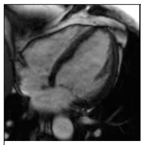
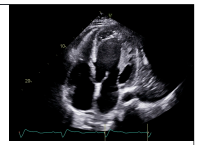


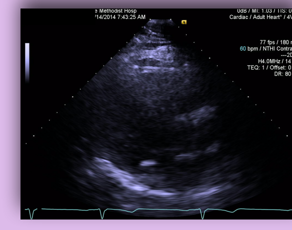


Assessing LV and RV Function

Dipan J. Shah, MD, FACC
Professor of Medicine, Weill Cornell Medical College
Director, Cardiovascular MRI Laboratory
Chief, Division of Cardiovascular Imaging
Houston Methodist DeBakey Heart & Vascular Center

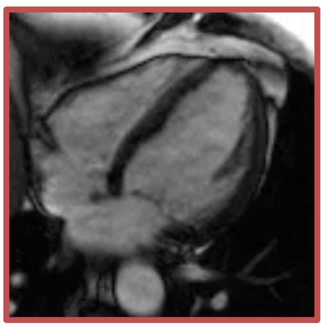
Chamber Size and Function

- Accurate assessment of chamber size and function is clinically important in many types of heart disease.
- Echo most widely used modality
  - low cost
  - portability
  - widespread availability
- Echo limitations:
  - suboptimal acoustic windows
  - operator dependence
  - use of geometric assumptions



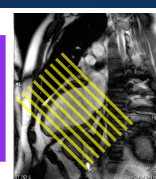
OUTLINE:

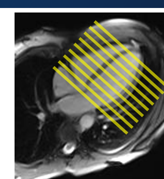
- CINE CMR IMAGING
  - How Its Performed
  - Limitations
  - Strategies To Overcome Limitations
- CMR DERIVATION OF VOLUMES AND EF
- EFFECT OF AGE AND GENDER ON VOLUMES
- VOLUMES BY CMR VS. ECHO
- HEMODYNAMICS BY CMR



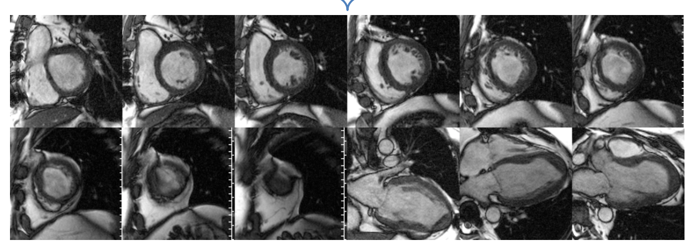
LV Function Study by CMR

- No need for IV, or contrast agent
- Can typically be acquired in 10-15 minutes



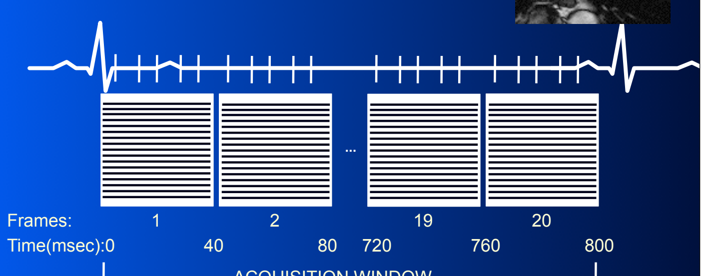


1. Localization: Perpendicular to long axis on 2 & 4 chamber views
2. Slice obtained every 10 mm
3. Use large FOV to avoid phase wrap



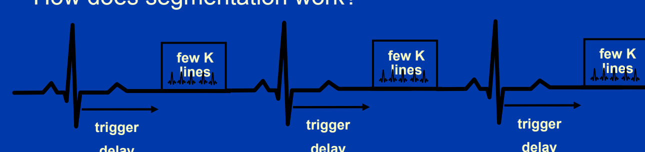
ECG GATING with segmentation

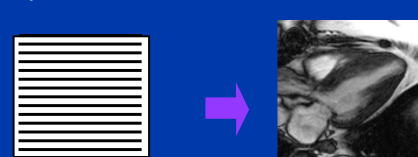
- Cine image is a series of 20-25 image frames at different points in the cardiac cycle that are played one after another to create a "movie"



ECG GATING with segmentation

How does segmentation work?

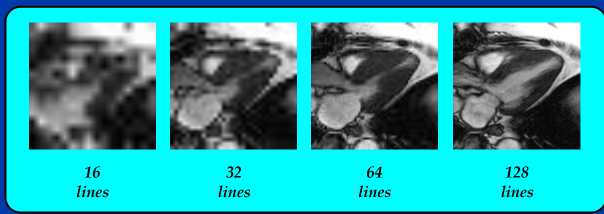




- Entire image is completed after 4 heart beats

Image Reconstruction

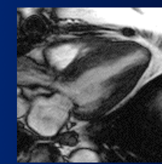
Methodist
DeBakey Heart
& Vascular Center

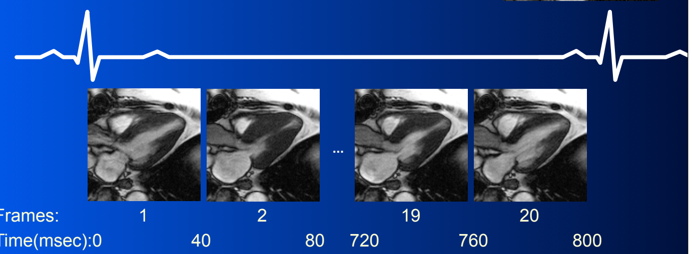


ECG GATING with segmentation

Methodist
DeBakey Heart
& Vascular Center

- Cine image is a series of 20-25 image frames at different points in the cardiac cycle that are played one after another to create a “movie”

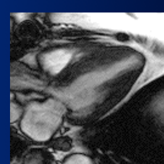


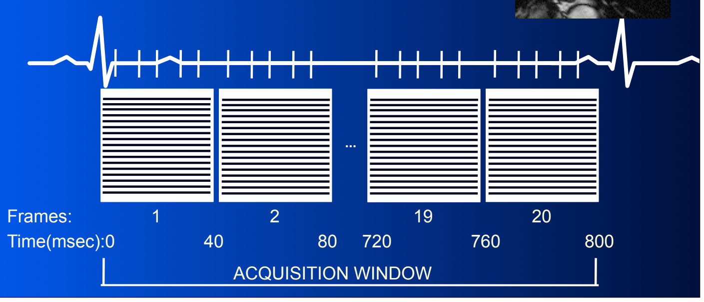


ECG GATING with segmentation

Methodist
DeBakey Heart
& Vascular Center

- Cine image is a series of 20-25 image frames at different points in the cardiac cycle that are played one after another to create a “movie”





CINE IMAGES

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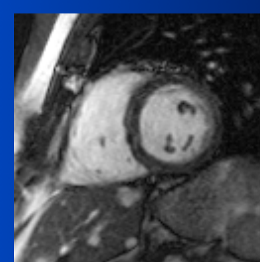
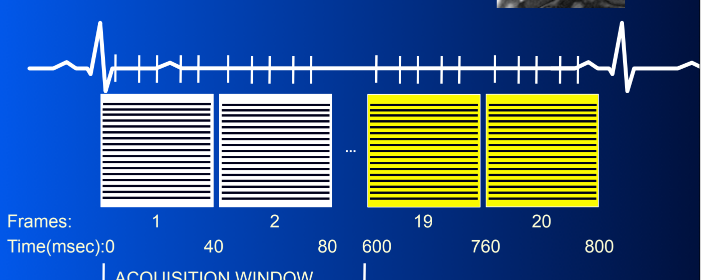
What is wrong with this image ?



ECG GATING with segmentation

Methodist
DeBakey Heart
& Vascular Center

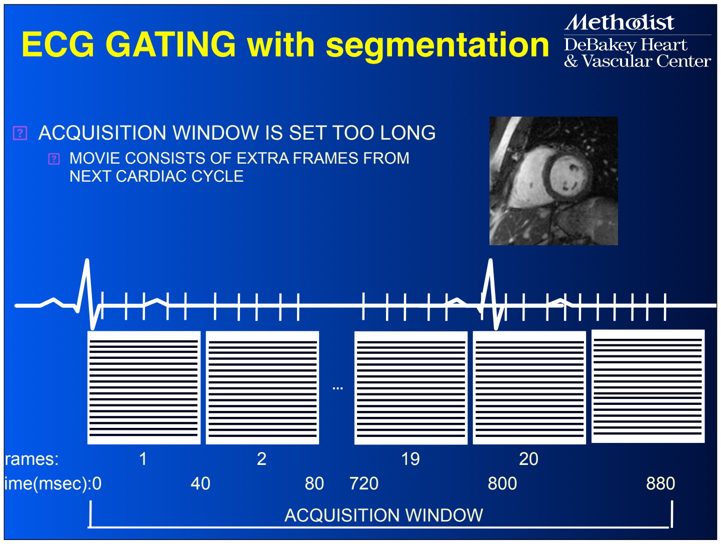
- ACQUISITION WINDOW IS TOO SHORT
  - MOVIE IS MISSING THE LAST FEW FRAMES OF THE CARDIAC CYCLE

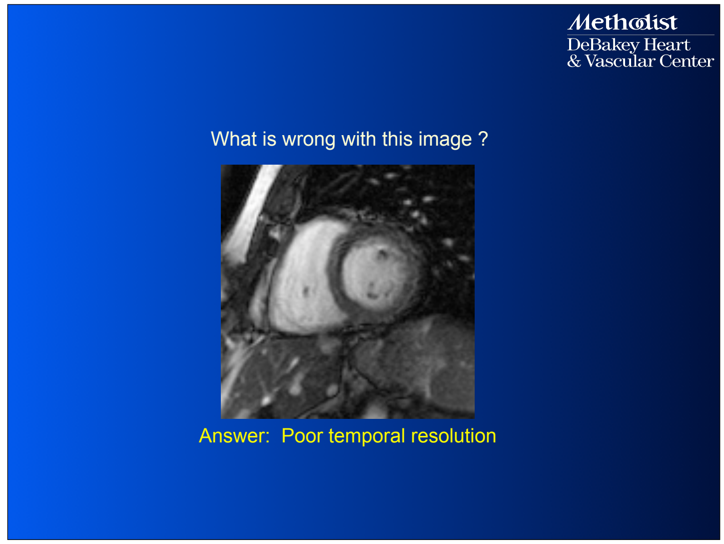


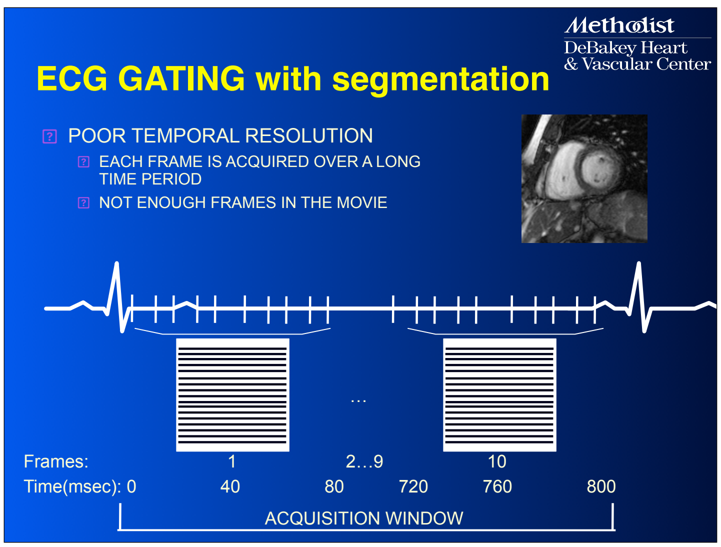
CINE IMAGES

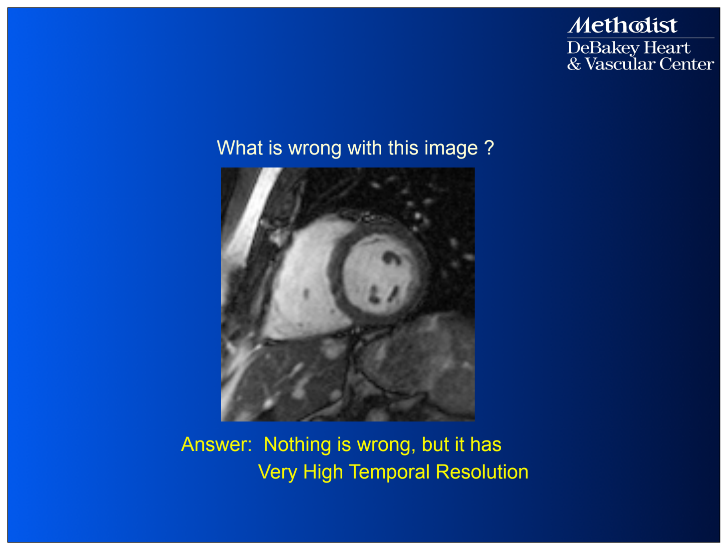
Methodist
DeBakey Heart
& Vascular Center

