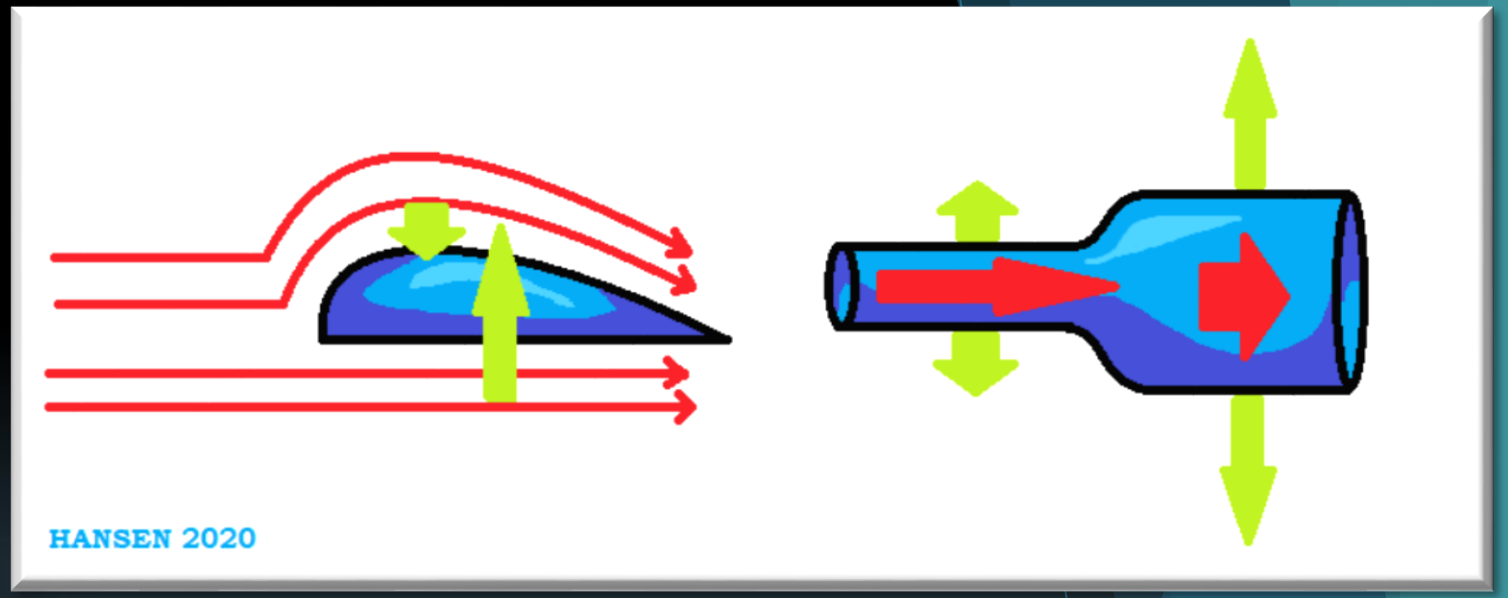


Diagram (left) shows changes in the velocity of blood across the aortic valve, calculated on the basis of the ROIs (A, B, and C) above the level of the aortic valve.

Step 4: Pressure gradient calculated according to modified Bernoulli equation.

- Pressure gradient (mm Hg) = 4 x $velocity_{peak}^{2}$ (Note: velocity in m/sec)

Modified Bernoulli equation



The modified Bernoulli equation states:

$\Delta P = 4 (V_2^2 - V_1^2)$

where V_1 is velocity pre-orifice and V2 is velocity post-orifice

V_1^2 is significantly less than V_2^2 in most physiological conditions and can be ignored, thus: $\Delta P = 4 V_2$. In aortic stenosis, peak pressure gradient is 4×(peak velocity)^2 through the valve.

If V_1 (LVOT) velocity is abnormally high, such as in obstructive cardiomyopathy (>1 m s^{-1}), the full equation should be used. If V_1 is <1 m s^{-1} (most common in clinical practice), then the simplified version is used.

Bernoulli's Principle

Fluid velocity

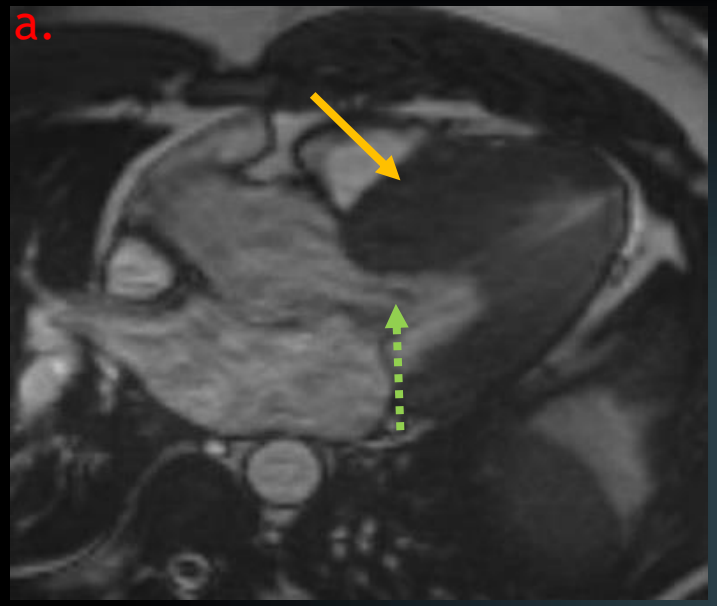
Static pressure (potential energy)

Hydrodynamica
Daniel Bernoulli (1738)

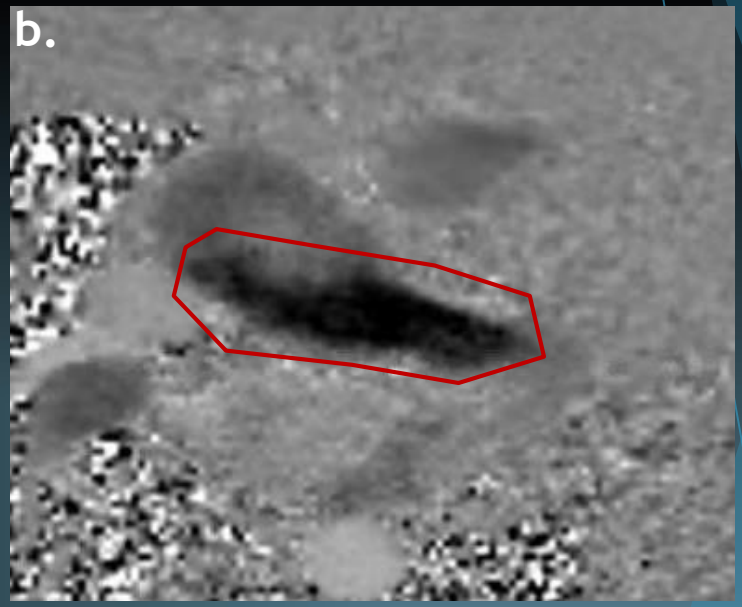
Harris P, Kuppurao L. Quantitative Doppler echocardiography. BJA Education, 16 (2): 46–52 (2016). Advance Access Publication Date: 10 June 2015; doi: 10.1093/bjaceaccp/mkv015

Peak Velocity and Gradient

Case example: Hypertrophic obstructive cardiomyopathy.



Three-chamber bSSFP image.



LVOT in-plane phase-contrast image.

Three-chamber bSSFP image obtained during systole **(a)** demonstrates **thickening of the basal septum (solid arrow)** and a **dephasing jet secondary to flow acceleration across the LVOT (dotted arrow).**
In-plane phase-contrast image **(b)** obtained during systole shows the **ROI drawn around flow** within the LVOT and proximal aorta. Calculated peak velocity was 2.0 m/sec. Using the modified Bernoulli equation ($4*V_{max}^2$), this equates to a resting gradient of 16 mm Hg.

Forward and Reverse Volumes

Repeat steps 1 and 2 as previously described.

