Quantification of CSF Flow at the Aqueduct with Phase Contrast MR Imaging

Kezhou Wang, Ph.D
Principle Software Engineer
Director of Engineering and Research
VasSol Inc.

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VasSol's Quantitative MRA™

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1. Introduction

- History of CSF flow measurement with PCMR imaging
- PCMR Technology Improvements
  - Image Quality
    - Less Noise, Higher Resolution
  - Scanning Time is reduced
    - Multi-Channel Coil/Multi Elements
    - Parallel Imaging, View Sharing
- Important Factors in PCMR imaging

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Brief History of Flow Quantification with PCMR

- 1. PCMR - concept
  - Singer JR, Science 1959
- 2. Blood flow from 1980s.
  - Cardiac Applications, O'Donnell M, Med Phys 1985.
  - Cerebral Vessel Blood Flow, Charbel FT, Magn Reson Imaging, 2000
- 3. CSF Flow Dynamics
  - William G. Bradley, Radiology 1992. Neuroradiology, 1996
- 4. 2D and 4D PCMR

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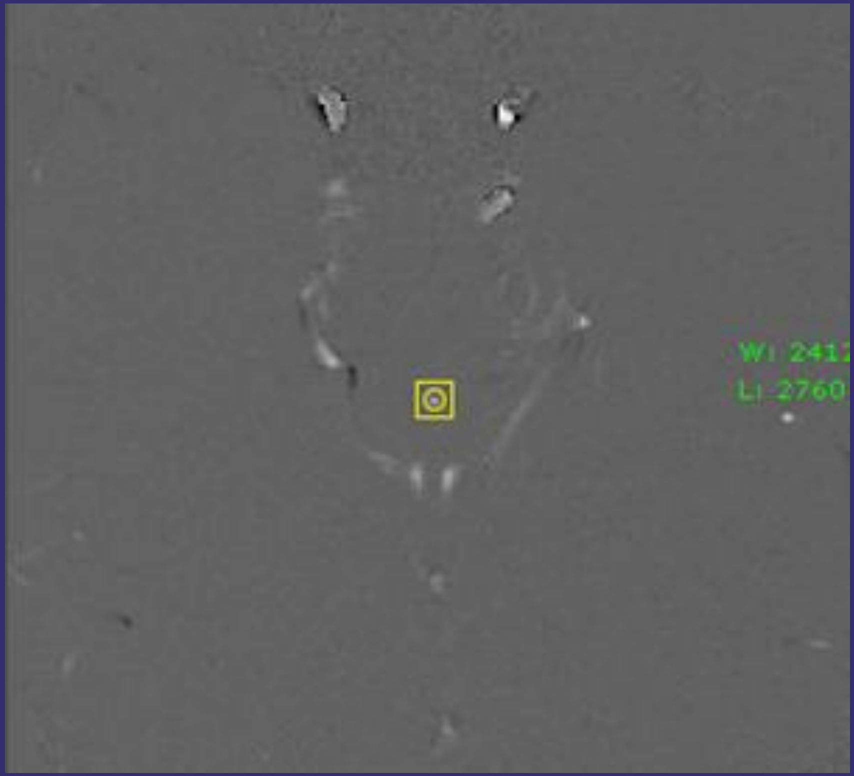
Image Quality Improvement With new PCMR protocols

Copied from Bradley CSF Paper 1992

30 slices, 14 Minutes

Sample image with new protocol from GE Discovery 3T 750, 2013



30 slices, 1.5 Minutes

Scanning Time on GE Discovery 3T 750 MR Scanner

View Per Segment (VPS)	Phases	Scanning Time
2	40	3 minutes 10 seconds
2	30	3 minutes 6 seconds
4	40	1 minutes 40 seconds
4	30	1 minutes 35 seconds
16	12	Less than 30 seconds

Matrix= 256 x 244, FOV/PFOV = 120/120, VENC =20

Important Factors in Measurement with PCMR Imaging

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- Temporal resolution ~ 0.5mm
- Spatial resolution ~25ms – 35ms
- Scanning time ~ 1 minute
- Measurement plane location
- ~Straight
- Measurement plane direction ~Perpendicular
- Aliasing correction