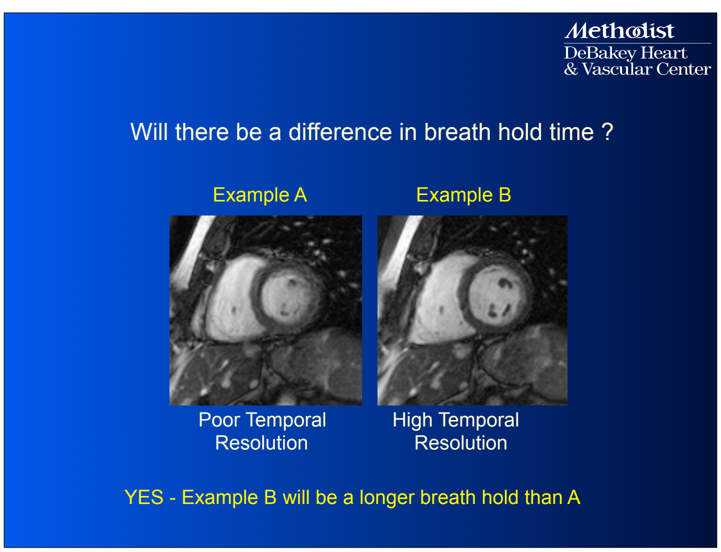
What is wrong with this image ?

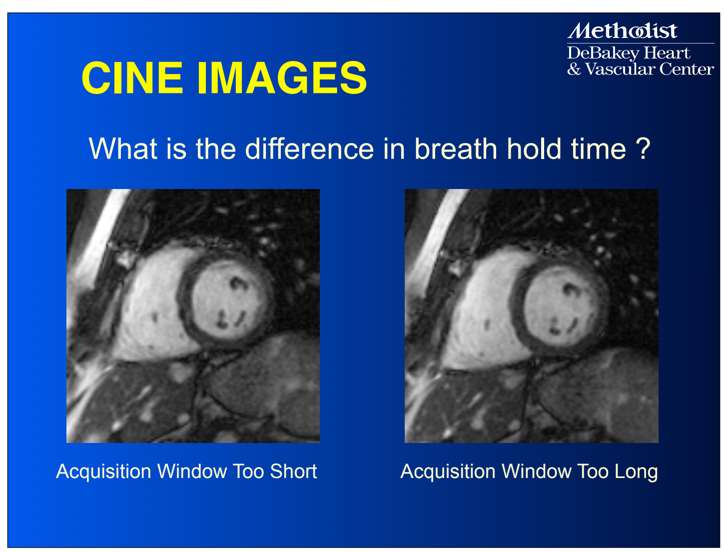

ECG GATING with segmentation
Methodist
DeBakey Heart
& Vascular Center
ACQUISITION WINDOW IS SET TOO LONG
MOVIE CONSISTS OF EXTRA FRAMES FROM NEXT CARDIAC CYCLE
...
rames: 1 2 19 20
ime(msec):0 40 80 720 800 880
ACQUISITION WINDOW


Methodist
DeBakey Heart
& Vascular Center
What is wrong with this image ?
Answer: Poor temporal resolution


Methodist
DeBakey Heart
& Vascular Center
ECG GATING with segmentation
POOR TEMPORAL RESOLUTION
EACH FRAME IS ACQUIRED OVER A LONG TIME PERIOD
NOT ENOUGH FRAMES IN THE MOVIE
...
Frames: 1 2…9 10
Time(msec): 0 40 80 720 760 800
ACQUISITION WINDOW


Methodist
DeBakey Heart
& Vascular Center
What is wrong with this image ?
Answer: Nothing is wrong, but it has
Very High Temporal Resolution


Methodist
DeBakey Heart
& Vascular Center
Will there be a difference in breath hold time ?
Example A
Example B
Poor Temporal Resolution
High Temporal Resolution
YES - Example B will be a longer breath hold than A


Methodist
DeBakey Heart
& Vascular Center
CINE IMAGES
What is the difference in breath hold time ?
Acquisition Window Too Short
Acquisition Window Too Long

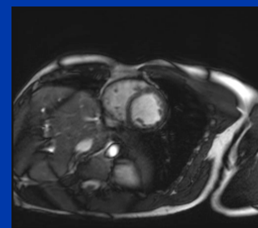
Methodist DeBakey Heart & Vascular Center

- Segmented Image Acquisition with cardiac gating:
  - Allows us to acquire high spatial and temporal resolution functional information about the beating heart
  - Requires adequate method of ECG gating Requires ability to breath hold in most cases

Breathing Artifact or Arrhythmia ?

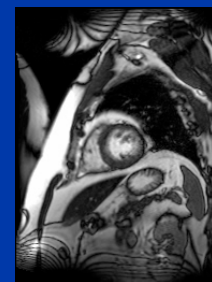
Houston Methodist DeBakey Heart & Vascular Center

Patient A



Breathing artifact

Patient B

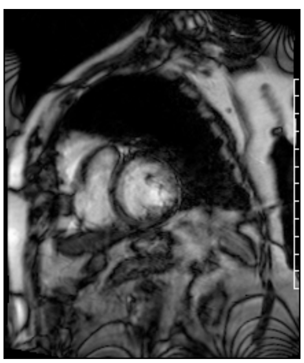


Arrhythmia

Breathing Artifact or Arrhythmia ?

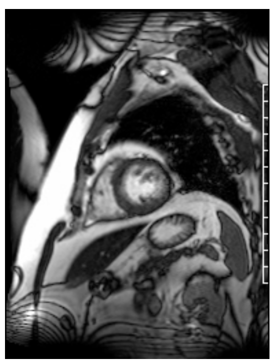
Houston Methodist DeBakey Heart & Vascular Center

Patient A



Breathing artifact

Patient B



Arrhythmia

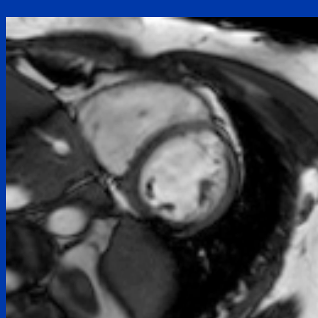
Arrhythmias

Houston Methodist DeBakey Heart & Vascular Center

- Occur when there is RR variability
  - Atrial fibrillation
  - Ventricular ectopy
- Classify arrhythmia as
  - Regularly irregular
  - Irregularly irregular

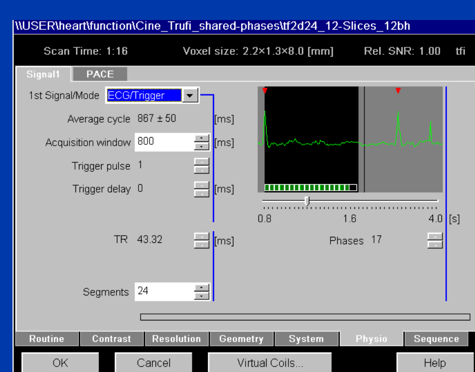
Ventricular Bigeminy

Houston Methodist DeBakey Heart & Vascular Center

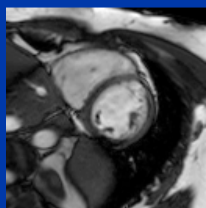


Use Prospective Triggering

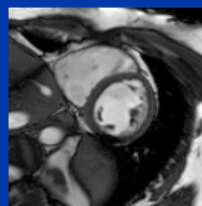
Houston Methodist DeBakey Heart & Vascular Center



Ventricular Bigeminy



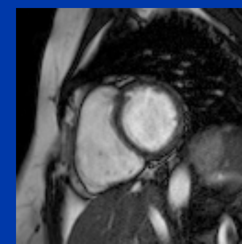
Retrospective Gating



Prospective Gating with 2 RR intervals

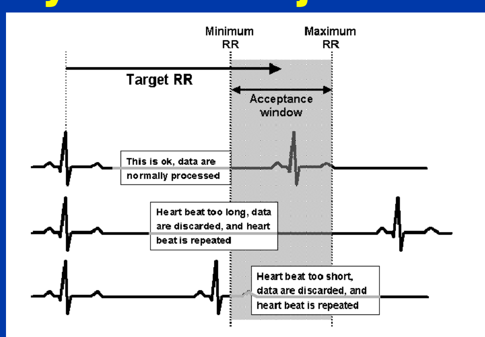
Irregularly Irregular

- Afib with variable RR
- Frequent PVC



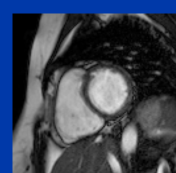
Poor Image Quality

Arrhythmia Rejection

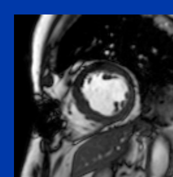


Irregularly Irregular

- Strategies:
  - Arrhythmia Rejection



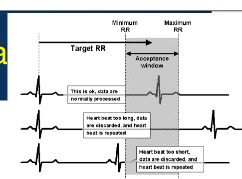
Poor Image Quality

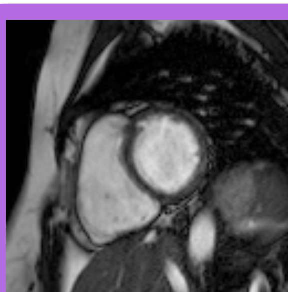


Arrhythmia Rejection

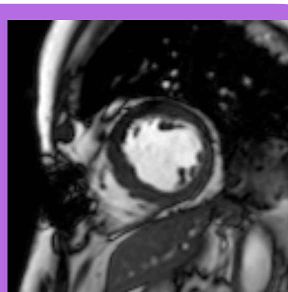
- Limitations:
  - Abnormal beat is rejected
  - Leads to increased breath hold time
  - Not feasible if there are many irregular beats

Overcoming Arrhythmia





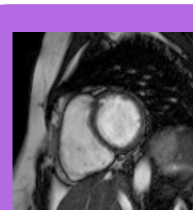
Poor Image Quality



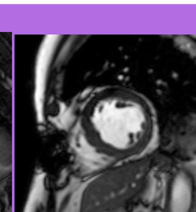
Arrhythmia Rejection

ARRHYTHMIAS

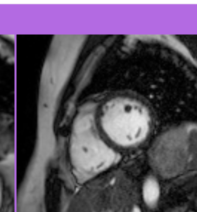
- Strategies:
  - Arrhythmia Rejection



Poor Image Quality



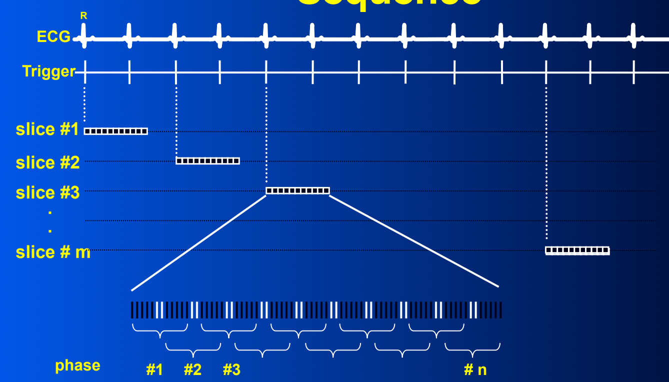
Arrhythmia Rejection



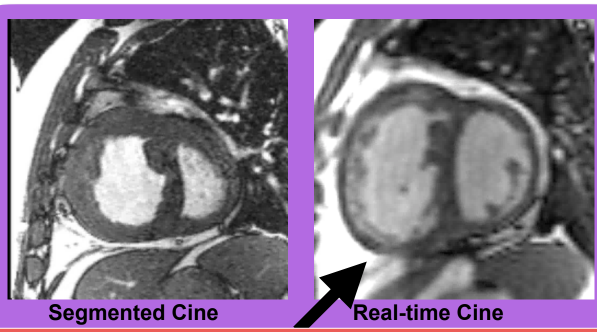
Prospective with short RR interval

What about patients who have significant arrhythmias or who can’t hold their breath ?