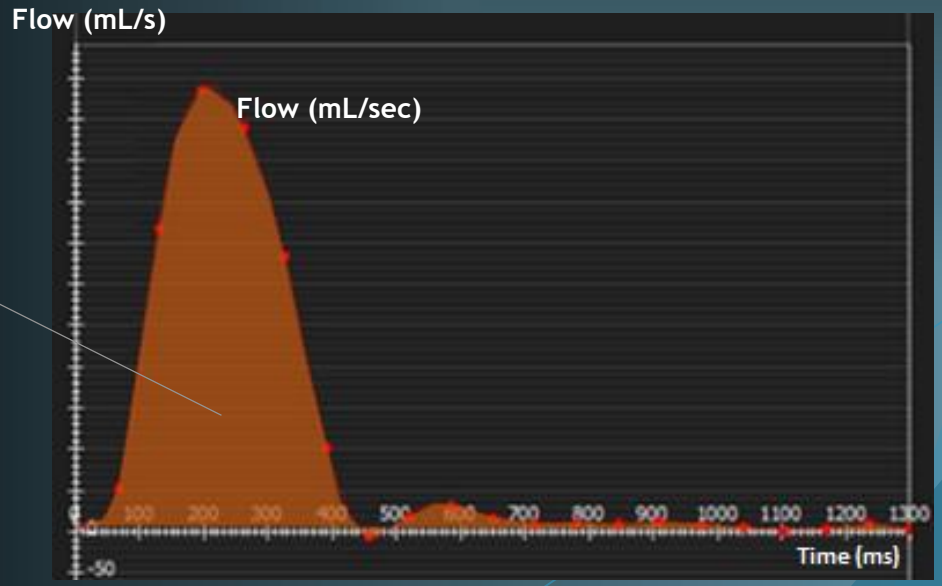
Step 3: Measurement of peak velocities for each phase.

- Plot of flow over time can be calculated by multiplying velocity by the cross-sectional area of the ROI.

Step 4: Forward and reverse volumes over cardiac cycle calculated by calculating areas under the curve during forward (positive) and reverse (negative) flows.

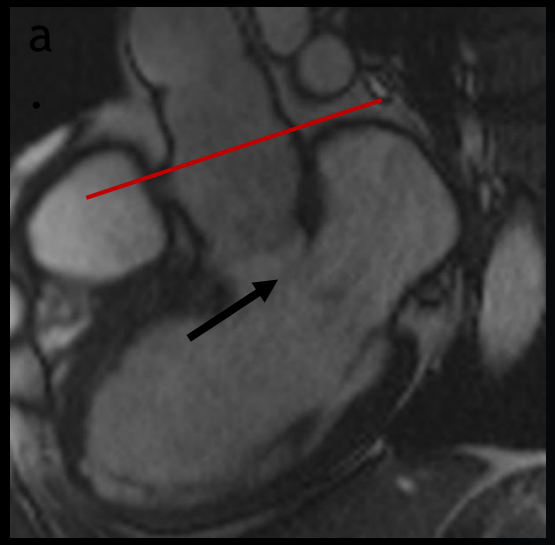
- **Tip:** In the absence of valvular regurgitation or shunt, forward volume should be nearly equal to SV.

Forward volume represented as area under flow vs time curve (orange).

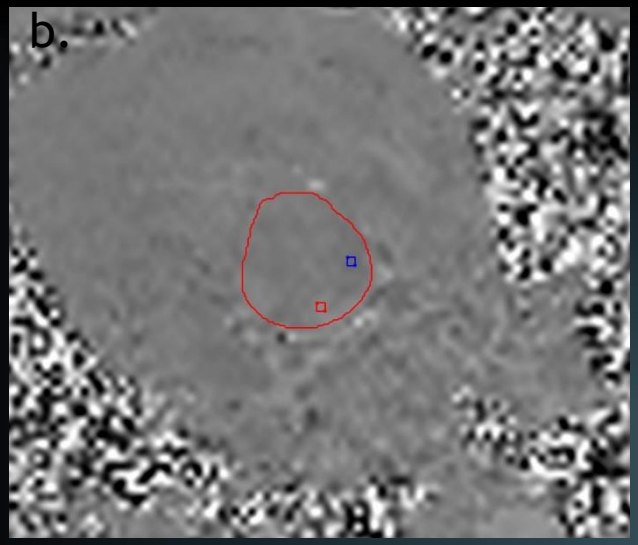


Forward and Reverse Volumes

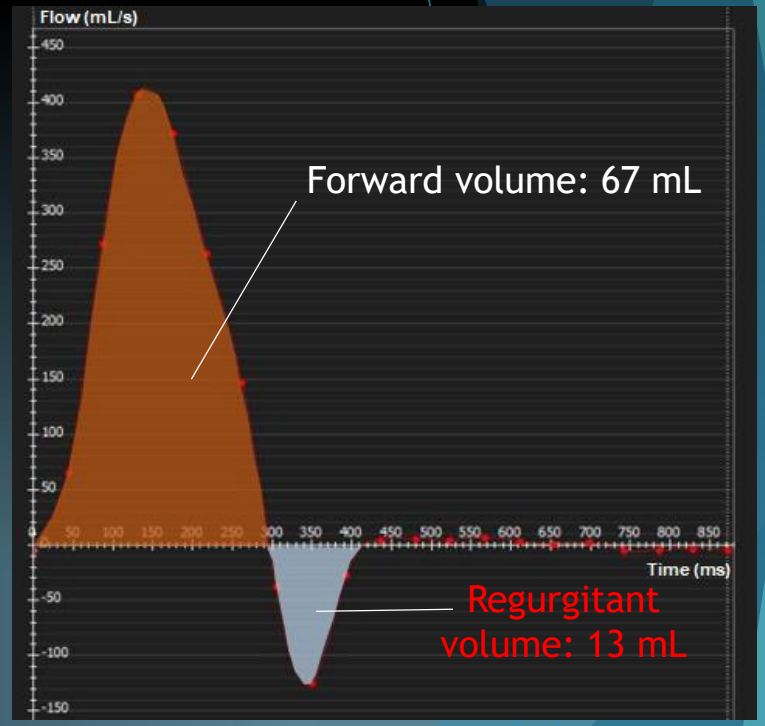
Case example: Aortic regurgitation.



Three-chamber bSSFP image.



Aortic valve through-plane phase-contrast image.



Patient with a history of Loeys-Dietz syndrome with a valve-sparing aortic root aneurysm repair.

Diastolic three-chamber bSSFP image (**a**) shows a qualitative aortic regurgitation jet (arrow). Through-plane phase-contrast image above the level of the valve (**b**, corresponding with the reference line in **a**) shows an ROI drawn around the ascending aorta. Plot of flow over time (right) illustrates the forward volume (orange shaded area) during systole and reverse volume (blue shaded area) during early diastole.

The calculated regurgitant fraction is 19%.

$$\text{Regurgitant fraction (\%)} = \frac{\text{Regurgitant volume}}{\text{Forward volume}}$$

RadioGraphics

RSNA

Forward and Reverse Volumes

Case example: Mitral regurgitation.

- Because of the motion of the atrioventricular valves throughout the cardiac cycle, direct quantification of regurgitation with through-plane phase-contrast images is less reliable.
- Mitral and tricuspid regurgitation quantified with indirect technique:

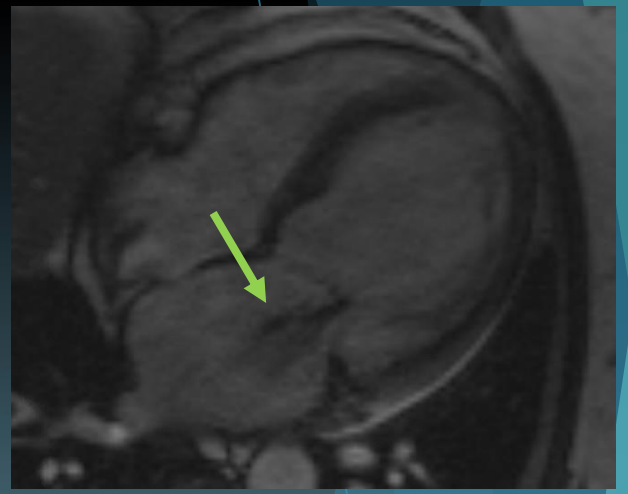
From bSSFP images

From aortic PC images

$$\text{Mitral regurgitant volume} = \text{LV SV} - \text{Aortic forward flow}$$

$$\text{Mitral regurgitant fraction} = \frac{\text{Mitral regurgitant volume}}{\text{LV SV}}$$

- **Tip:** If the patient also has aortic regurgitation, the aortic regurgitant volume should also be subtracted from the mitral regurgitant volume.