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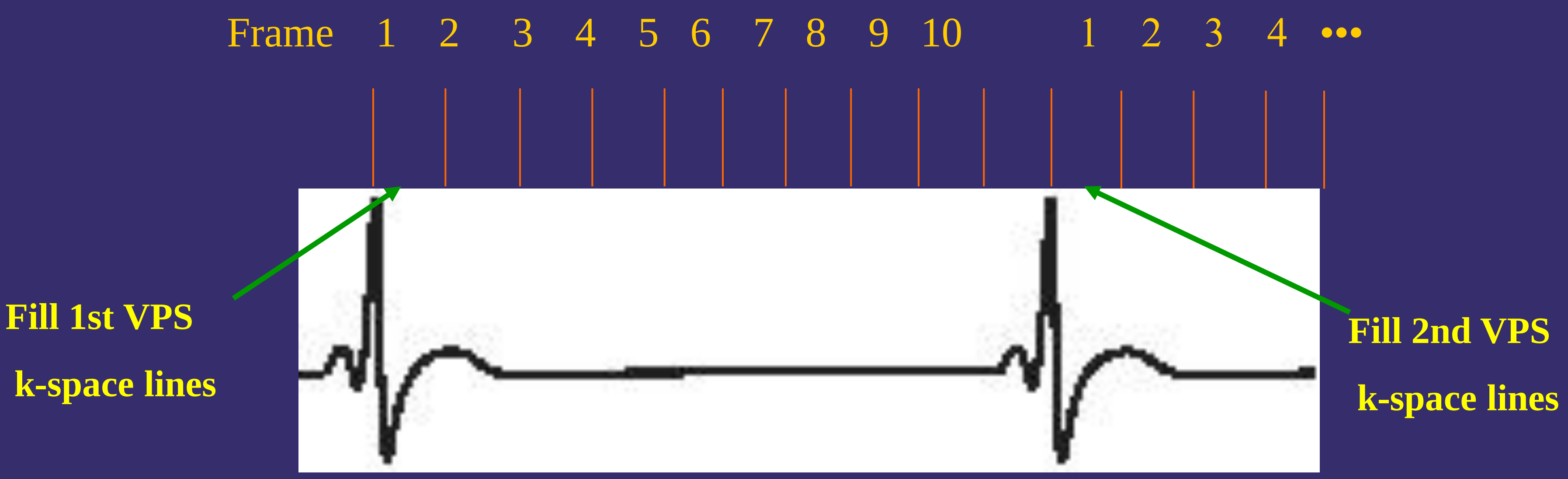
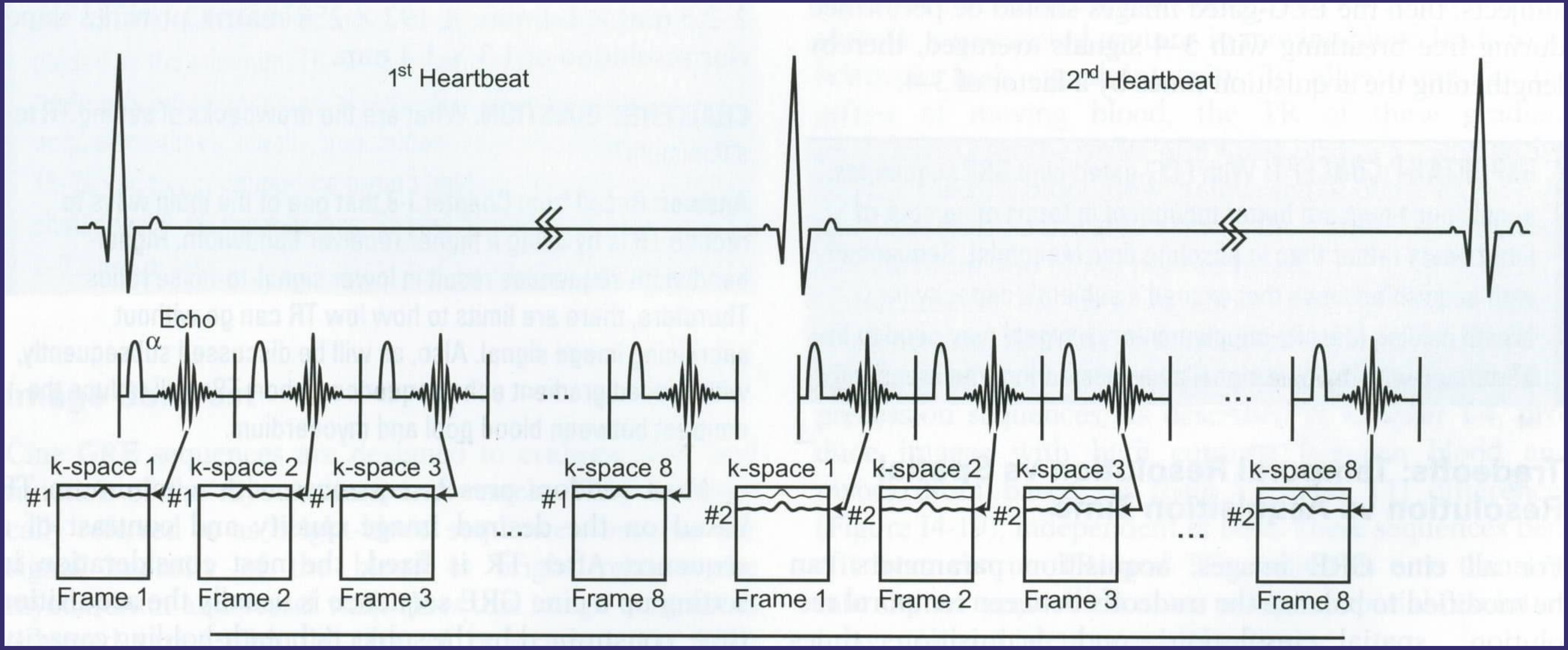
Retrospectively gated fast 2D phase contrast (FastCine)