Realtime Cine Sequence

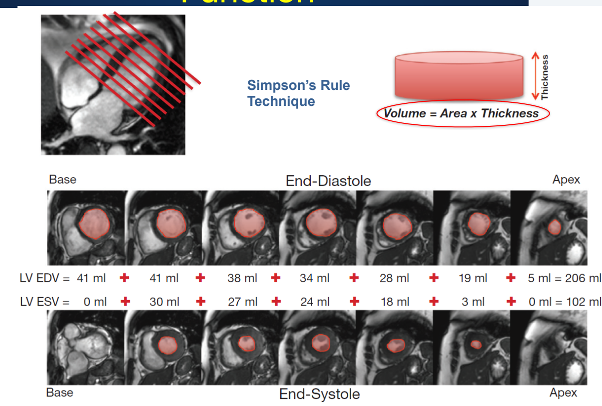


Realtime Cine



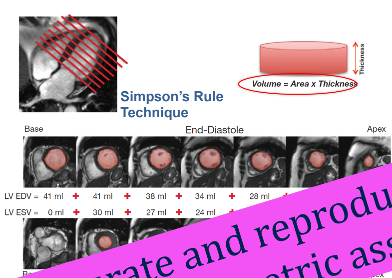
Do not let perfection be the enemy of the good.
CMR image quality should never be worse than this !!

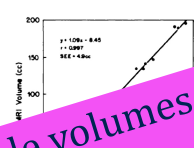
SSFP: Ventricular Volumes & Function



Shah. Curr Opin Cardiol 2012, 27:485–491

SSFP: Ventricular Volumes & Function





…gy 1985;156:717–9

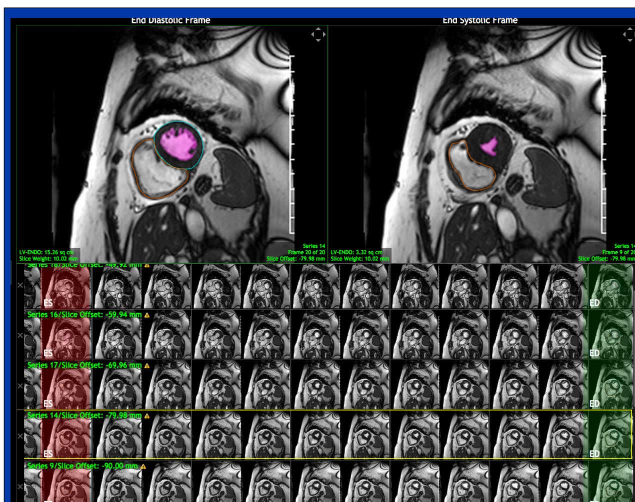
- …MR volumetry validated:
  - Animals
  - In vitro
  - In vivo
  - Ex vivo
- *Superior* to ECHO
  - Highly accurate
  - Highly reproducible
  - Low intra-observer variability
  - Low inter-observer variability
    - LVEF: 2-7%
  - Low inter-study variability

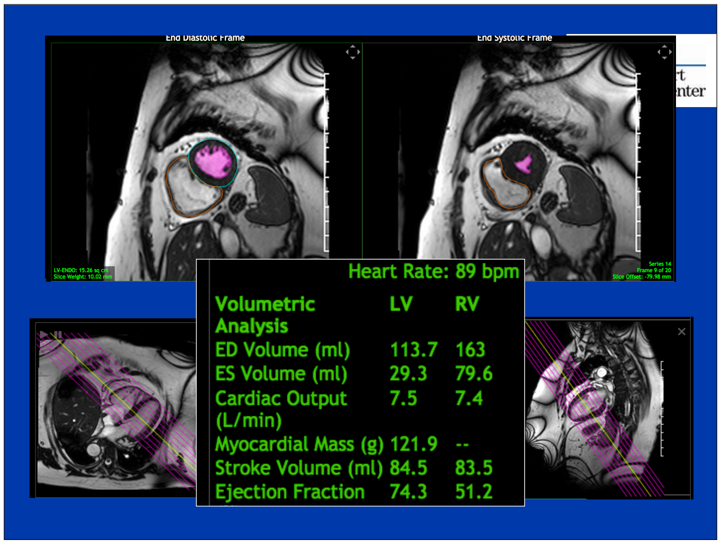
…2)/206 = 50%

…urr Opin Cardiol 2012, 27:485–491

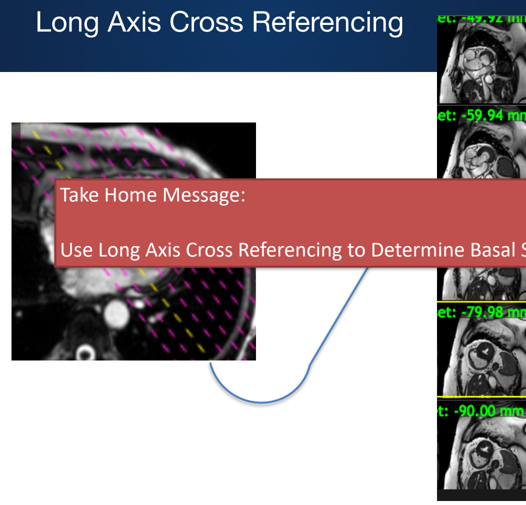
Pattynama PM. Radiology 1993;187:261–8.
Semelka RC. Am Heart J 1990;119:1367–73.
Stratemeier EJ.Radiology 1986;158:775–7.

Accurate and reproducible volumes
No geometric assumptions





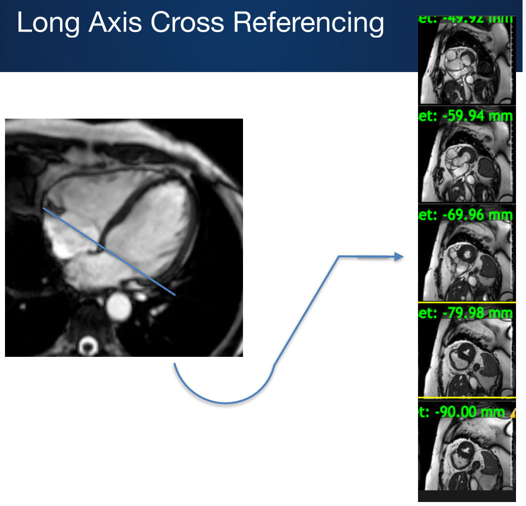
Long Axis Cross Referencing



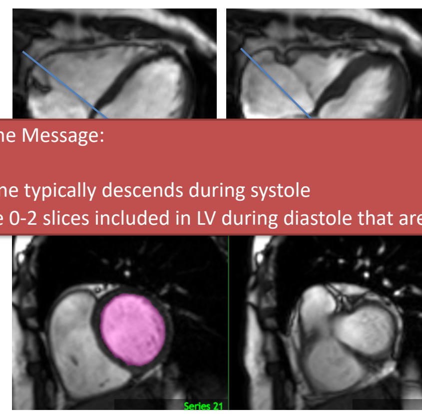
Take Home Message:

Use Long Axis Cross Referencing to Determine Basal Slice

Long Axis Cross Referencing



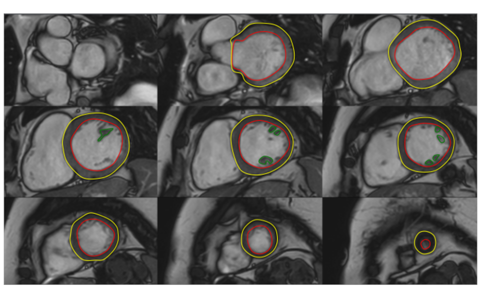
Basal Plane Descent



Take Home Message:

Basal plane typically descends during systole
May have 0-2 slices included in LV during diastole that are LA during systole

Papillary Muscle



Trabeculae and papillary muscles = 6.2% - 8.9% of LV mass
Janik et al, J Hypertens 2008
Vogel-Claussen et al, J Comput Assist Tomogr 2006

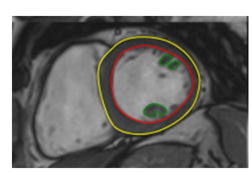
Papillary Muscles

Contouring time: 25 +/- 4 mins vs. 13 +/- 3 minutes
Sievers et al, JCMR 2004

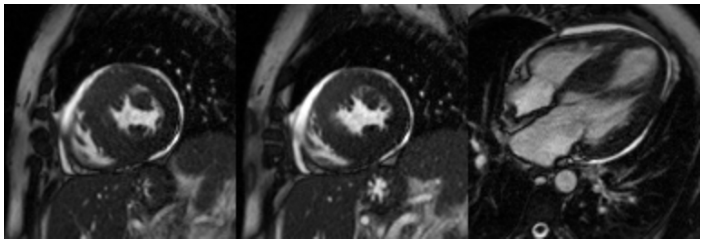
First author, year	CMR technique	N, male: female	Age range (yrs)
Alfakih, 2003 [3]	Short axis SSFP, papillary muscle included in LV mass	30:30	20-65
Hudsmith, 2005 [4]	Short axis SSFP, papillary muscle included in LV mass	63:45	21-68
Maceira, 2006 [5]	Short axis SSFP, papillary muscle included in LV mass	60:60	20-80

SSFP = steady-state free precession; LV = left ventricle; yrs = years.

Kawel-Boehm et al. Journal of Cardiovascular Magnetic Resonance (2015)



Papillary Muscle Attribution:

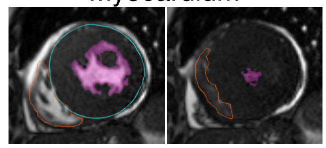


What is the LV Ejection Fraction here ?

A. LVEF < 60%
B. LVEF 60-69%
C. LVEF ≥70%

Papillary Muscle Attribution:

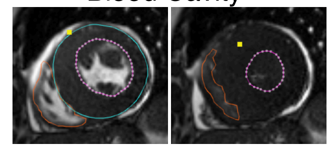
Myocardium



Send to Report

Volumetric Analysis	LV
ED Volume (ml)	130
ES Volume (ml)	26
Cardiac Output (L/min)	7.18
Myocardial Mass (g)	259
Stroke Volume (ml)	104
Ejection Fraction (%)	80

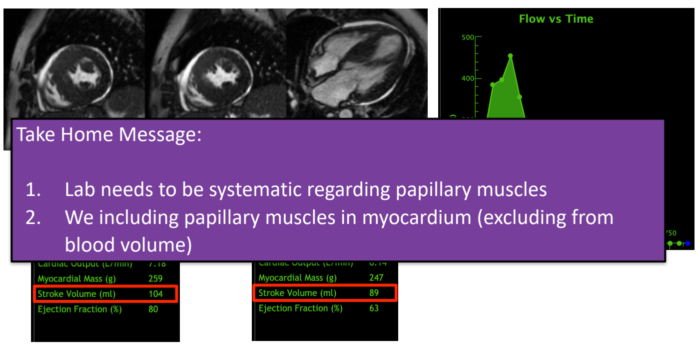
Blood Cavity



Send to Report

Volumetric Analysis	LV
ED Volume (ml)	142
ES Volume (ml)	53
Cardiac Output (L/min)	6.14
Myocardial Mass (g)	247
Stroke Volume (ml)	89
Ejection Fraction (%)	63

Papillary Muscle Attribution:

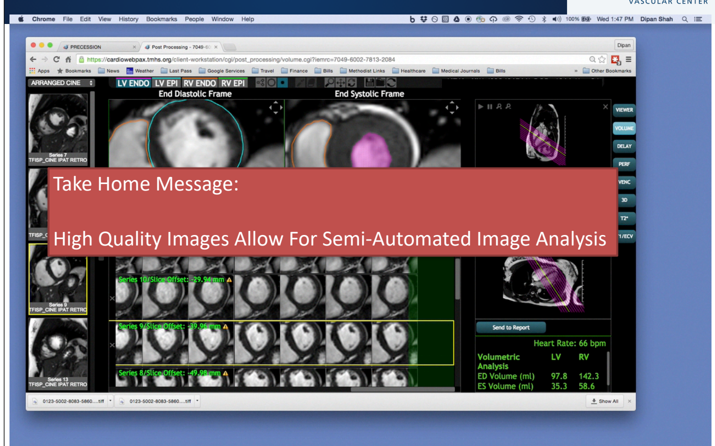


Take Home Message:

1. Lab needs to be systematic regarding papillary muscles
2. We including papillary muscles in myocardium (excluding from blood volume)

Is there Mitral Regurgitation ?