Four-chamber bSSFP image.

Systolic four-chamber SSFP image demonstrates a centrally directed regurgitant jet (arrow). Aortic forward volume was 47 mL, and LV SV was 72 mL. This corresponds to a regurgitant volume of 25 mL and regurgitant fraction of 35%.

Shunt Quantification

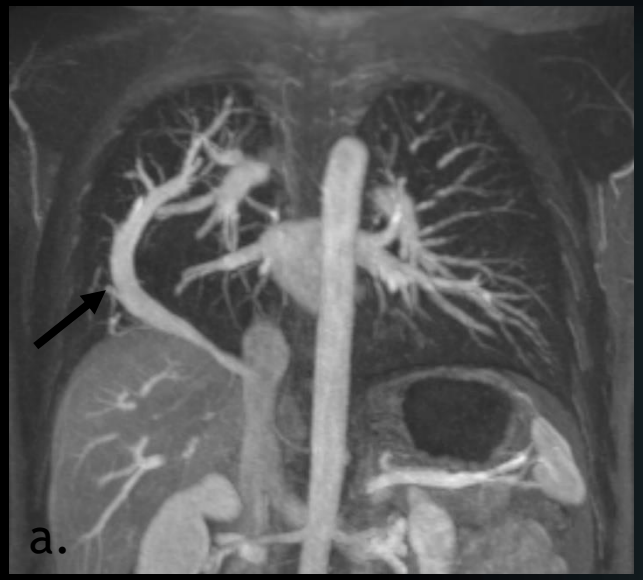
- Intra- and extracardiac shunts can be quantified with direct and indirect techniques.

- **Direct technique:** Phase-contrast images obtained in-plane or through-plane with respect to the shunt itself.
  - Evaluate flow through the shunt.
  - May help in delineating shunt margins.
  - **Tip:** Lower VENC (ie, 50-80 cm/sec) required to depict slower flows.

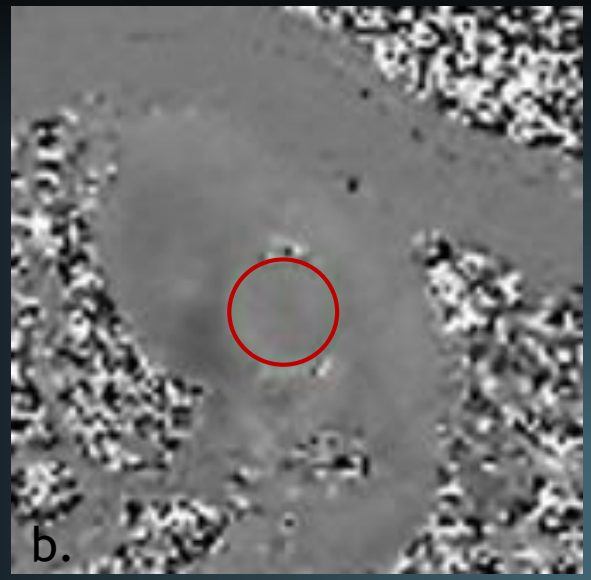
- **Indirect technique:** Through-plane phase-contrast images acquired above the level of the pulmonic and aortic valves.
  - Shunt fraction (Qp:Qs) = ratio of pulmonic and aortic forward flows.
    - Normal: Qp:Qs = 1; left-to-right shunt: Qp:Qs > 1; right-to-left shunt: Qp:Qs < 1
  - Qp:Qs is an important factor in determining hemodynamic significance and appropriateness for repair.
    - Qp:Qs > 1.5 generally considered for repair of left-to-right shunts.[3]

Shunt Quantification

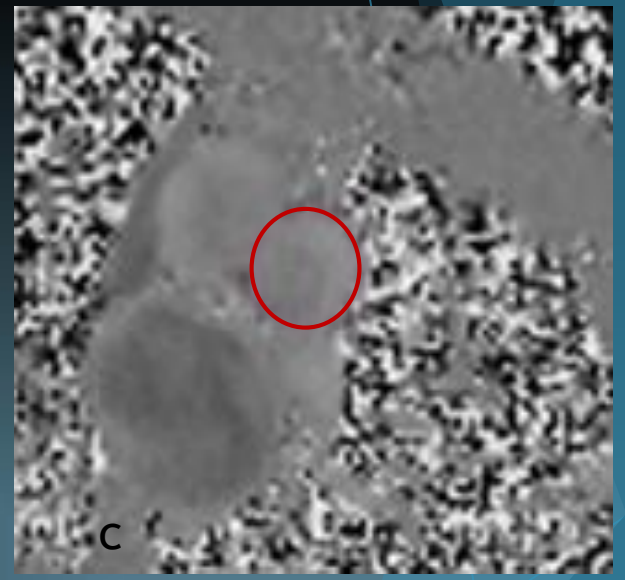
Case example: Partial anomalous pulmonary venous return—indirect shunt evaluation.



Coronal maximum intensity projection (MIP) MR angiogram.



Aortic through-plane phase-contrast image.



Pulmonic through-plane phase-contrast image.

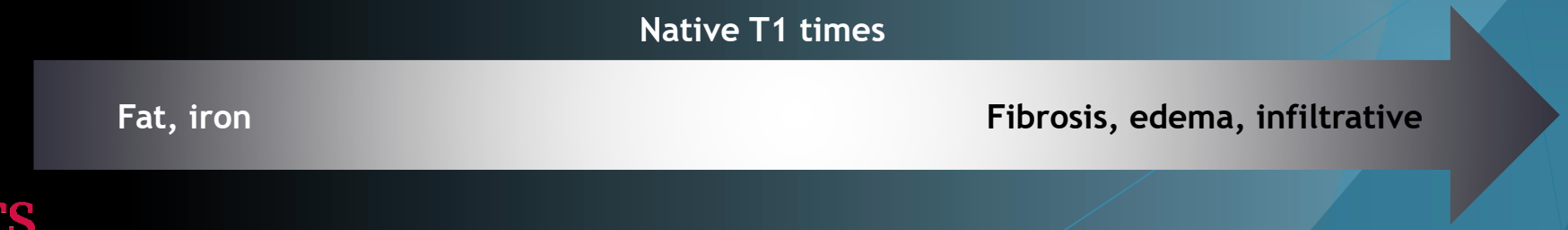
Coronal MIP MR angiogram **(a)** demonstrates a scimitar vein (arrow) draining from the right upper lobe to the inferior vena cava. Through-plane phase-contrast image obtained above the level of the aortic valve **(b)** shows the ROI (red circle) drawn around the aorta. Flow within the aorta was calculated as 4.03 L/min. Through-plane phase-contrast image obtained above the level of the pulmonic valve **(c)** shows the ROI (red circle) drawn around the main pulmonary artery. Flow within the pulmonary artery was calculated as 5.33 L/min. The calculated Qp:Qs is 1.32, confirming the presence of a left-to-right shunt.

Parametric Mapping

- Myocardial characterization of edema, fibrosis, and interstitial processes has traditionally been qualitative.
  - Quantification of myocardial edema and fibrosis was only possible when there was a difference between normal and abnormal myocardium.
  - Diffuse myocardial disease has been traditionally difficult to depict.
- Parametric mapping allows quantification of these myocardial parameters.
- Secondary images (maps) are generated, in which each pixel represents a specific magnetic tissue property, allowing qualitative assessment.
- Parameters can be measured directly (T1, T2, T2*) or represent derived parameters (ECV).

T1 Mapping and ECV

- T1: time constant representing the recovery of longitudinal magnetization (spin-lattice relaxation).
- Various methods of calculating T1 values.
  - Most common method is modified Look-Locker imaging (MOLLI): multiple inversion pulses followed by readouts at various fixed inversion times.
- Can be performed precontrast (native) or postcontrast.
  - Native T1 quantifies T1 values without contrast material.
  - Postcontrast images obtained 10-30 minutes after injection of contrast material.
- Most pathologic conditions cause T1 prolongation.



T1 Mapping and ECV

- Measured T1 times vary depending on several factors (ie, field strength, pulse sequence, myocardial T2, hematocrit).
  - Commonly referenced normal T1 range: 950-1050 msec (1.5 T).
  - Tip: Local or scanner-specific reference ranges should be used for T1 values.