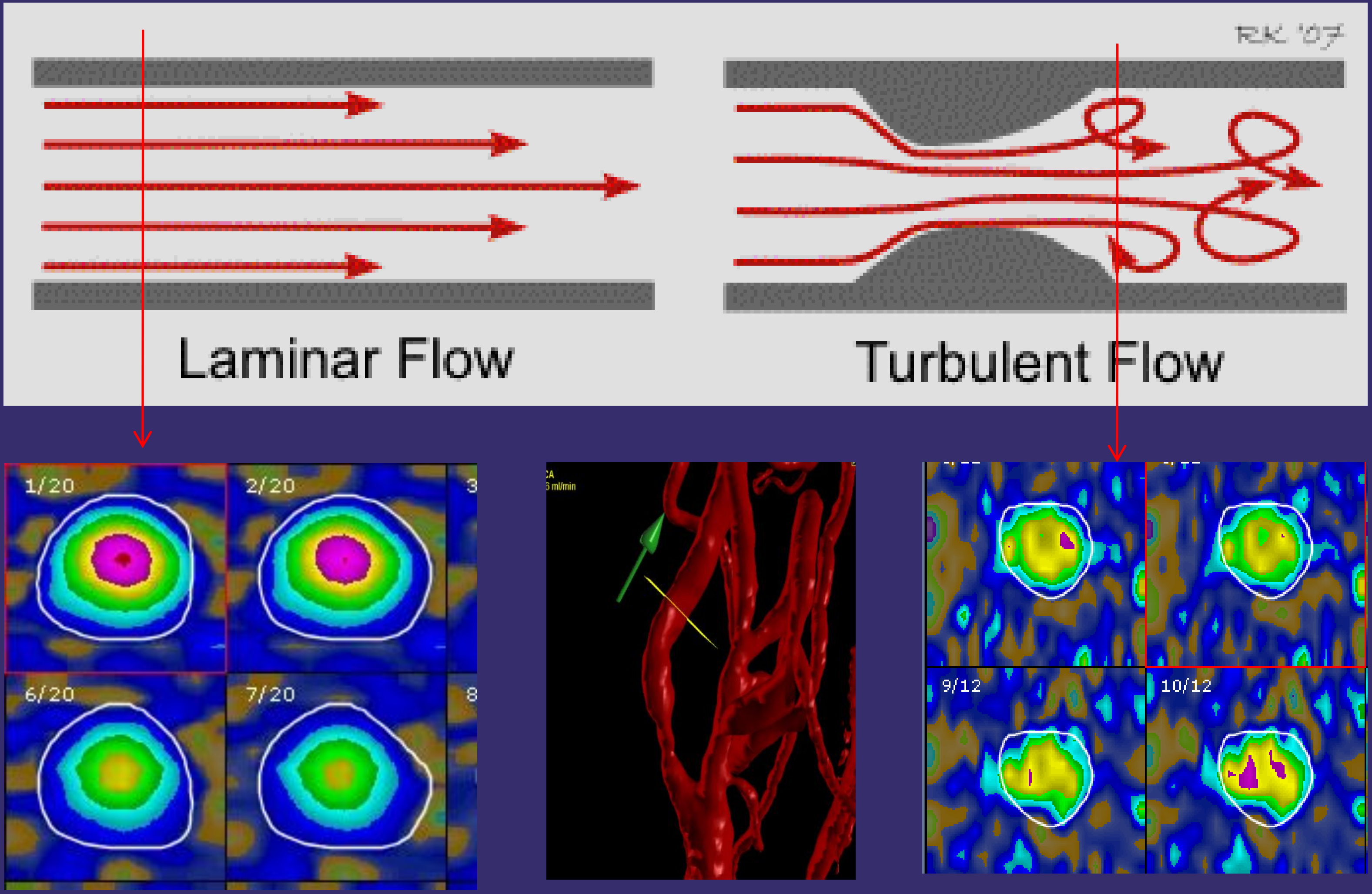
- The time resolution *T* of such a phase-contrast sequence is defined as follows: T = 2 * TR * VPS
- Problem: Arrhythmia patient