Mitral Regurgitation = LVSV - AO Forward Flow



Take Home Message:

High Quality Images Allow For Semi-Automated Image Analysis

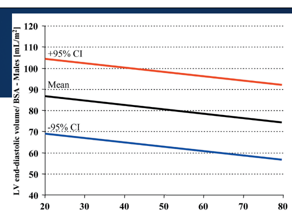


Table 4. All subjects: Left ventricular volumes, systolic function and mass (absolute and indexed to body surface area) by age decile (mean, 95% confidence interval)

All subjects	20–29 years	30–39 years	40–49 years	50–59 years	60–69 years	70–79 years
			Absolute values			
EDV [mL] SD 21	153 (112, 193)	149 (108, 189)	144 (104, 185)	140 (100, 181)	136 (96, 177)	132 (91, 172)
ESV [mL] SD 10	53 (32, 73)	50 (30, 71)	48 (28, 69)	46 (26, 67)	44 (24, 65)	42 (21, 62)
SV [mL] SD 14	100 (72, 128)	98 (70, 126)	96 (68, 124)	94 (66, 122)	92 (64, 120)	90 (62, 118)
EF [%] SD 4.6	66 (57, 74)	66 (57, 75)	67 (58, 76)	67 (58, 76)	68 (59, 77)	69 (60, 77)
Mass [g] SD 19	127 (90, 164)	127 (90, 164)	127 (90, 164)	127 (90, 164)	127 (90, 164)	127 (90, 164)
			Indexed to body surface area			
EDV /BSA [mL/m²] SD 8.8	84 (67, 101)	81 (64, 98)	79 (62, 96)	76 (59, 93)	74 (57, 91)	71 (54, 88)
ESV /BSA [mL/m²] SD 5.1	29 (19, 39)	28 (18, 38)	26 (16, 36)	25 (15, 35)	24 (14, 34)	22 (12, 32)
SV /BSA[mL/m²] SD 6.2	55 (43, 67)	54 (42, 66)	52 (40, 65)	51 (39, 63)	50 (38, 62)	49 (37, 61)
Mass /BSA [g/m²] SD 8.1	69 (53, 85)	69 (53, 85)	69 (53, 84)	68 (53, 84)	68 (52, 84)	68 (52, 84)

EDV, End-Diastolic Volume; ESV, End-Systolic Volume; SV, Stroke Volume; EF, Ejection Fraction; BSA, Body Surface Area; SD, Standard Deviation.

Maceria et al. Journal of Cardiovascular Magnetic Resonance 2016

LV EJECTION FRACTION

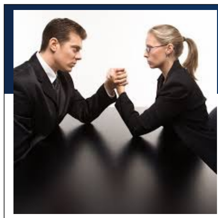
Table 4. All subjects: Left ventricular volumes, systolic function and mass (absolute and indexed to body surface area) by age decile (mean, 95% confidence interval)

All subjects	20–29 years	30–39 years	40–49 years	50–59 years	60–69 years	70–79 years
			Absolute values			
EDV [mL] SD 21	153 (112, 193)	149 (108, 189)	144 (104, 185)	140 (100, 181)	136 (96, 177)	132 (91, 172)
ESV [mL] SD 10	53 (32, 73)	50 (30, 71)	48 (28, 69)	46 (26, 67)	44 (24, 65)	42 (21, 62)
SV [mL] SD 14	100 (72, 128)	98 (70, 126)	96 (68, 124)	94 (66, 122)	92 (64, 120)	90 (62, 118)
EF [%] SD 4.6	66 (57, 74)	66 (57, 75)	67 (58, 76)	67 (58, 76)	68 (59, 77)	69 (60, 77)
Mass [g] SD 19	127 (90, 164)	127 (90, 164)	127 (90, 164)	127 (90, 164)	127 (90, 164)	127 (90, 164)
			Indexed to body surface area			
EDV /BSA [mL/m²] SD 8.8	84 (67, 101)	81 (64, 98)	79 (62, 96)	76 (59, 93)	74 (57, 91)	71 (54, 88)
ESV /BSA [mL/m²] SD 5.1	29 (19, 39)	28 (18, 38)	26 (16, 36)	25 (15, 35)	24 (14, 34)	22 (12, 32)
SV /BSA[mL/m²] SD 6.2	55 (43, 67)	54 (42, 66)	52 (40, 65)	51 (39, 63)	50 (38, 62)	49 (37, 61)
Mass /BSA [g/m²] SD 8.1	69 (53, 85)	69 (53, 85)	69 (53, 84)	68 (53, 84)	68 (52, 84)	68 (52, 84)

EDV, End-Diastolic Volume; ESV, End-Systolic Volume; SV, Stroke Volume; EF, Ejection Fraction; BSA, Body Surface Area; SD, Standard Deviation.

Maceria et al. Journal of Cardiovascular Magnetic Resonance 2016

MEN VS. WOMEN



Echo Normal LV End Diastolic Volumes:
Men: 34–74 ml/m2
Women: 29-61 ml/m2
- Lange et al. JASE 2015

Table 2

EDV [ml]						
EDV /BSA						
ESV [ml]						
ESV/BSA						
SV [ml]						
SV/BSA						
EF [%]						
Mass [g]	134	21	92-176	98	21	56-140
Mass/BSA [g/m²]	67	9	49-85	61	10	41-81

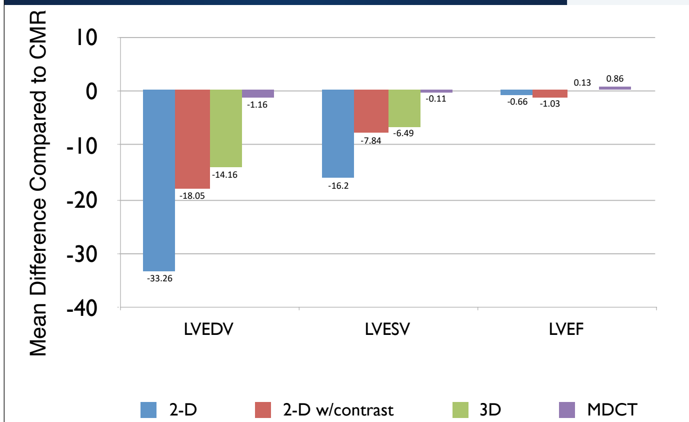
LV papillary muscle mass *included as part of LV mass*. Pooled weighted mean values from references [3-5]. $Mean_p$ = pooled weighted mean; SD_p = pooled standard deviation; * = calculated as $mean_p \pm 2*SD_p$; EDV = end-diastolic volume; ESV = end-systolic volume; SV = stroke volume; EF = ejection fraction; BSA = body surface area; SD = standard deviation; **from references [4,5] only.

Take Home Message:

1. Normal ventricular volumes decrease with age
2. Normal EF increases with age
3. Normal volumes are different between men and women
4. Normal values are quite different that echocardiography

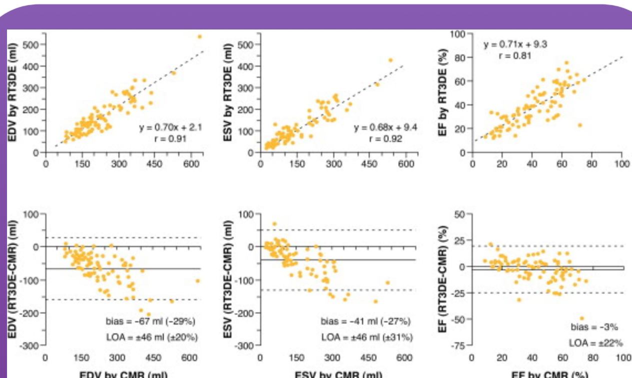
Kawel-Boehm et al. Journal of Cardiovascular Magnetic Resonance (2015)

Meta-Analysis: 65 studies, 2888 patients



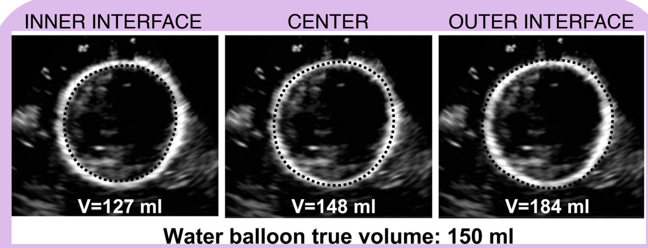
Rigolli et al, Open Heart 2016.

CMR vs. 3D Echo

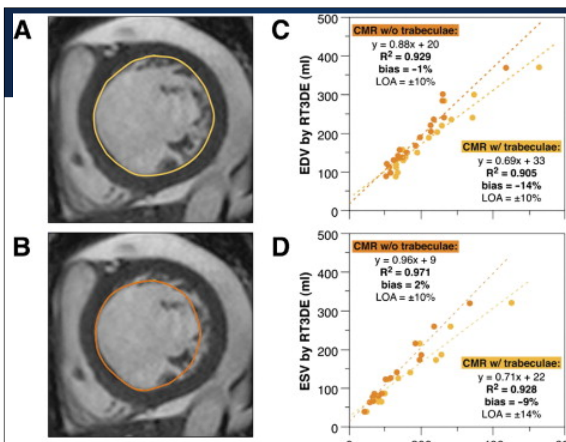


Mor-Avi et al. JACC: Cardiovascular Imaging, Volume 1, Issue 4, 2008, 413–423

SOURCE OF UNDERESTIMATION



Mor-Avi et al. JACC: Cardiovascular Imaging, Volume 1, Issue 4, 2008, 413–423

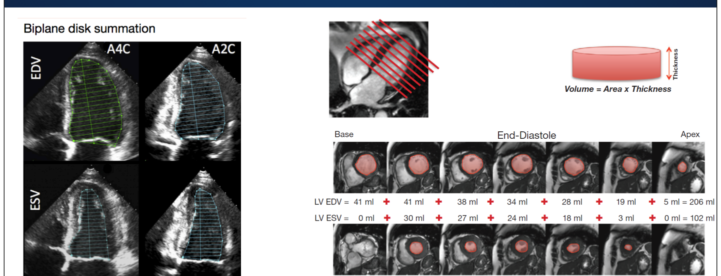


THE NEGATIVE BIAS OF 3D ECHO COMPARED TO CMR MAY BE DUE TO INABILITY TO RESOLVE LV TRABECULAE

Mor-Avi et al. JACC: Cardiovascular Imaging, Volume 1, Issue 4, 2008, 413–423

Interstudy Variability in LVEF Quantification

Biplane disk summation



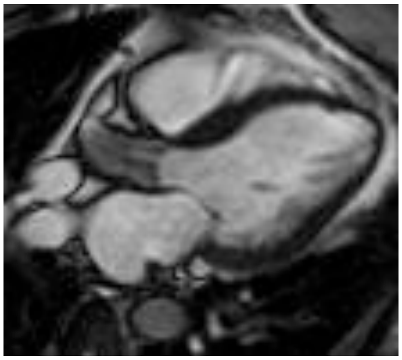
Lang et al, JASE 2015

Echo
9-10%

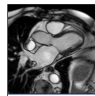
CMR
3-5%

Grothues et al, Am J Cardiol 2002.