- Extracellular volume (ECV) is a marker of myocardial tissue remodeling.
  - More reproducible between different field strengths, vendors, and acquisition techniques than native and postcontrast T1 times.
  - Calculated from native and postcontrast blood and myocardial T1 times normalized to the patient's hematocrit.
  - Normal range: 25 ± 4%.

$$ECV = (1 - Hct)\frac{\frac{1}{\text{Post } T1_{myo}} - \frac{1}{\text{Native } T1_{myo}}}{\frac{1}{\text{Post } T1_{blood}} - \frac{1}{\text{Native } T1_{blood}}}$$

EXTRACELLULAR VOLUME

...MADE SIMPLE!

$$ECV = 1 - Hct \left(\frac{\frac{1}{pT1my} - \frac{1}{nT1my}}{\frac{1}{pT1bp} - \frac{1}{nT1bp}} \right)$$

my = myocardium
bp = blood pool
Hct = hematocrit

n = native
p = postcontrast

HANSEN 2020

EXTRACELLULAR VOLUME

...MADE SIMPLE!

$$ECV = 1 - Hct \left(\frac{\frac{1}{pT1my} - \frac{1}{nT1my}}{\frac{1}{pT1bp} - \frac{1}{nT1bp}} \right)$$

my = myocardium
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HANSEN 2020

EXTRACELLULAR VOLUME

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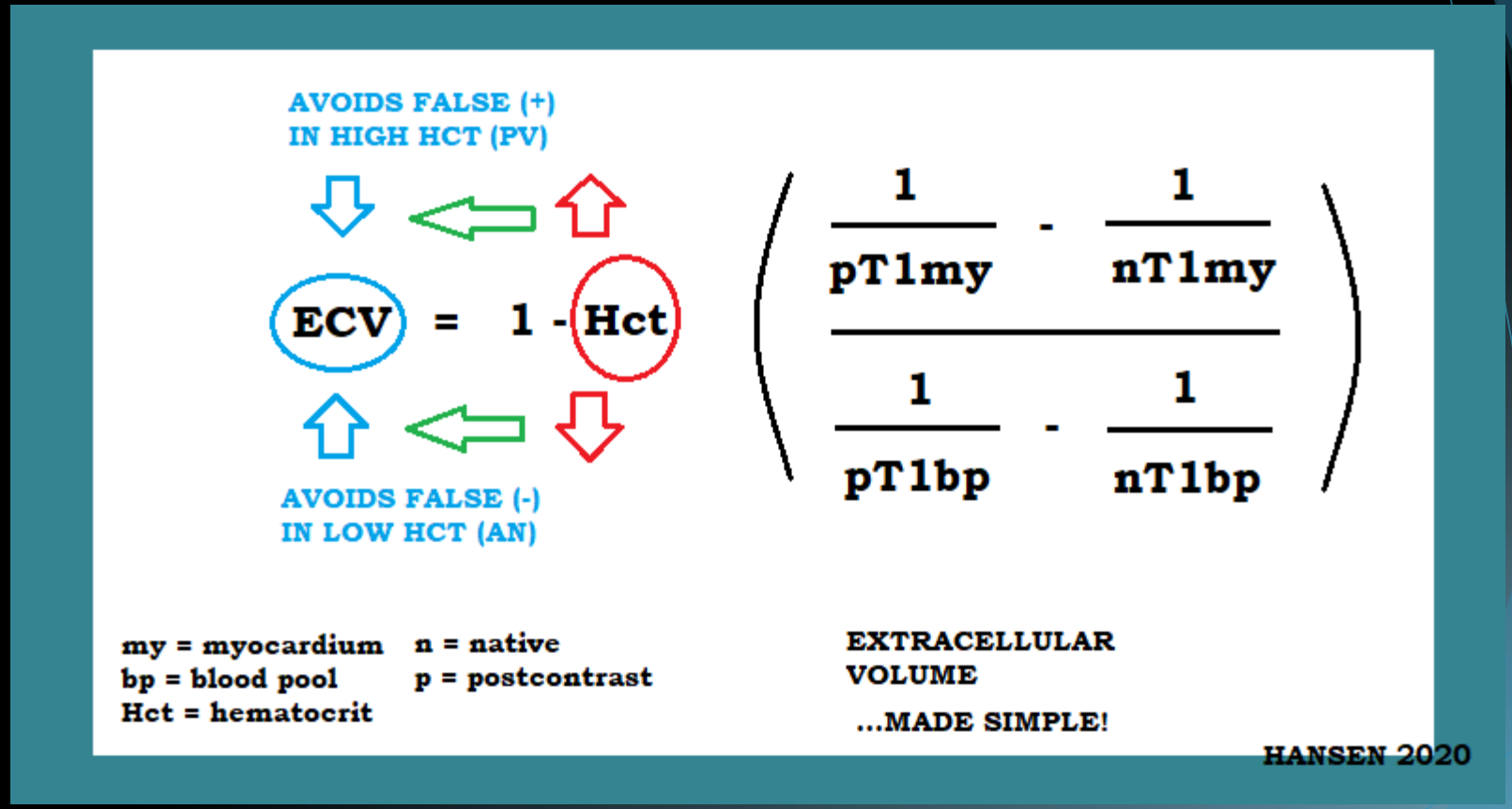
my = myocardium
bp = blood pool
Hct = hematocrit

n = native
p = postcontrast

HANSEN 2020



EXTRACELLULAR VOLUME

...MADE SIMPLE!

Difference between poscontrast and native = net effect of enhancement

$$ECV = 1 - Hct \left(\frac{\frac{1}{pT1my} - \frac{1}{nT1my}}{\frac{1}{pT1bp} - \frac{1}{nT1bp}} \right)$$

my = myocardium
bp = blood pool
Hct = hematocrit

n = native
p = postcontrast

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EXTRACELLULAR VOLUME

...MADE SIMPLE!

$$ECV = 1 - Hct \left(\frac{\frac{1}{pT1my} - \frac{1}{nT1my}}{\frac{1}{pT1bp} - \frac{1}{nT1bp}} \right)$$

Difference between myocardial signal and blood pool (contrast material that remains in intravascular space)

Net value of extracellular signal

my = myocardium
bp = blood pool
Hct = hematocrit

n = native
p = postcontrast

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EXTRACELLULAR VOLUME

...MADE SIMPLE!

$$ECV = 1 - Hct \left(\frac{\frac{1}{pT1my} - \frac{1}{nT1my}}{\frac{1}{pT1bp} - \frac{1}{nT1bp}} \right)$$

my = myocardium
bp = blood pool
Hct = hematocrit

n = native
p = postcontrast

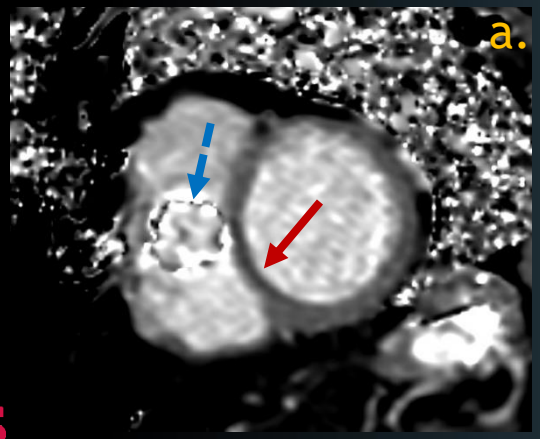
Difference between myocardial signal and blood pool (contrast material that remains in intravascular space)

Net value of extracellular signal

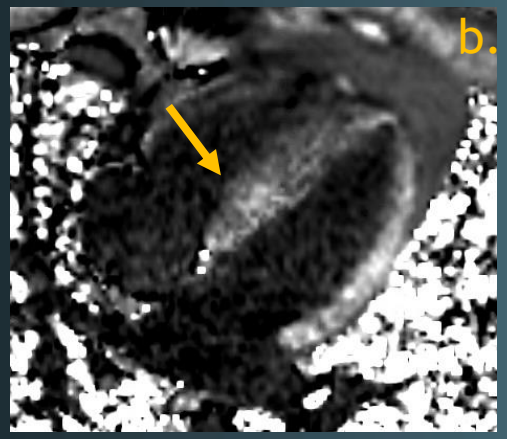
HANSEN 2020

T1 Mapping and ECV

- Three short-axis images (base, mid, apex) are most commonly used for analysis.
- Map images (gray-scale or color) are generated at the scanner from source images.
- Before quantification:
  - Native and postcontrast maps obtained at the same corresponding level.
  - Map images are free of significant artifact (motion, susceptibility, misregistration).
    - Tip: Evaluate source images to detect artifacts and their causes.
  - Hematocrit level within 24 hours is available for ECV calculation.