Multiple Heart Beats to Fill the Images

Multiple PCMR images cover a cardiac cycle
- **ECG/ peripheral gating**
- **Each heartbeat, a few lines of data collected**
- **Need multiple cardiac cycles to fill the whole images**



Measurement location is important



2D PCMR Plane Position?

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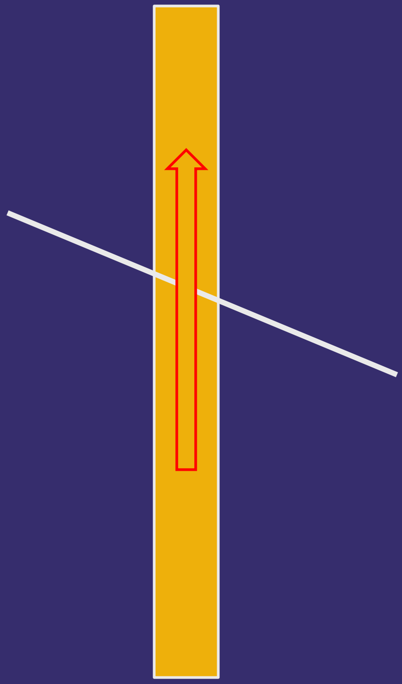

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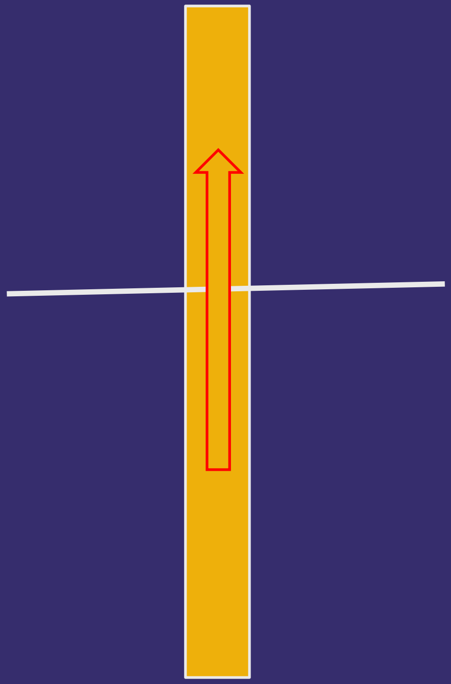

Good

How?

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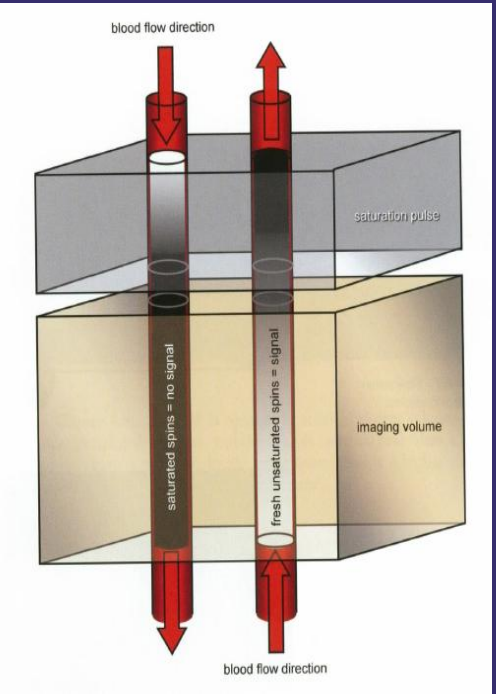
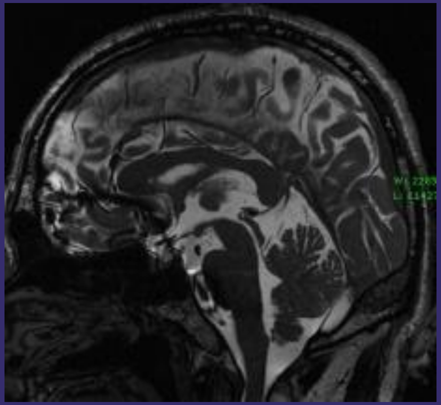
QMRA (NOVA) 3D Localizer