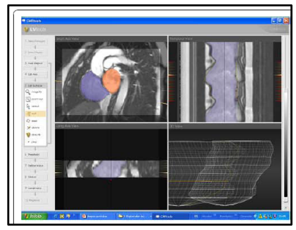
Left Atrium



Left Atrial Volumes

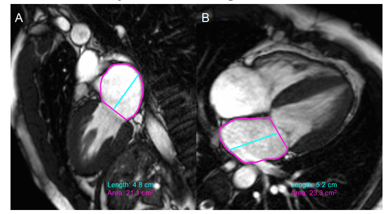


3D Modeling Approach



Maceira et al. Journal of Cardiovascular Magnetic Resonance 2010, 12:65

Biplane Area-length Method



Left Atrial Volume = $8/3\,\pi \left[\frac{(A_1)(A_2)}{(L)}\right]$

A1 = Area 2 Chamber
A2 = Area 4 Chamber
L = Shortest Atrial Length

Khan et al. Journal of Cardiovascular Magnetic Resonance 2019

Left Atrial Volumes

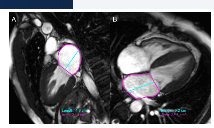
Khan et al. Journal of Cardiovascular Magnetic Resonance (2019) 21:4
https://doi.org/10.1186/s12968-018-0517-0

Journal of Cardiovascular Magnetic Resonance

RESEARCH Open Access

Association of left atrial volume index and all-cause mortality in patients referred for routine cardiovascular magnetic resonance: a multicenter study

Mohammad A. Khan[1,5], Eric Y. Yang[1], Yang Zhan[1], Robert M. Judd[3], Wenyaw Chan[4], Faisal Nabi[1], John F. Heitner[2], Raymond J. Kim[3], Igor Klem[3], Sherif F. Nagueh[1] and Dipan J. Shah[1*]



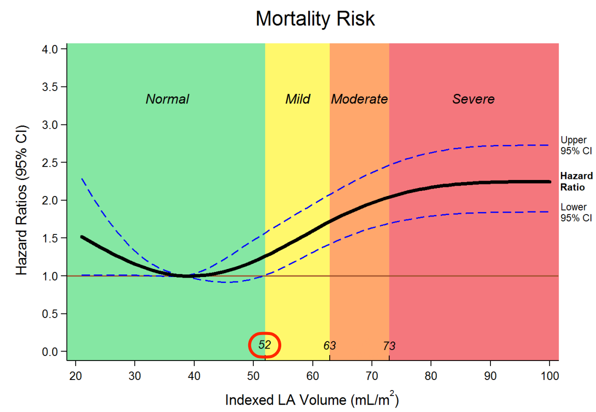
CMR Upper Limits Normal LA Volume Index:
Men - 52 ml/m2
Women - 52 ml/m2

Khan et al. Journal of Cardiovascular Magnetic Resonance 2019

The upper normal limit for 2D echocardiographic LA volume is 34 mL/m2 for both genders.

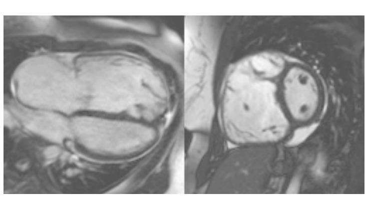
Lange et al. JASE 2015

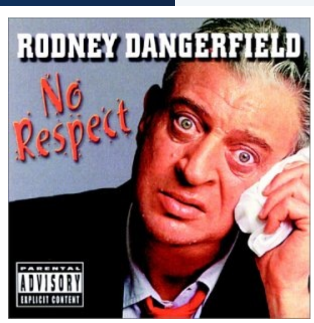
LA Volumes and Outcomes



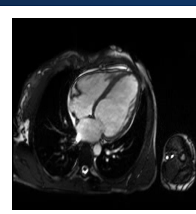
Khan et al. Journal of Cardiovascular Magnetic Resonance 2019

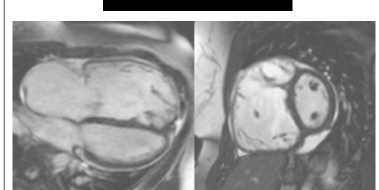
- **Right Ventricle**
  - The forgotten ventricle



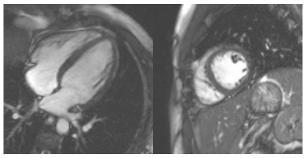


CMR Imaging for the Right Heart

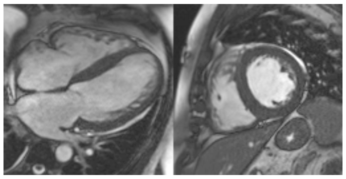




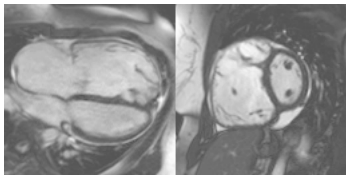
- Advantages:
  - Large FOV
    - Intra/extra cardiac anatomy
  - Unlimited imaging planes for the RV
  - Superior image resolution
  - Tissue characterization
    - Fibrosis, inflammation, scar, fat, thrombus
  - Volumetric based technique: RV volumes, RVEF and Regurg Vol/RF



Normal RV

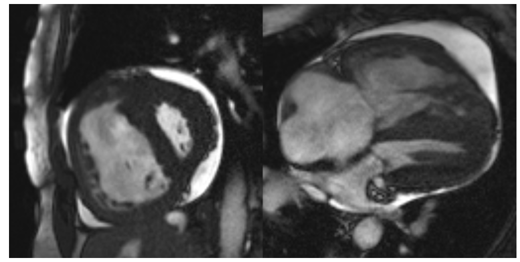


Severe RV Dysfunction



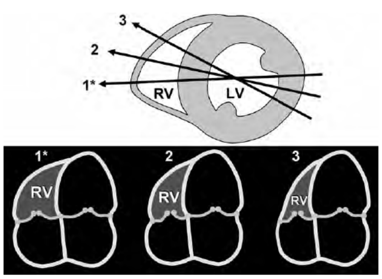
Severe RV Dilation

Severe RVH



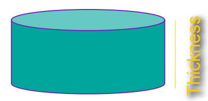
What is the ideal way to assess the RV:

- Complete endocardial definition
- Quantitative methods that do not require geometry assumptions
- Reproducibility
- Established reference normal values



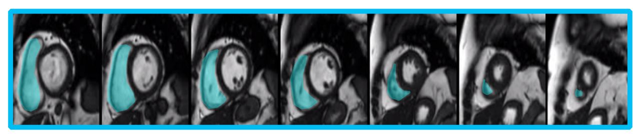
Rudski.J Am Soc Echocardiogr 2010;23:685-713

CMR for Right Heart Volumes & Function



Volume = Area x Thickness

Base Apex

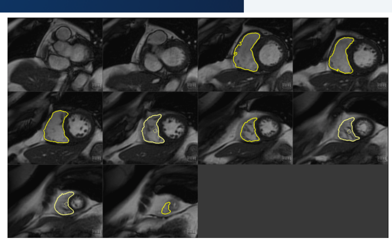


40 ml + 32 ml + 27 ml + 25 ml + 20 ml + 10 ml + 5 ml

RV EDV = 159 ml

CMR May Be The Reference Standard for Right Heart Volumes & Function

- Highly accurate
- Highly reproducible
- Low variability
  - intra-observer
  - inter-observer
  - Low inter-study (5-6%)



Accurate RV volumes & EF can aid in:
1. **Initial clinical assessment of the impact of PI/TR**
2. **Long term with serial measurements**

Boxt LM. J Thorac Imaging 1993;8:92–7.
Doherty NE III. Am J Cardiol 1992;69:1223–8.
Katz J.J Am Coll Cardiol 1993;21:1475–81.
Pattynama PM. Magn Reson Imaging 1995;13:53–63.
Rominger MB. J Magn Reson Imaging 1999;10:908–18.

Reference RV Values Normalized to Age, Gender and Body Surface Area

Table 8 RV summary data for all ages (mean ± SD, 95% confidence interval)

	All	Males	Females
EDV (mL)	144 ± 23 (98, 190)	163 ± 25 (113, 213)	126 ± 21 (84, 168)
EDV/BSA (mL/m^2)	78 ± 11 (57, 99)	83 ± 12 (60, 106)	73 ± 9 (55, 92)
ESV (mL)	50 ± 14 (22, 78)	57 ± 15 (27, 86)	43 ± 13 (17, 69)
ESV/BSA (mL/m^2)	27 ± 7 (13, 41)	29 ± 7 (14, 43)	25 ± 7 (12, 38)
SV (mL)	94 ± 15 (64, 124)	106 ± 17 (72, 140)	83 ± 13 (57, 108)
SV/BSA (mL/m^2)	51 ± 7 (37, 65)	54 ± 8 (38, 70)	48 ± 6 (36, 60)
EF (%)	66 ± 6 (54, 78)	66 ± 6 (53, 78)	66 ± 6 (54, 78)
EF/BSA (%/m^2)	36 ± 5 (27, 45)	34 ± 4 (26, 41)	39 ± 5 (29, 49)
Mass (g)	48 ± 13 (23, 73)	66 ± 14 (38, 94)	48 ± 11 (27, 69)
Mass/BSA (g/m^2)	31 ± 6 (19, 43)	34 ± 7 (20, 47)	28 ± 5 (18, 38)

NORMAL RV VOLUMES DIFFER BETWEEN MEN AND WOMEN

Maceira.European Heart Journal (2006) 27, 2879–2888

Reference RV Values Normalized to Age, Gender and Body Surface Area

Table 2 Males: RV volumes, systolic function and mass (absolute and normalized to BSA) by age decile (mean, 95% confidence interval)

Age (years)	20–29	30–39	40–49	50–59	60–69	70–79
Absolute values						
EDV (mL) SD 25.4	177 (127, 227)	171 (121, 221)	166 (116, 216)	160 (111, 210)	155 (105, 205)	150 (100, 200)
ESV (mL) SD 15.2	68 (38, 98)	64 (34, 94)	59 (29, 89)	55 (25, 85)	50 (20, 80)	46 (16, 76)
SV (mL) SD 17.4	108 (74, 143)	108 (74, 142)	107 (73, 141)	106 (72, 140)	105 (71, 139)	104 (70, 138)
EF (%) SD 6.5	61 (48, 74)	63 (50, 76)	65 (52, 77)	66 (53, 79)	68 (55, 81)	70 (57, 83)
Mass (g) SD 14.4	70 (42, 99)	69 (40, 97)	67 (39, 95)	65 (37, 94)	63 (35, 92)	62 (33, 90)
Normalized to BSA						
EDV/BSA (mL/m^2) SD 11.7	91 (68, 114)	88 (65, 111)	85 (62, 108)	82 (59, 105)	79 (56, 101)	75 (52, 98)
ESV/BSA (mL/m^2) SD 7.4	35 (21, 50)	33 (18, 47)	30 (16, 45)	28 (13, 42)	25 (11, 40)	23 (8, 37)
SV/BSA (mL/m^2) SD 8.2	56 (40, 72)	55 (39, 71)	55 (39, 71)	54 (38, 70)	53 (37, 69)	52 (36, 69)
EF/BSA (%/m^2) SD 4	32 (24, 40)	32 (25, 40)	33 (25, 41)	34 (26, 42)	35 (27, 42)	35 (27, 43)
Mass/BS[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible], 44)

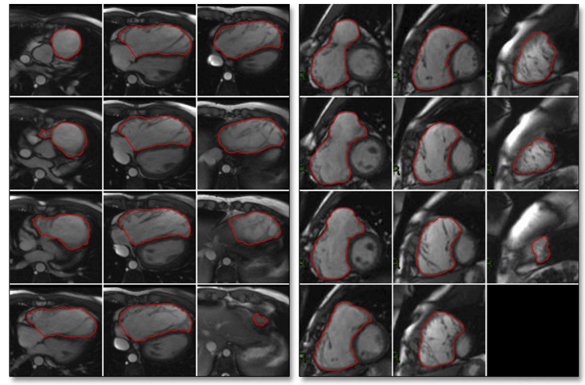
Table 3 F[illegible] nterval)

Age (years[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Absolute v[illegible]						
EDV (mL[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]69, 153)
ESV (mL[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible], 58)
SV (mL) SD 13.1	87 (61, 112)	85 (59, 111)	84 (58, 109)	82 (56, 108)	80 (55, 106)	79 (53, 105)
EF (%) SD 6	61 (49, 73)	63 (51, 75)	65 (53, 77)	67 (55, 79)	69 (57, 81)	71 (59, 83)
Mass (g) SD 10.6	54 (33, 74)	51 (31, 72)	49 (28, 70)	47 (26, 68)	45 (24, 66)	43 (22, 63)
Normalized to BSA						
EDV/BSA (mL/m^2) SD 9.4	84 (65, 102)	80 (61, 98)	76 (57, 94)	72 (53, 90)	68 (49, 86)	64 (45, 82)
ESV/BSA (mL/m^2) SD 6.6	32 (20, 45)	30 (17, 43)	27 (14, 40)	24 (11, 37)	21 (8, 34)	19 (6, 32)
SV/BSA (mL/m^2) SD 6.1	51 (39, 63)	50 (38, 62)	49 (37, 61)	48 (36, 60)	46 (34, 58)	45 (33, 57)
EF/BSA (%/m^2) SD 5.2	37 (27, 47)	38 (27, 48)	38 (28, 49)	39 (29, 49)	40 (30, 50)	41 (31, 51)
Mass/BSA (g/m^2) SD 5.2	32 (22, 42)	30 (20, 40)	29 (19, 39)	27 (17, 37)	26 (16, 36)	24 (14, 35)

NORMAL RV VOLUMES CHANGE WITH AGE

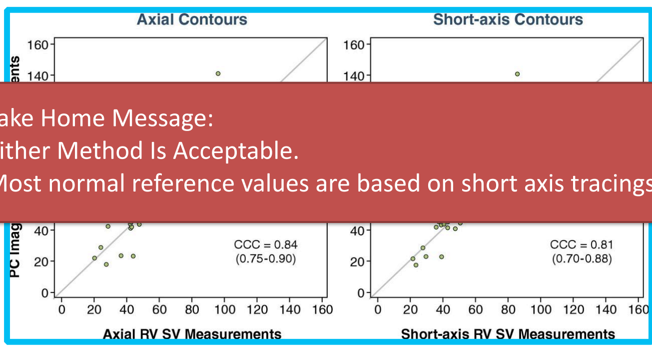
Maceira.European Heart Journal (2006) 27, 2879–2888

Axial vs. Short Axis Tracing of RV



Christopher J. Clarke et al. JIMG 2012;5:28-37

Axial vs. Short Axis Tracing of RV



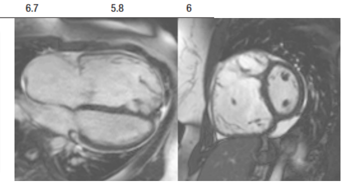
Take Home Message:
Either Method Is Acceptable.
Most normal reference values are based on short axis tracings.