Short-axis base native T1 map.



Four-chamber postcontrast T1 map.

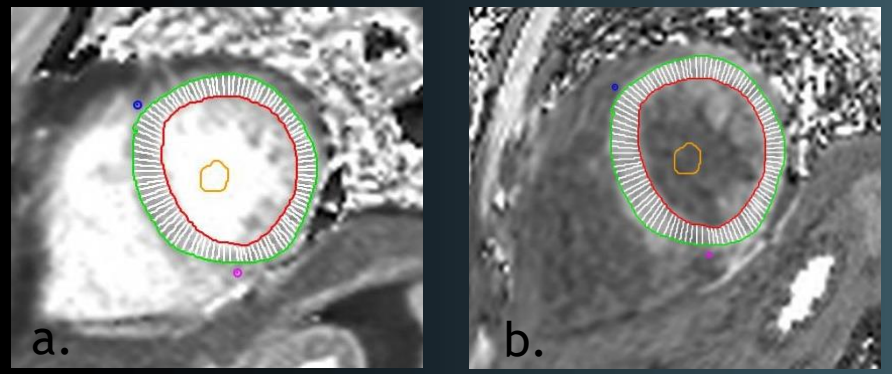
a. Apparent low T1 values within the basal inferoseptum (solid arrow) secondary to adjacent susceptibility artifact (dashed arrow).

b. Apparent low T1 values within the septum (arrow) secondary to motion artifact from arrhythmia.

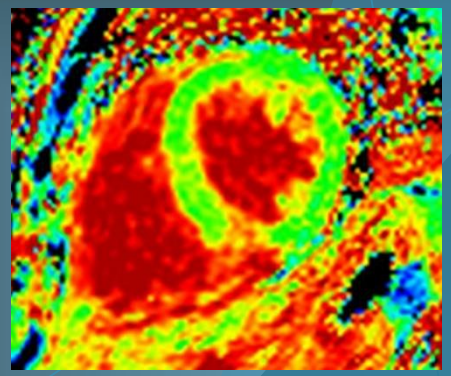
T1 Mapping and ECV

- Maps may be analyzed manually with postprocessing software or by drawing ROIs.

- Postprocessing software:
  - Allows measurements of native and postcontrast T1 times at the global, section, or segmental level.
  - Epicardial and endocardial contours are drawn on pre- and postcontrast T1 maps at each level.
  - ROIs placed within blood pool on each level.
  - Corresponding ECV maps can be generated.



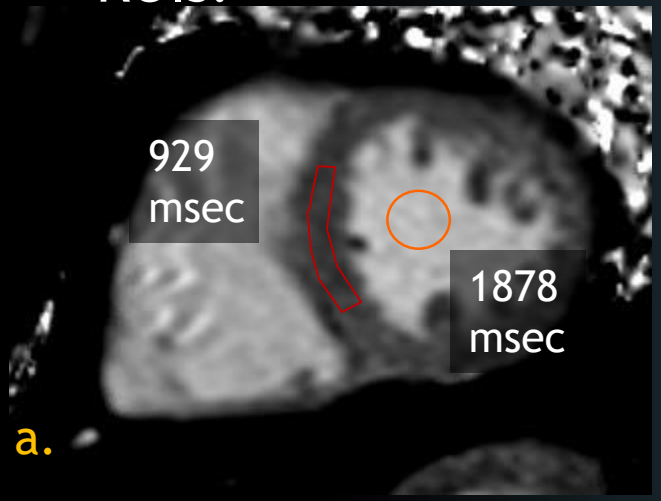
Short-axis basal native (a) and postcontrast (b) maps with epicardial (green) and endocardial (red) contours and blood pool ROIs (orange) drawn.



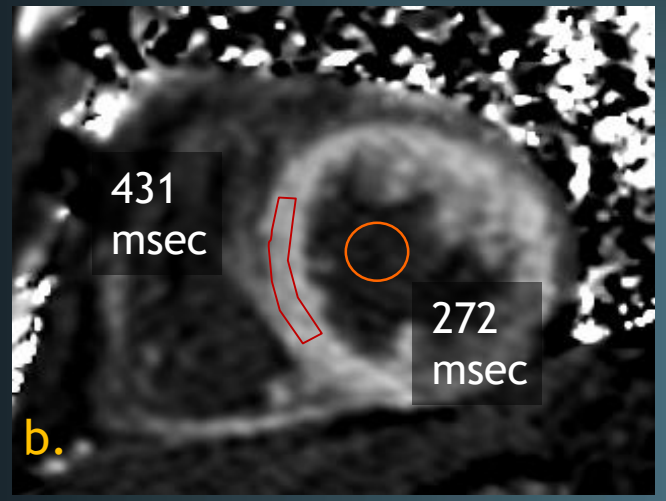
Short-axis calculated ECV map.

T1 Mapping and ECV

- ROI assessment:
  - Global diffuse disease: single ROI drawn in the mid (or basal) septum is an appropriate representation of the global myocardium.
  - Focal abnormalities: ROI should be drawn in the abnormal segment.
  - Values obtained from ROIs drawn within the same regions of myocardium and blood pool allow ECV calculation.
  - Tip: Avoid blood pool, epicardial fat or fluid, and artifacts when drawing ROIs.



Mid short-axis native T1 map.



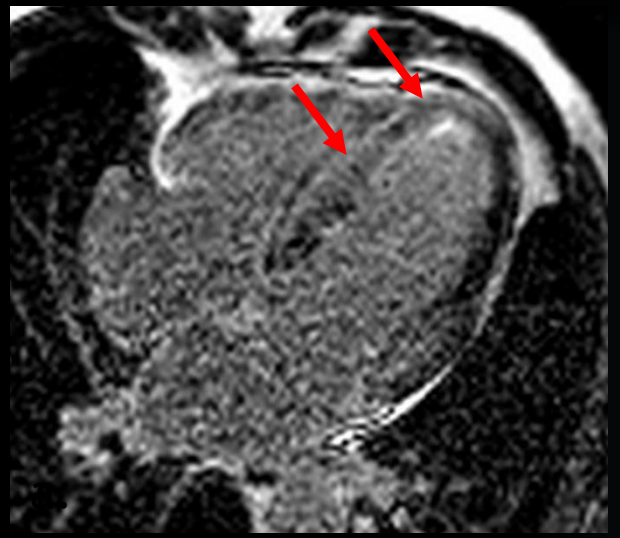
Mid short-axis postcontrast T1 map.

Mid short-axis native **(a)** and postcontrast **(b)** T1 maps. ROIs have been drawn within the mid septum (red contours) and blood pool (orange contours).

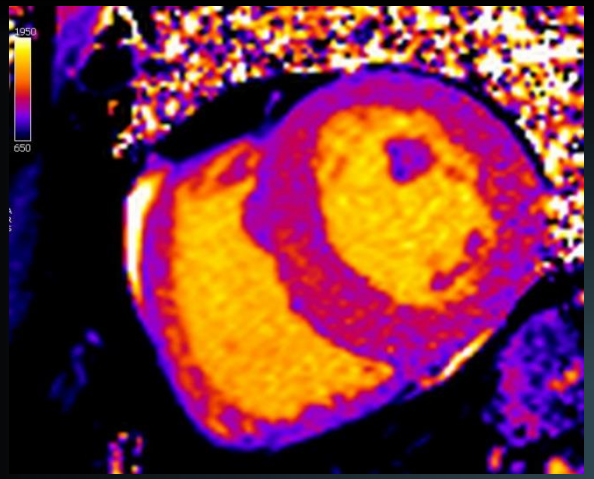
With a hematocrit of 0.47, calculated ECV is normal at 25%.