Christopher J. Clarke et al. JIMG 2012;5:28-37

Reproducibility of Ventricular Size and Function Measured by CMR

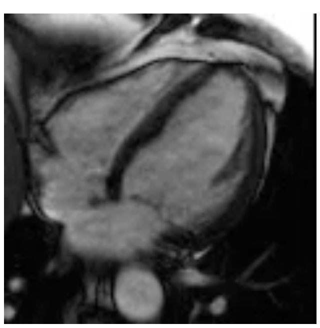
	Mooij et al[12]	Grothues et al[15]	Hudsmith et al[16]	Karamitsos et al (post-training)[13]	Karamitsos et al (expert)[13]	Moon et al[9]
No. of patients	60	60	12	10	10	20
Diagnosis	Normal/ASD/TOF	Normal/CHF/LVH	Normal	Normal	Normal	Normal/CHF
CMR technique	SSFP	FLASH	SSFP	SSFP	SSFP	SSFP
Right ventricle, %						
EDV	6.4	6.2	9.6			
ESV	13.0	14.1				
EF	8.0	8.3	10.7			
Mass	11.3	8.7				
Left ventricle, %						
EDV	3.6		2.7	4.6	2.6	2.6
ESV	10.5			7.4	6.9	10.5
EF	5.8		3.3	3.7	2.9	6
Mass	5.3		5.2	6.7	5.8	6

Reproducibility of RV Measurements by CMR is robust, but not as robust as for the LV



LA Volumes

- Generally the left atrial appendage is included as part of the left atrial volume while the pulmonary veins are excluded.
- The maximal left atrial volume is achieved during ventricular systole.
- Using cine images, the maximum volume can be defined as last image before opening of the mitral valve.
- Accordingly the minimal left atrial volume can be defined as first image after closure of the mitral valve



SUMMARY:

- CMR MAY BE THE REFERENCE STANDARD FOR VOLUMES AND EF
  - Optimal image quality
  - Limited need for geometric assumptions
- ESTABLISHED NORMAL VOLUMES AND EF
  - Vary with age and gender
- CMR NORMAL VOLUMES DIFFER FROM ECHO

Thank you for your attention
Dipan J. Shah, MD, FACC
djshah@houstonmethodist.org

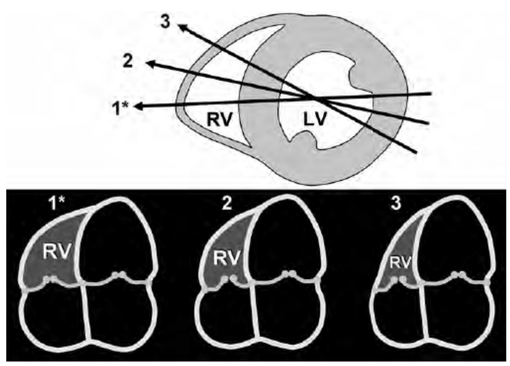
Echo is a great technique, but …….

CONCLUSION

• Assessment of complex congenital heart disease including anomalies of coronary circulation, great vessels, and cardiac chambers and valves • Procedures may include LV/RV mass and volumes, MR angiography, quantification of valvular disease, and contrast enhancement	A (9)
• Evaluation of LV function following myocardial infarction OR in heart failure patients • Patients with technically limited images from echocardiogram	A (8)
• Quantification of LV function • Discordant information that is clinically significant from prior tests	A (8)

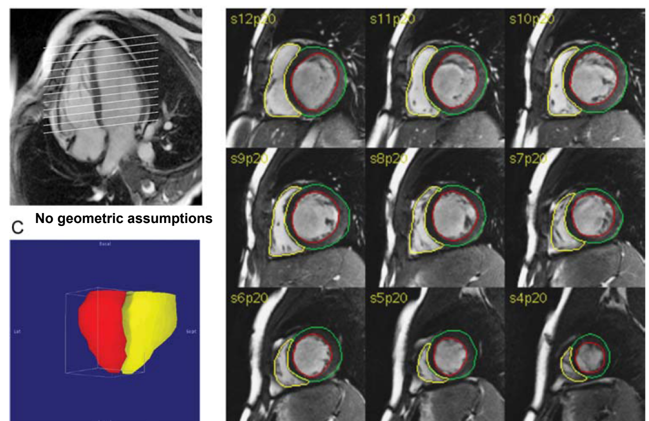
Thank you for your attention
Dipan J. Shah, MD, FACC
djshah@houstonmethodist.org

Will the real RV please stand up:



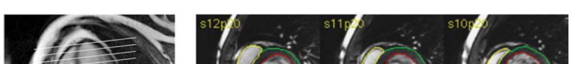
Rudski.J Am Soc Echocardiogr 2010;23:685-713

CMR is Reference Standard for Right Heart Volumes, Mass, Function



Buechel.European Heart Journal (2012) 33, 949–960

CMR is Reference Standard for Right Heart Volumes, Mass, Function

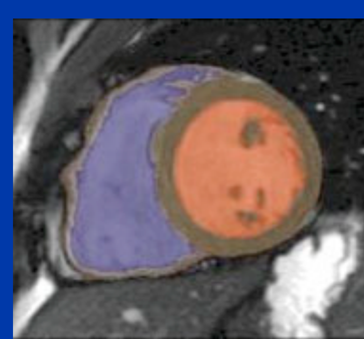


• Assessment of complex congenital heart disease including anomalies of coronary circulation, great vessels, and cardiac chambers and valves • Procedures may include LV/RV mass and volumes, MR angiography, quantification of valvular disease, and contrast enhancement	A (9)
• Evaluation of LV function following myocardial infarction OR in heart failure patients • Patients with technically limited images from echocardiogram	A (8)
• Quantification of LV function • Discordant information that is clinically significant from prior tests	A (8)

Buechel.European Heart Journal (2012) 33, 949–960

RV Volumes

Methodist DeBakey Heart & Vascular Center



Maceira et al. European Heart Journal 2006.

Normal RV volumes

Methodist DeBakey Heart & Vascular Center

Table 2 Males: RV volumes, systolic function and mass (absolute and normalized to BSA) by age decile (mean, 95% confidence interval)

Age (years)	20–29	30–39	40–49	50–59	60–69	70–79
Absolute values						
EDV (mL) SD 25.4	177 (127, 227)	171 (121, 221)	166 (116, 216)	160 (111, 210)	155 (105, 205)	150 (100, 200)
ESV (mL) SD 15.2	68 (38, 98)	64 (34, 94)	59 (29, 89)	55 (25, 85)	50 (20, 80)	46 (16, 76)
SV (mL) SD 17.4	108 (74, 143)	108 (74, 142)	107 (73, 141)	106 (72, 140)	105 (71, 139)	104 (70, 138)
EF (%) SD 6.5	61 (48, 74)	63 (50, 76)	65 (52, 77)	66 (53, 79)	68 (55, 81)	70 (57, 83)
Mass (g) SD 14.4	70 (42, 99)	69 (40, 97)	67 (39, 95)	65 (37, 94)	63 (35, 92)	62 (33, 90)
Normalized to BSA						
EDV/BSA (mL/m^2) SD 11.7	91 (68, 114)	88 (65, 111)	85 (62, 108)	82 (59, 105)	79 (56, 101)	75 (52, 98)
ESV/BSA (mL/m^2) SD 7.4	35 (21, 50)	33 (18, 47)	30 (16, 45)	28 (13, 42)	25 (11, 40)	23 (8, 37)
SV/BSA (mL/m^2) SD 8.2	56 (40, 72)	55 (39, 71)	55 (39, 71)	54 (38, 70)	53 (37, 69)	52 (36, 69)
EF/BSA (%/m^2) SD 4	32 (24, 40)	32 (25, 40)	33 (25, 41)	34 (26, 42)	35 (27, 42)	35 (27, 43)
Mass/BSA (g/m^2) SD 6.8	36 (23, 50)	35 (22, 49)	34 (21,48)	33 (20, 46)	32 (19, 45)	31 (18, 44)

Maceira et al. European Heart Journal 2006.

Sample Size

Methodist DeBakey Heart & Vascular Center

TABLE 3 Sample Sizes Required to Detect a Clinically Significant Change in End-Diastolic Volume, End-Systolic Volume, Ejection Fraction, and LV Mass (with a 90% power and an α error of 0.05)*

	Echocardiography		CMR		Reduction in Sample Size by CMR
	SD	Sample Size	SD	Sample Size	
Total study group					
10-ml change in end-diastolic volume	13.5	39	6.7	10	74%
10-ml change in end-systolic volume	14.0	42	5.4	7	83%
10-ml change in stroke volume	13.1	37	5.2	6	84%
3% absolute change in ejection fraction	6.1	87	2.1	11	87%
10-g change in LV mass	25.0	132	7.7	13	90%
Normals					
10-ml change in end-diastolic volume	6.4	9	4.3	4	55%
10-ml change in end-systolic volume	7.0	11	2.8	2	81%
10-ml change in stroke volume	8.0	14	4.0	4	71%
3% absolute change in ejection fraction	5.6	73	1.7	7	90%
10-g change in LV mass	15.9	54	4.2	4	93%
Heart failure					
10-ml change in end-diastolic volume	17.6	66	7.6	13	80%
10-ml change in end-systolic volume	19.7	82	7.4	12	85%
10-ml change in stroke volume	18.0	69	5.9	8	88%
3% absolute change in ejection fraction	7.0	115	2.4	14	88%
10-g change in LV mass	30.4	194	9.6	20	90%
LV hypertrophy					
10-ml change in end-diastolic volume	13.9	41	7.3	12	71%
10-ml change in end-systolic volume	12.2	32	4.6	5	84%
10-ml change in stroke volume	11.5	28	5.5	7	75%
3% absolute change in ejection fraction	5.9	82	2.2	12	85%
10-g change in LV mass	26.9	152	8.4	15	90%

*Note that for studies comparing active treatment with placebo, these sample size numbers must be doubled.

Grothues et al, Am J Cardiol 2002.