T1 Mapping and ECV

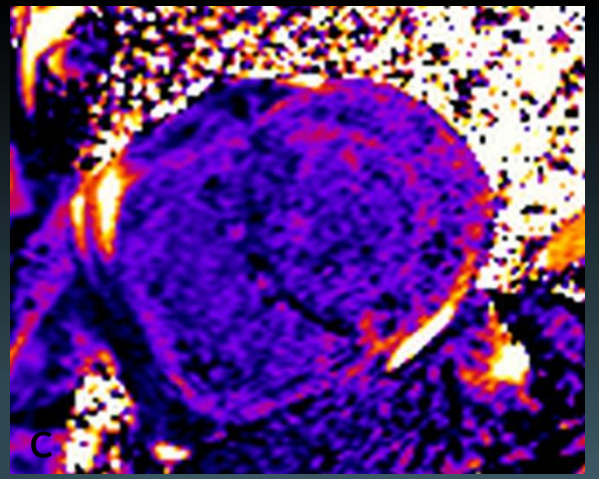
Case example: Amyloidosis.



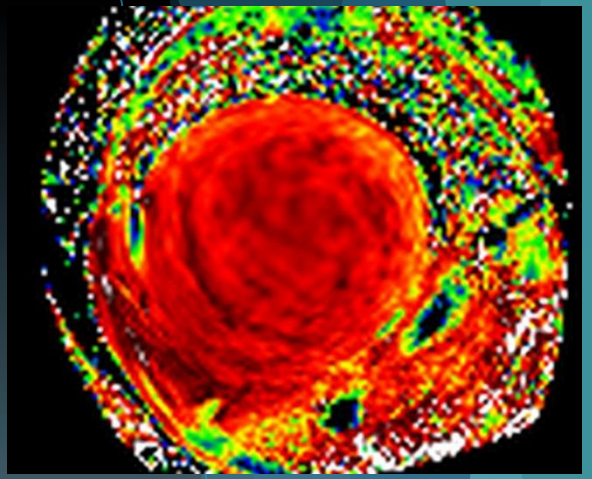
Four-chamber late gadolinium enhancement (LGE) image.



Mid short-axis native T1 map.



Mid short-axis postcontrast T1 map.



Mid short-axis ECV map.

Four-chamber LGE image

(a) demonstrates diffuse patchy myocardial enhancement most pronounced within the mid and apical interventricular septum (arrows).

(b) Mid short-axis native color T1 map demonstrates elevated native T1 values (1100 msec across entire section).

(c) and mid short-axis postcontrast color T1 map demonstrates decreased postcontrast T1 values (319 msec across entire section). Accounting for blood pool T1 values (native $T1_{blood}$: 1612 msec, post $T1_{blood}$: 313 msec) and hematocrit (0.42)

(d) A corresponding color ECV map is generated. The ECV for the mid section was markedly elevated at 50%, which is consistent with diffuse amyloid infiltration.

RadioGraphics

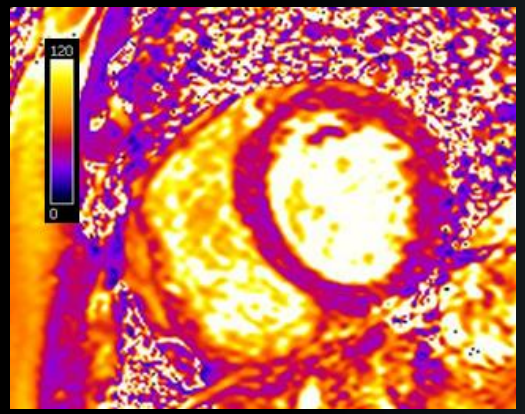
RSNA

T2 Mapping

- T2: Time constant representing the decay of transverse magnetization (spin-spin relaxation).
- Depicts increase in myocardial water tissue content or edema.
  - Applications: acute myocardial infarction, myocarditis, sarcoidosis, cardiac allograft rejection.
- Images obtained precontrast are usually in the same locations as T1 maps.
- Commonly referenced normal T2 range: 49-55 msec (1.5 T).
- Tip: Local or scanner-specific reference ranges should be used for T2 values.

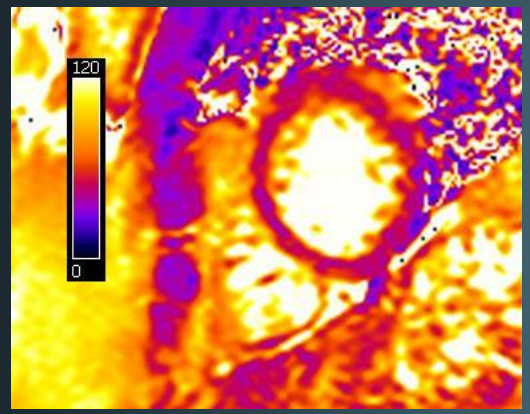
T2 Mapping

- Perform same quality check as T1 maps prior to quantification.
- Maps may be analyzed using similar ROI and postprocessing software techniques described previously.
- Tip: Regional or segmental analysis is more useful as certain pathologic conditions (ie, myocarditis) produce regional areas of myocardial edema.



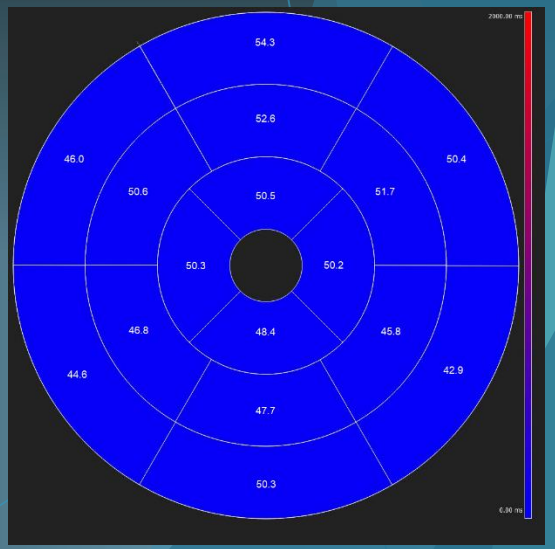
Base short-axis color T2 map.

...



Apex short-axis color T2 map.

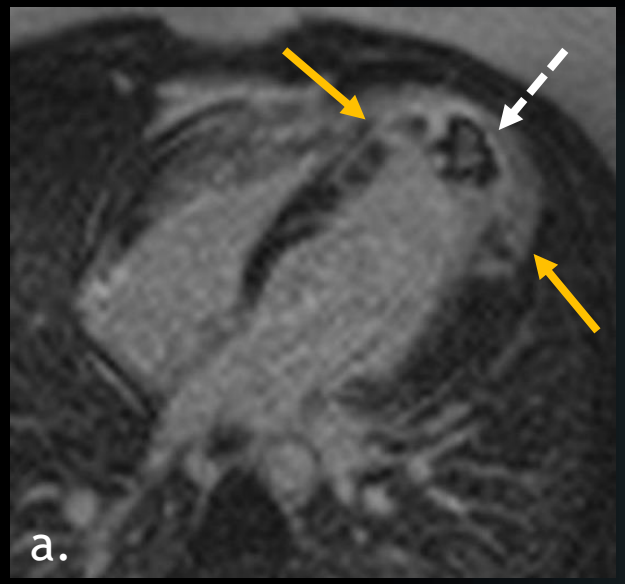
Normal T2 mapping example



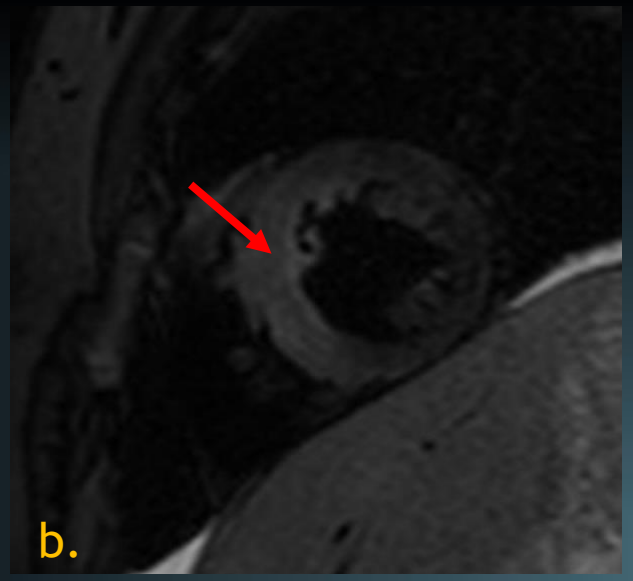
American Heart Association 16-segment results map.

T2 Mapping

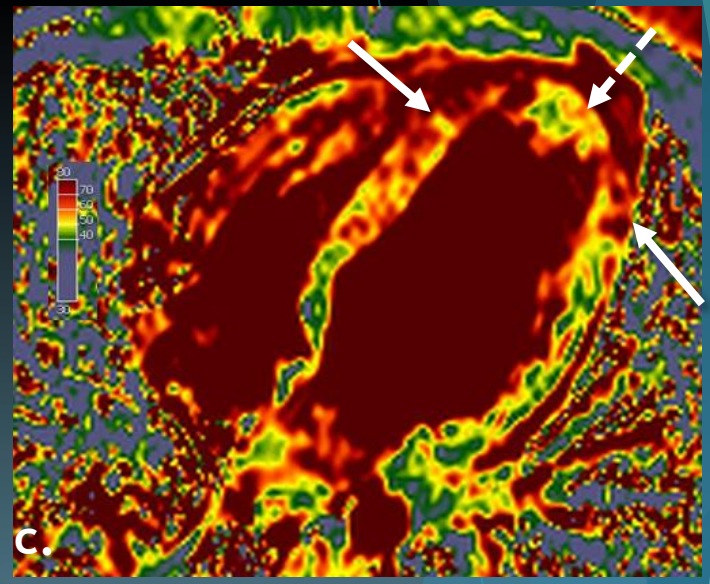
Case example: Acute myocardial infarction.



Four-chamber LGE image.



Mid short-axis short inversion time inversion recovery (STIR) image.



Four-chamber T2 map.

(a) Four-chamber LGE (late gadolinium enhancement) image demonstrates transmural delayed enhancement with areas of **microvascular obstruction** of the mid septum and entire apex (solid arrows) consistent with infarction with an associated apical thrombus (dashed arrow).
(b) Mid short-axis STIR image demonstrates increased signal intensity within the septum consistent with myocardial edema.
(c) Four-chamber color T2 map demonstrates **increased** T2 values with an infarcted mid to apical left anterior descending artery (LAD) territory (solid arrows) measuring up to 79 msec. T2 values are decreased within the apical thrombus (dashed arrow).

T2* Mapping

- T2*: Time constant representing the decay of transverse magnetization in the presence of local field inhomogeneities.
- GRE sequence with images typically acquired at eight different echoes (2-18 msec).
- Most commonly used for assessment of myocardial iron and hemorrhage.
- Tip: Measure ROI in the mid section within the septum to avoid susceptibility artifact.
- References ranges for iron overload (1.5 T):
  - Normal: T2* > 40 msec
  - Low risk for cardiac iron overload: T2* >20 msec
  - Medium risk: T2* 10-20 msec
  - High risk: T2* <10

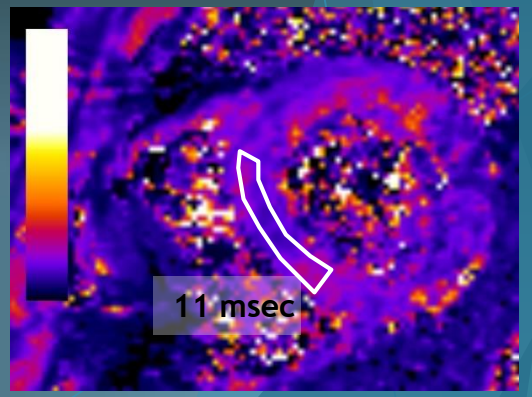
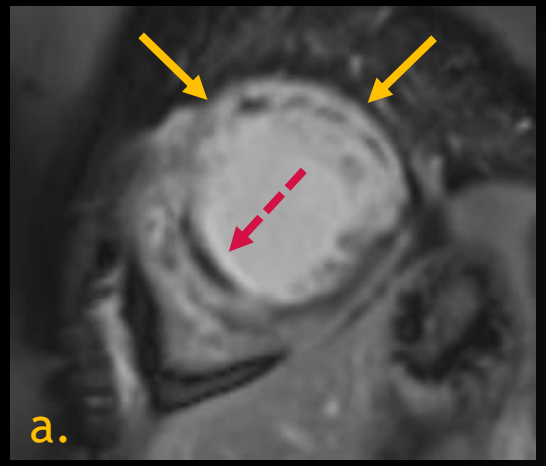


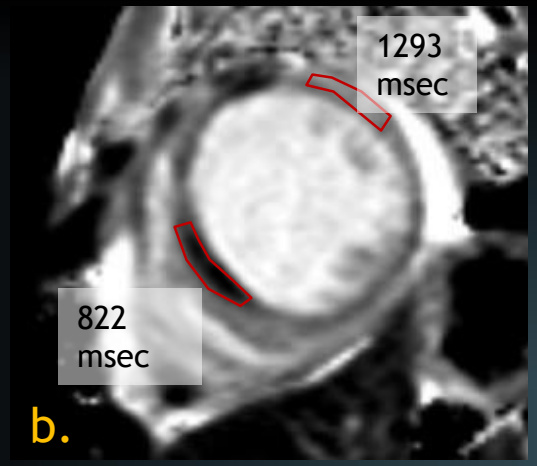
Image in a patient with **hemochromatosis**. Mid short-axis T2* map with ROI (white contour) placed over the septum (T2* 11 msec).

T2* Mapping

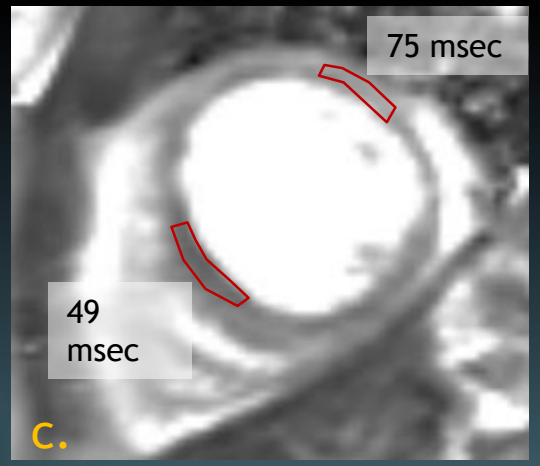
Case example: Myocardial hemorrhage.



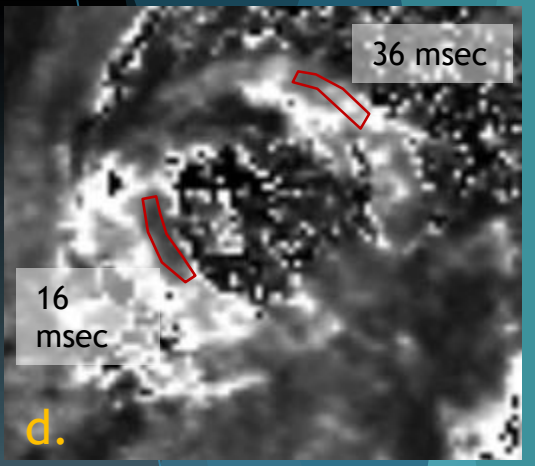
Mid short-axis LGE image.



Mid short-axis native T1 image.



Mid short-axis T2 image.



Mid short-axis T2* image.

(a) Mid short-axis late gadolinium enhancement (LGE) image demonstrates **extensive delayed enhancement (solid arrows)** consistent with **infarction** with areas of nonenhancement concerning for **microvascular obstruction (dashed arrow).**

(b) Corresponding native T1 map demonstrates decreased native T1 (822 msec) within the septum with elevated times elsewhere within the infarcted myocardium.

(c) T2 map demonstrates normal to slightly decreased (49 msec) times within the septum with elevated times within the surrounding myocardium.

(d) T2* map shows how the combination of decreased native T1 and T2 times is **suggestive of hemorrhage**, which is confirmed by decreased T2* values (16 msec).

Take-home Points

- Cardiac MRI allows quantification of myocardial structure and function, velocities, and flows as well as a more objective assessment of fibrosis, edema, and iron.

- Although postprocessing is becoming increasingly automated with more sophisticated software with artificial intelligence, user input is mandatory to ensure accurate quantification.

- Interpreting radiologists must be knowledgeable of the basic steps and principles of cardiac quantification and recognize and troubleshoot common pitfalls.