Normal LV Volumes

Methodist DeBakey Heart & Vascular Center

Table 2. LV and RV measurements in 108 healthy volunteers

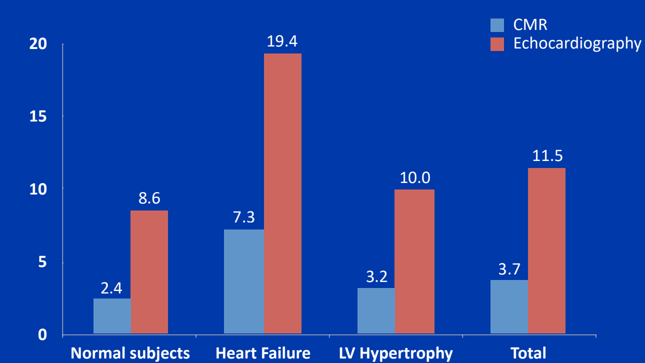
	Mean ± SD (n = 108)	Male (n = 63)	Female (n = 45)	p value
LV ejection fraction (%)	69 ± 6	69 ± 6 (57–81)	69 ± 6 (57–81)	.80
LV mass (g)	112 ± 27	123 ± 21 (81–165)	96 ± 27 (42–150)	< .001
LV mass index (g/m^2)	59.2 ± 11	62.5 ± 9.0 (45–81)	54.6 ± 12 (31–79)	< .001
LV end-diastolic volume (mL)	150 ± 31	160 ± 29 (102–218)	135 ± 26 (83–187)	< .001
LV end-diastolic volume index (mL/m^2)	80 ± 13	82 ± 13 (56–108)	78 ± 12 (54–102)	.16
LV end-systolic volume (mL)	47 ± 15	50 ± 16 (18–82)	42 ± 12 (18–66)	.007
LV end-systolic volume index (mL/m^2)	25 ± 7	25 ± 8 (9–41)	24 ± 6 (12–36)	.53
LV stroke volume (mL)	104 ± 21	112 ± 19 (74–150)	91 ± 17 (57–125)	< .001
LV stroke volume index (mL/m^2)	55 ± 8	56 ± 8 (40–72)	54 ± 9 (36–72)	.12
RV ejection fraction (%)	61 ± 6	59 ± 6 (47–71)	63 ± 5 (53–73)	.002
RV mass (g)	38 ± 8	41 ± 8 (25–57)	35 ± 7 (21–49)	< .001
RV mass index (g/m^2)	20.3 ± 3.6	20.6 ± 3.7 (13–28)	20.0 ± 3.5 (13–27)	.371
RV end-diastolic volume (mL)	173 ± 39	190 ± 33 (124–256)	148 ± 35 (78–218)	< .001
RV end-diastolic volume index (mL/m^2)	91 ± 16	96 ± 15 (66–126)	84 ± 17 (50–118)	< .001
RV end-systolic volume (mL)	69 ± 22	78 ± 20 (38–118)	56 ± 18 (20–92)	< .001
RV end-systolic volume index (mL/m^2)	36 ± 10	39 ± 10 (19–59)	32 ± 10 (12–52)	< .001
RV stroke volume (mL)	104 ± 21	113 ± 19 (75–151)	90 ± 19 (52–128)	< .001
RV stroke volume index (mL/m^2)	55 ± 9	57 ± 8 (41–73)	53 ± 9 (35–71)	.02

Values are given as mean ± SD; reference ranges in brackets, calculated as ± 2SD of the mean.

Hudsmith et al, Journal of Cardiovascular Magnetic Resonance 2005.

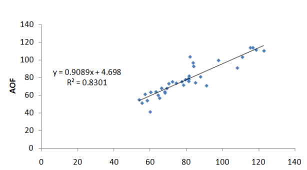
Coefficient of Variability

Methodist DeBakey Heart & Vascular Center

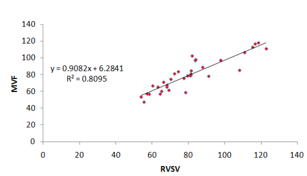


Grothues et al, Am J Cardiol 2002.

Correlation between RVSV and AOF in all patients

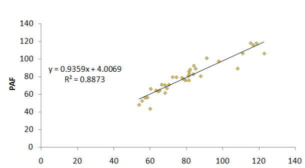


Correlation between RVSV and MVF in all patients

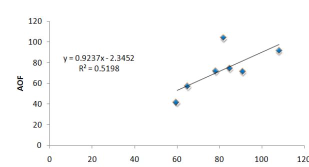


* MVF could not be assessed in 2 patients due to marked heart rate variability

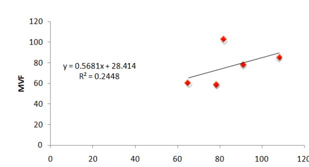
Correlation between RVSV and PAF in all patients



Correlation between RVSV and AOF in patients with heart rate variability

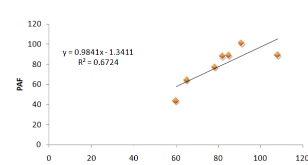


Correlation between RVSV and MVF in patients with heart rate variability

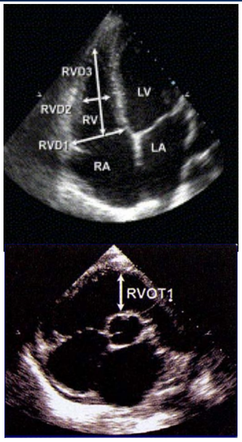


* MVF could not be assessed in 2 patients due to marked heart rate variability

Correlation between RVSV and PAF in patients with heart rate variability



Echo Limitations for Right Heart Disease Assessment



- TTE is first-line imaging study for RHD
- Limitations:
  - Poor imaging windows (location just behind the sternum)
  - Difficult to visualize:
    - Endocardial borders of the RV lateral wall and apex
    - Trabeculations
    - Pulmonic valve

GUIDELINES AND STANDARDS

Guidelines for the Echocardiographic Assessment of the Right Heart in Adults: A Report from the American Society of Echocardiography

Endorsed by the European Association of Echocardiography, a registered branch of the European Society of Cardiology, and the Canadian Society of Echocardiography

Lawrence G. Rudski, MD, FASE, Chair, Wyman W. Lai, MD, MPH, FASE, Jonathan Afilalo, MD, Msc, Lanqi Hua, RDCS, FASE, Mark D. Handschumacher, BSc, Krishnaswamy Chandrasekaran, MD, FASE, Scott D. Solomon, MD, Eric K. Louie, MD, and Nelson B. Schiller, MD, *Montreal, Quebec, Canada; New York, New York; Boston, Massachusetts; Phoenix, Arizona; London, United Kingdom; San Francisco, California*

Table 1 Summary of reference limits for recommended measures of right heart structure and function

Variable	Unit	Abnormal
Chamber dimensions		
RV basal diameter	cm	>4.2
RV subcostal wall thickness	cm	>0.5
RVOT PSAX distal diameter	cm	>2.7
RVOT PLAX proximal diameter	cm	>3.3
RA major dimension	cm	>5.3
RA minor dimension	cm	>4.4
RA end-systolic area	cm^2	>18
Systolic function		
TAPSE	cm	<1.6
Pulsed Doppler peak velocity at the annulus	cm/s	<10
Pulsed Doppler MPI	—	>0.40
Tissue Doppler MPI	—	>0.55
FAC (%)	%	<35
Diastolic function		
E/A ratio	—	<0.8 or >2.1
E/E′ ratio	—	>6
Deceleration time (ms)	ms	<120

FAC, Fractional area change; *MPI*, myocardial p *PLAX*, parasternal long-axis; *PSAX*, parasternal s atrium; *RV*, right ventricle; *RVD*, right ventricula right ventricular outflow tract; *TAPSE*, tricus systolic excursion.

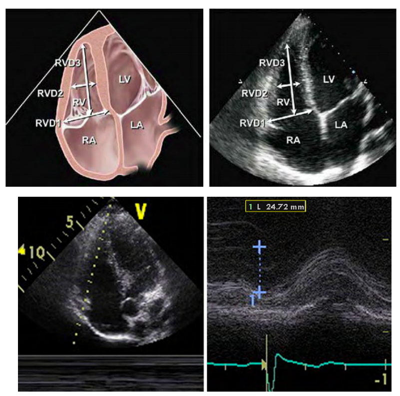
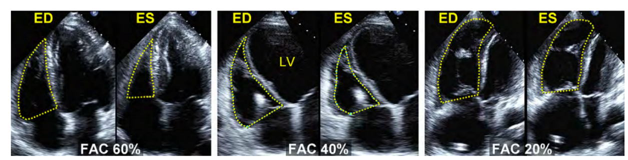


Figure 17 Measurement of tricuspid annular plane systolic excursion (TAPSE).

Rudski.J Am Soc Echocardiogr 2010;23:685-713

Fractional Area Change



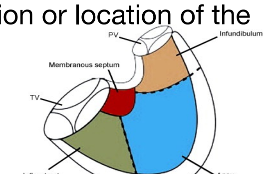
Two-dimensional Fractional Area Change is one of the recommended methods of quantitatively estimating RV function, with a lower reference value for normal RV systolic function of 35%.

Rudski.J Am Soc Echocardiogr 2010;23:685-713

ECHO: NO Accurate Method to Quantify RV Volumes and Function

- Difficulties in the estimation of RV
  - crescentic shape of RV
  - separation between RV ... ow
  - no uniform geom... for measuring v...
  - Cann... re RV in a single view
  - ... direction or location of the ...tion

Two dimensionally derived estimation of RV EF is not recommended, because of the heterogeneity of methods and the numerous geometric assumptions.

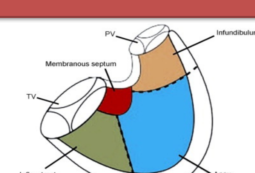


Rudski.J Am Soc Echocardiogr 2010;23:685-713

ECHO: NO Accurate Method to Quantify RV Volumes and Function

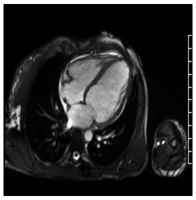
Two dimensionally derived estimation of RV EF is not recommended, because of the heterogeneity of methods and the numerous geometric assumptions.

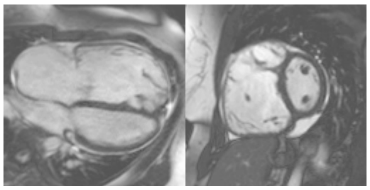
In studies in selected patients with RV dilatation or dysfunction, 3D echocardiography using the disk summation method may be used to report RV EFs. A lower reference limit of 44% has been obtained from pooled data. Until more studies are published, it may be reasonable to reserve 3D methods for serial volume and EF determinations.



Rudski.J Am Soc Echocardiogr 2010;23:685-713

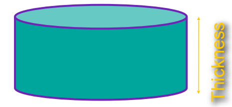
CMR Imaging for the Right Heart





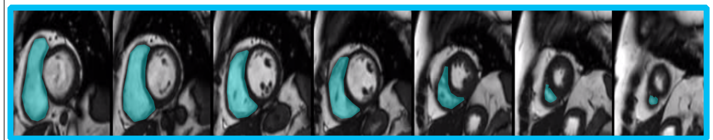
- Advantages:
  - Large FOV
    - Intra/extra cardiac anatomy
  - Unlimited imaging planes for the RV
  - Superior image resolution
  - Tissue characterization
    - Fibrosis, inflammation, scar, fat, thrombus
  - Volumetric based technique: RV volumes, RVEF and Regurg Vol/RF

Chambers Quantification



Volume = Area x Thickness

Base | Apex

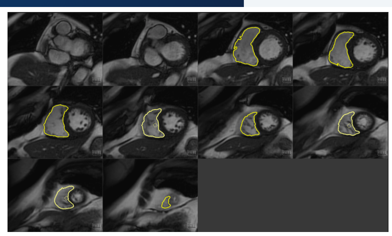


40 ml + 32 ml + 27 ml + 25 ml + 20 ml + 10 ml + 5 ml

RV EDV = 159 ml

CMR is *Superior* to ECHO for Right Ventricular Measurements

- Highly accurate
- Highly reproducible
- Low variability
  - intra-observer
  - inter-observer
  - Low inter-study (5-6%)



Accurate RV volumes & EF can aid in:
1. **Initial clinical assessment of the impact of PI/TR**
2. **Long term with serial measurements**

Boxt LM. J Thorac Imaging 1993;8:92–7.
Doherty NE III. Am J Cardiol 1992;69:1223–8.
Katz J.J Am Coll Cardiol 1993;21:1475–81.
Pattynama PM. Magn Reson Imaging 1995;13:53–63.
Rominger MB. J Magn Reson Imaging 1999;10:908–18.