Suggested Readings

- Haaf, P., et al. Cardiac T1 Mapping and Extracellular Volume (ECV) in clinical practice: a comprehensive review. J Cardiovasc Magn Reason 2016;18(1):89.
- Kramer, C. M., et al. Standardized cardiovascular magnetic resonance imaging (CMR) protocols: 2020 update. J Cardiovasc Magn Reson 2020;22(1):17.
- Lotz, J., et al. Cardiovascular flow measurement with phase-contrast MR imaging: basic facts and implementation. Radiographics 2002;22(3):651-671.
- Messroghli, D. R., et al. Clinical recommendations for cardiovascular magnetic resonance mapping of T1, T2, T2* and extracellular volume: a consensus statement by the Society for Cardiovascular Magnetic Resonance (SCMR) endorsed by the European Association for Cardiovascular Imaging (EACVI). J Cardiovasc Magn Reason 2017;19(1):75.
- Petersen, S. E., et al. Reference ranges for cardiac structure and function using cardiovascular magnetic resonance (CMR) in Caucasians from the UK Biobank population cohort. J Cardiovasc Magn Reson 2017;19(1):18.
- Schulz-Menger, J., et al. Standardized image interpretation and post processing in cardiovascular magnetic resonance: Society for Cardiovascular Magnetic Resonance (SCMR) board of trustees task force on standardized post processing. J Cardiovasc Magn Reson 2013;15:35.
- Srichai, M. B., et al. Cardiovascular applications of phase-contrast MRI. AJR Am J Roentgenol 2009;192(3):662-675.

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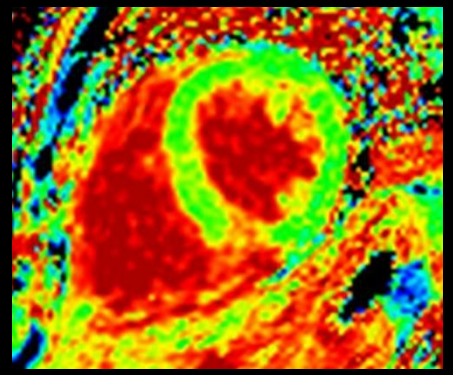
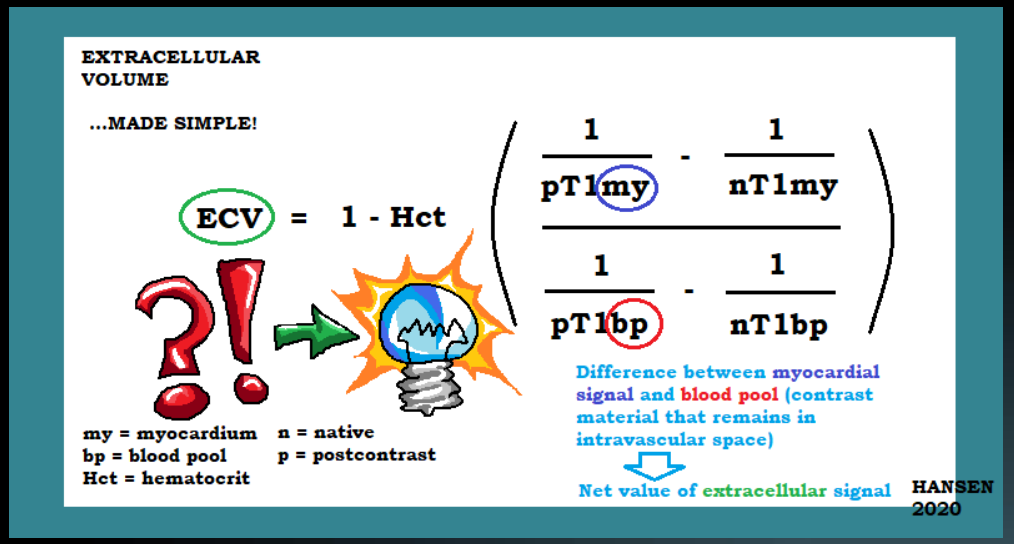
1. Chuang ML et al. Correlation of trabeculae and papillary muscles with clinical and cardiac characteristics and impact on CMR measures of LV anatomy and function. JACC Cardiovascular Imaging 2012;5(11):1115-23.

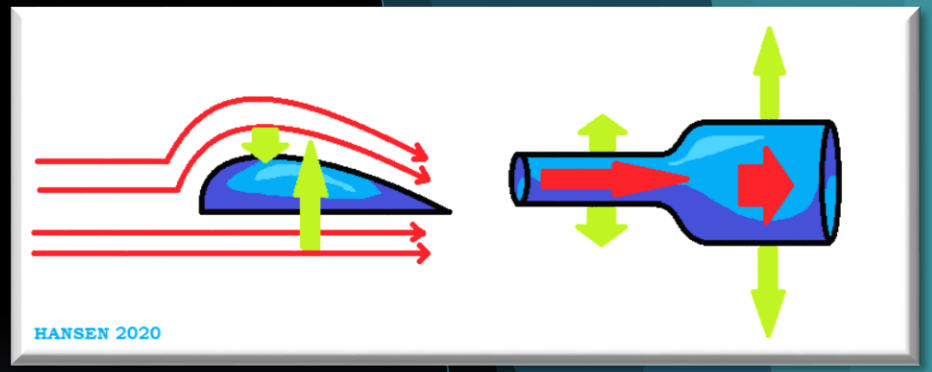
2. Gersh BJ et al. 2011 ACCF/AHA guideline for the diagnosis and treatment of hypertrophic cardiomyopathy: a report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines. Circulation 2011;124(24):e783-831.

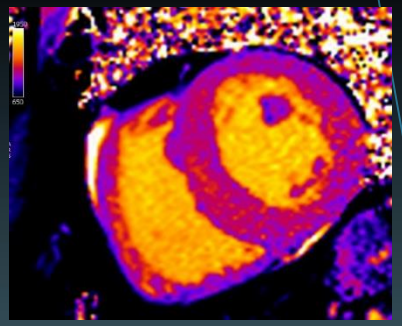
3. Stout et al. 2018 AHA/ACC Guideline for the Management of Adults With Congenital Heart Disease: Executive Summary—a Report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines. Circulation 2019;139(14):e637-e697.

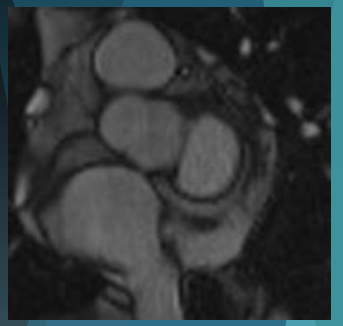
THANKS! FROM THE BOTTOM OF MY HEART…

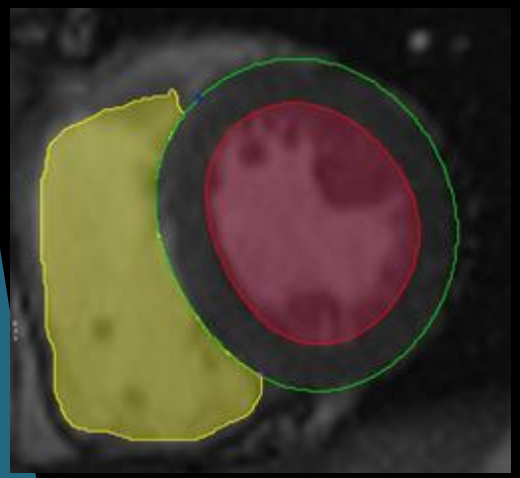


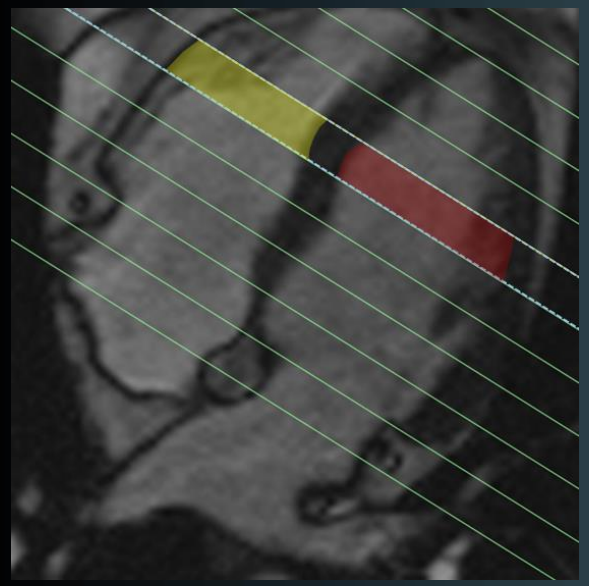












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