Reference RV Values Normalized to Age, Gender and Body Surface Area

Table 8 RV summary data for all ages (mean ± SD, 95% confidence interval)

	All	Males	Females
EDV (mL)	144 ± 23 (98, 190)	163 ± 25 (113, 213)	126 ± 21 (84, 168)
EDV/BSA (mL/m²)	78 ± 11 (57, 99)	83 ± 12 (60, 106)	73 ± 9 (55, 92)
ESV (mL)	50 ± 14 (22, 78)	57 ± 15 (27, 86)	43 ± 13 (17, 69)
ESV/BSA (mL/m²)	27 ± 7 (13, 41)	29 ± 7 (14, 43)	25 ± 7 (12, 38)
SV (mL)	94 ± 15 (64, 124)	106 ± 17 (72, 140)	83 ± 13 (57, 108)
SV/BSA (mL/m²)	51 ± 7 (37, 65)	54 ± 8 (38, 70)	48 ± 6 (36, 60)
EF (%)	66 ± 6 (54, 78)	66 ± 6 (53, 78)	66 ± 6 (54, 78)
EF/BSA (%/m²)	36 ± 5 (27, 45)	34 ± 4 (26, 41)	39 ± 5 (29, 49)
Mass (g)	48 ± 13 (23, 73)	66 ± 14 (38, 94)	48 ± 11 (27, 69)
Mass/BSA (g/m²)	31 ± 6 (19, 43)	34 ± 7 (20, 47)	28 ± 5 (18, 38)

Maceira.European Heart Journal (2006) 27, 2879–2888

Reference RV Values Normalized to Age, Gender and Body Surface Area

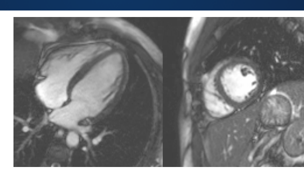
Table 2 Males: RV volumes, systolic function and mass (absolute and normalized to BSA) by age decile (mean, 95% confidence interval)

Age (years)	20–29	30–39	40–49	50–59	60–69	70–79
Absolute values						
EDV (mL) SD 25.4	177 (127, 227)	171 (121, 221)	166 (116, 216)	160 (111, 210)	155 (105, 205)	150 (100, 200)
ESV (mL) SD 15.2	68 (38, 98)	64 (34, 94)	59 (29, 89)	55 (25, 85)	50 (20, 80)	46 (16, 76)
SV (mL) SD 17.4	108 (74, 143)	108 (74, 142)	107 (73, 141)	106 (72, 140)	105 (71, 139)	104 (70, 138)
EF (%) SD 6.5	61 (48, 74)	63 (50, 76)	65 (52, 77)	66 (53, 79)	68 (55, 81)	70 (57, 83)
Mass (g) SD 14.4	70 (42, 99)	69 (40, 97)	67 (39, 95)	65 (37, 94)	63 (35, 92)	62 (33, 90)
Normalized to BSA						
EDV/BSA (mL/m²) SD 11.7	91 (68, 114)	88 (65, 111)	85 (62, 108)	82 (59, 105)	79 (56, 101)	75 (52, 98)
ESV/BSA (mL/m²) SD 7.4	35 (21, 50)	33 (18, 47)	30 (16, 45)	28 (13, 42)	25 (11, 40)	23 (8, 37)
SV/BSA (mL/m²) SD 8.2	56 (40, 72)	55 (39, 71)	55 (39, 71)	54 (38, 70)	53 (37, 69)	52 (36, 69)
EF/BSA (%/m²) SD 4	32 (24, 40)	32 (25, 40)	33 (25, 41)	34 (26, 42)	35 (27, 42)	35 (27, 43)
Mass/BSA (g/m²) SD 6.8	36 (23, 50)	35 (22, 49)	34 (21,48)	33 (20, 46)	32 (19, 45)	31 (18, 44)

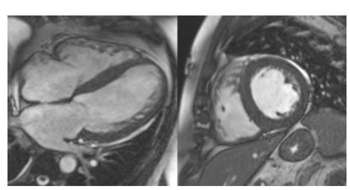
Table 3 Females: RV volumes, systolic function and mass (absolute and normalized to BSA) by age decile (mean, 95% confidence interval)

Age (years)	20–29	30–39	40–49	50–59	60–69	70–79
Absolute values						
EDV (mL) SD 21.6	142 (100, 184)	136 (94, 178)	130 (87, 172)	124 (81, 166)	117 (75, 160)	111 (69, 153)
ESV (mL) SD 13.3	55 (29, 82)	51 (25, 77)	46 (20, 72)	42 (15, 68)	37 (11, 63)	32 (6, 58)
SV (mL) SD 13.1	87 (61, 112)	85 (59, 111)	84 (58, 109)	82 (56, 108)	80 (55, 106)	79 (53, 105)
EF (%) SD 6	61 (49, 73)	63 (51, 75)	65 (53, 77)	67 (55, 79)	69 (57, 81)	71 (59, 83)
Mass (g) SD 10.6	54 (33, 74)	51 (31, 72)	49 (28, 70)	47 (26, 68)	45 (24, 66)	43 (22, 63)
Normalized to BSA						
EDV/BSA (mL/m²) SD 9.4	84 (65, 102)	80 (61, 98)	76 (57, 94)	72 (53, 90)	68 (49, 86)	64 (45, 82)
ESV/BSA (mL/m²) SD 6.6	32 (20, 45)	30 (17, 43)	27 (14, 40)	24 (11, 37)	21 (8, 34)	19 (6, 32)
SV/BSA (mL/m²) SD 6.1	51 (39, 63)	50 (38, 62)	49 (37, 61)	48 (36, 60)	46 (34, 58)	45 (33, 57)
EF/BSA (%/m²) SD 5.2	37 (27, 47)	38 (27, 48)	38 (28, 49)	39 (29, 49)	40 (30, 50)	41 (31, 51)
Mass/BSA (g/m²) SD 5.2	32 (22, 42)	30 (20, 40)	29 (19, 39)	27 (17, 37)	26 (16, 36)	24 (14, 35)

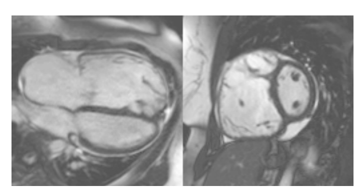
Maceira.European Heart Journal (2006) 27, 2879–2888



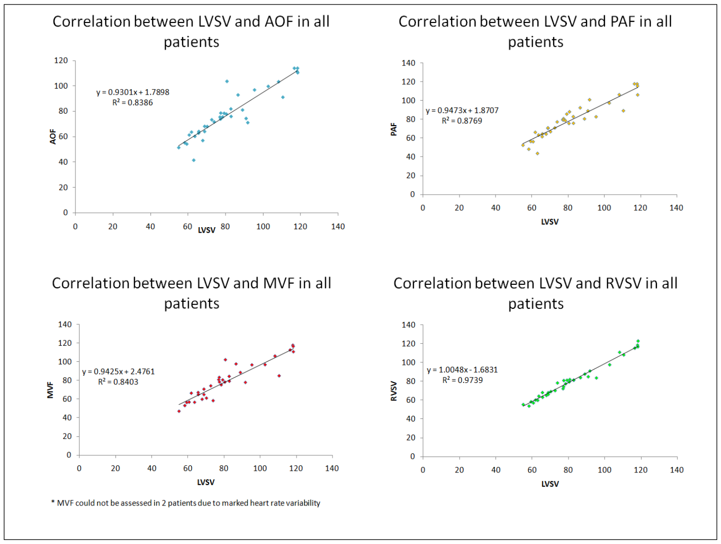
Normal RV

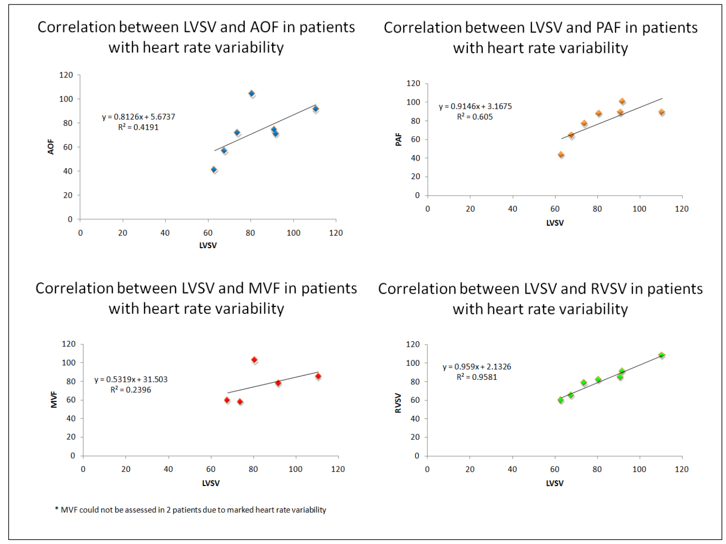


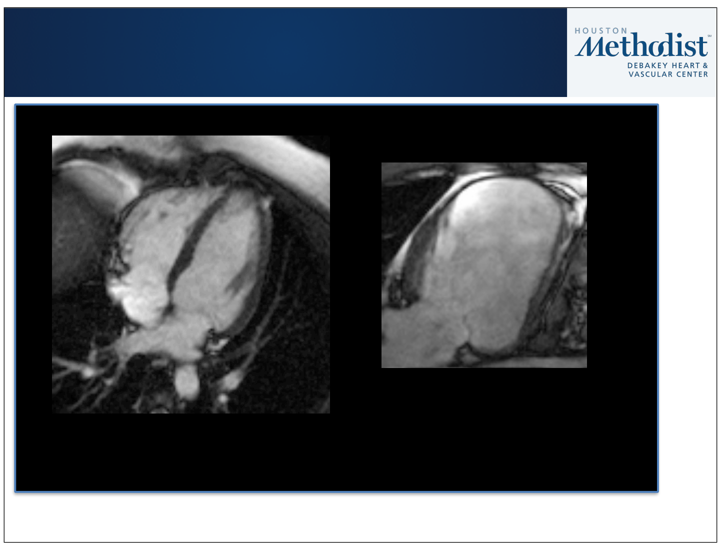
Severe RV Dysfunction



Severe RV Dilation


Correlation between LVSV and AOF in all patients
y = 0.9301x + 1.7898
R² = 0.8386
AOF
LVSV
Correlation between LVSV and PAF in all patients
y = 0.9473x + 1.8707
R² = 0.8769
PAF
LVSV
Correlation between LVSV and MVF in all patients
y = 0.9425x + 2.4761
R² = 0.8403
MVF
LVSV
Correlation between LVSV and RVSV in all patients
y = 1.0048x - 1.6831
R² = 0.9739
RVSV
LVSV
* MVF could not be assessed in 2 patients due to marked heart rate variability


Correlation between LVSV and AOF in patients with heart rate variability
y = 0.8126x + 5.6737
R² = 0.4191
AOF
LVSV
Correlation between LVSV and PAF in patients with heart rate variability
y = 0.9146x + 3.1675
R² = 0.605
PAF
LVSV
Correlation between LVSV and MVF in patients with heart rate variability
y = 0.5319x + 31.503
R² = 0.2396
MVF
LVSV
Correlation between LVSV and RVSV in patients with heart rate variability
y = 0.959x + 2.1326
R² = 0.9581
RVSV
LVSV
* MVF could not be assessed in 2 patients due to marked heart rate variability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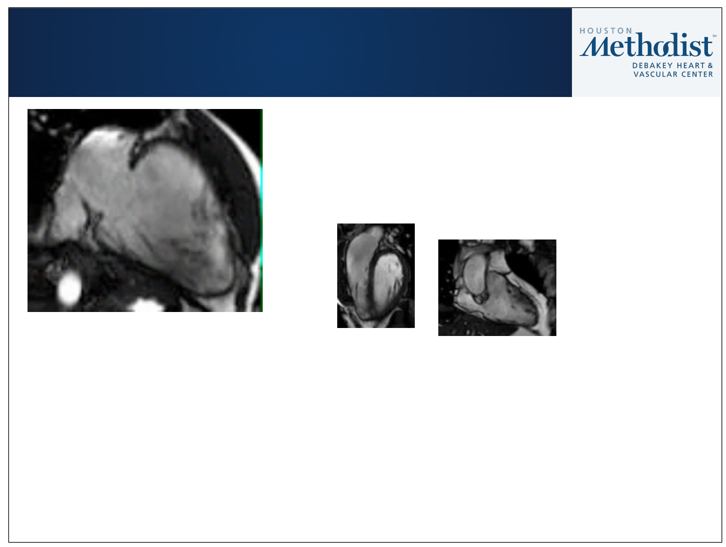
DEBAKEY HEART & VASCULAR CENTER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