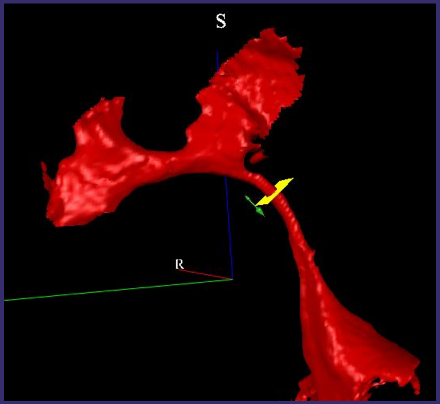


TOF MRA

NOVA 3D Localizer

GE FIESTA

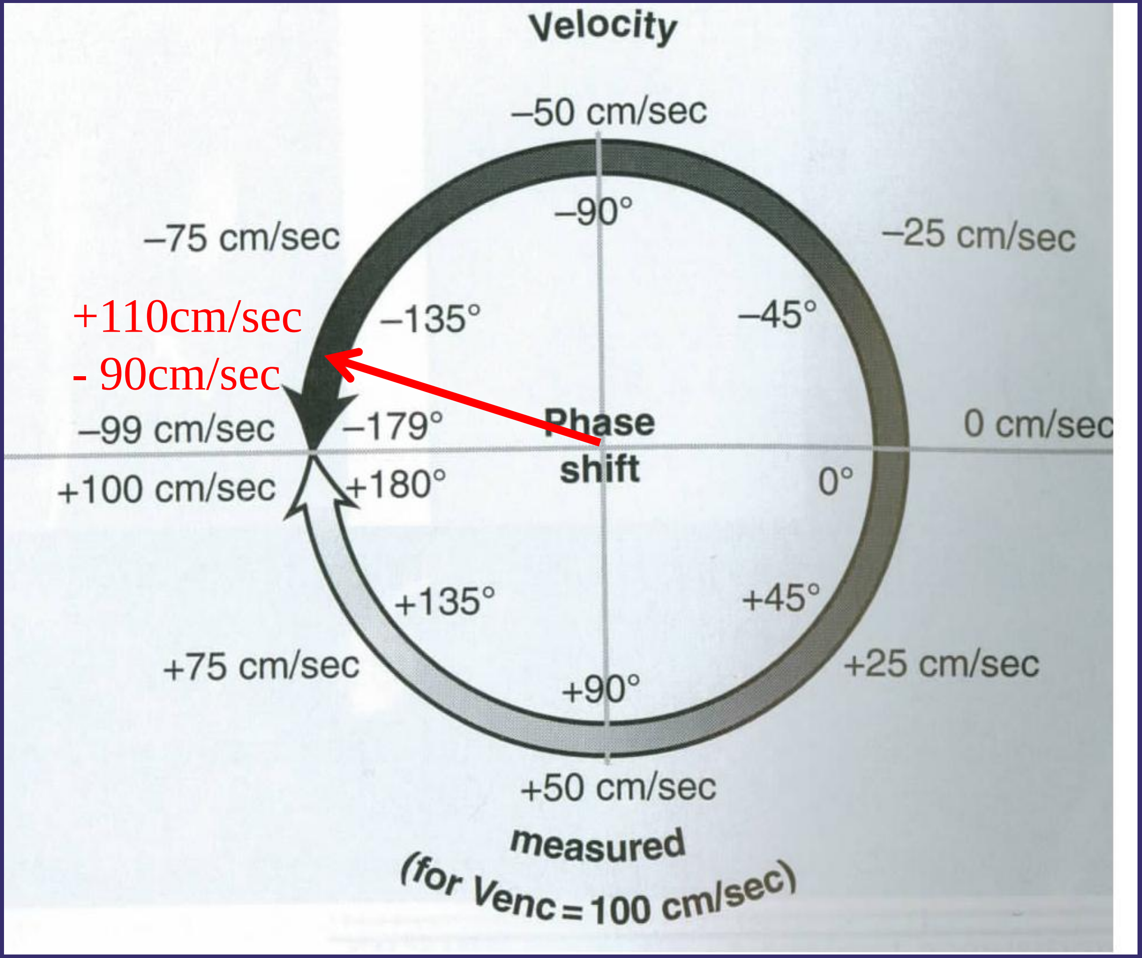




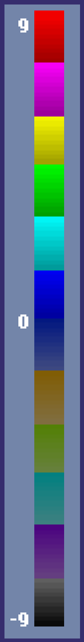
Velocity Encoding(VENC) and Aliasing

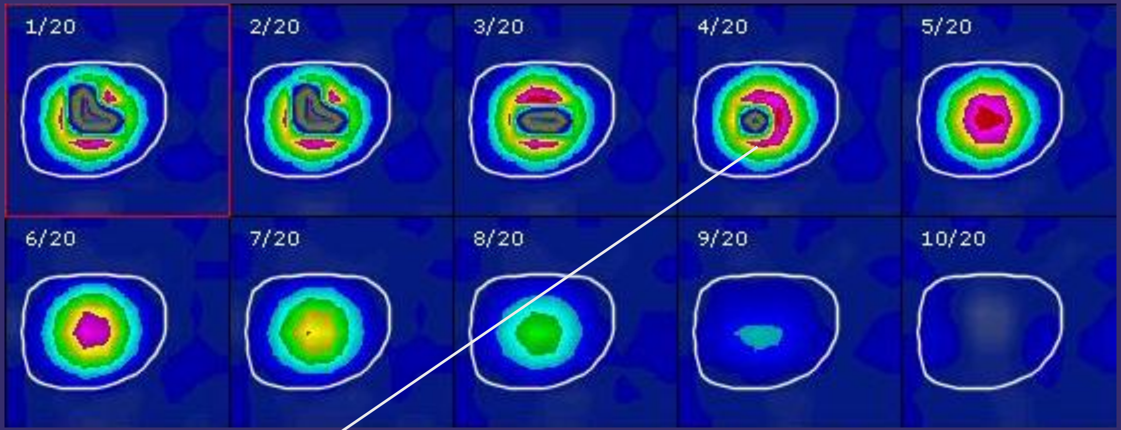
Phase shift proportional to velocity

- Phase Range (-180º to 180º)
- Flow Range (-Venc to Venc)
- Forward flow (positive phase-white on the image)
- Reverse flow (negative phase-black on the image)

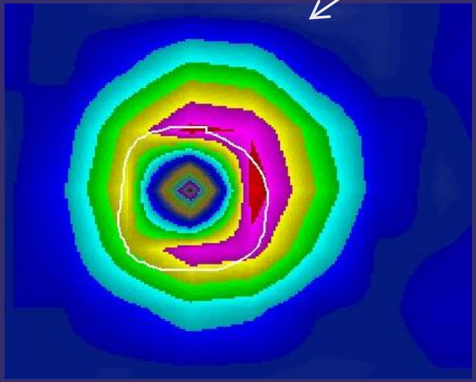


Identify and Correct Flow Aliasing

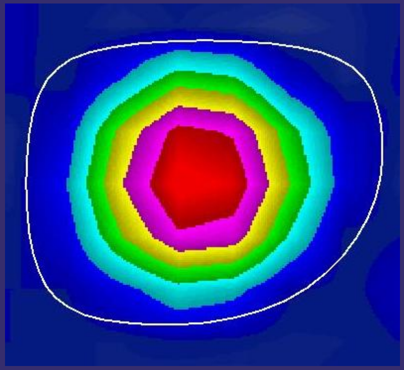




In phase term 181 degree = -179 degree



Aliasing Correction



2. PCMR Protocol Optimization with Slow Flow Phantom

- 1. Difference between CSF and Blood Flow
- 2. Phantom Study Setup
- 3. Experiments
- 4. Results

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Physical Difference Between CSF and Blood Flow

- Velocity
  - Blood Flow Velocity: ~100 cm/s
  - CSF Flow Velocity: ~ 10 cm/s
- Flow Pattern
  - Blood Flow: uni-directional
  - CSF Flow: bi-directional, more complex
- Flow domain
  - Blood Flow: within blood vessels
  - CSF Flow: Ventricles and subarachnoid space

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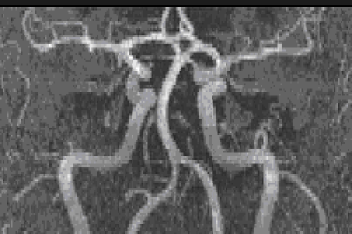
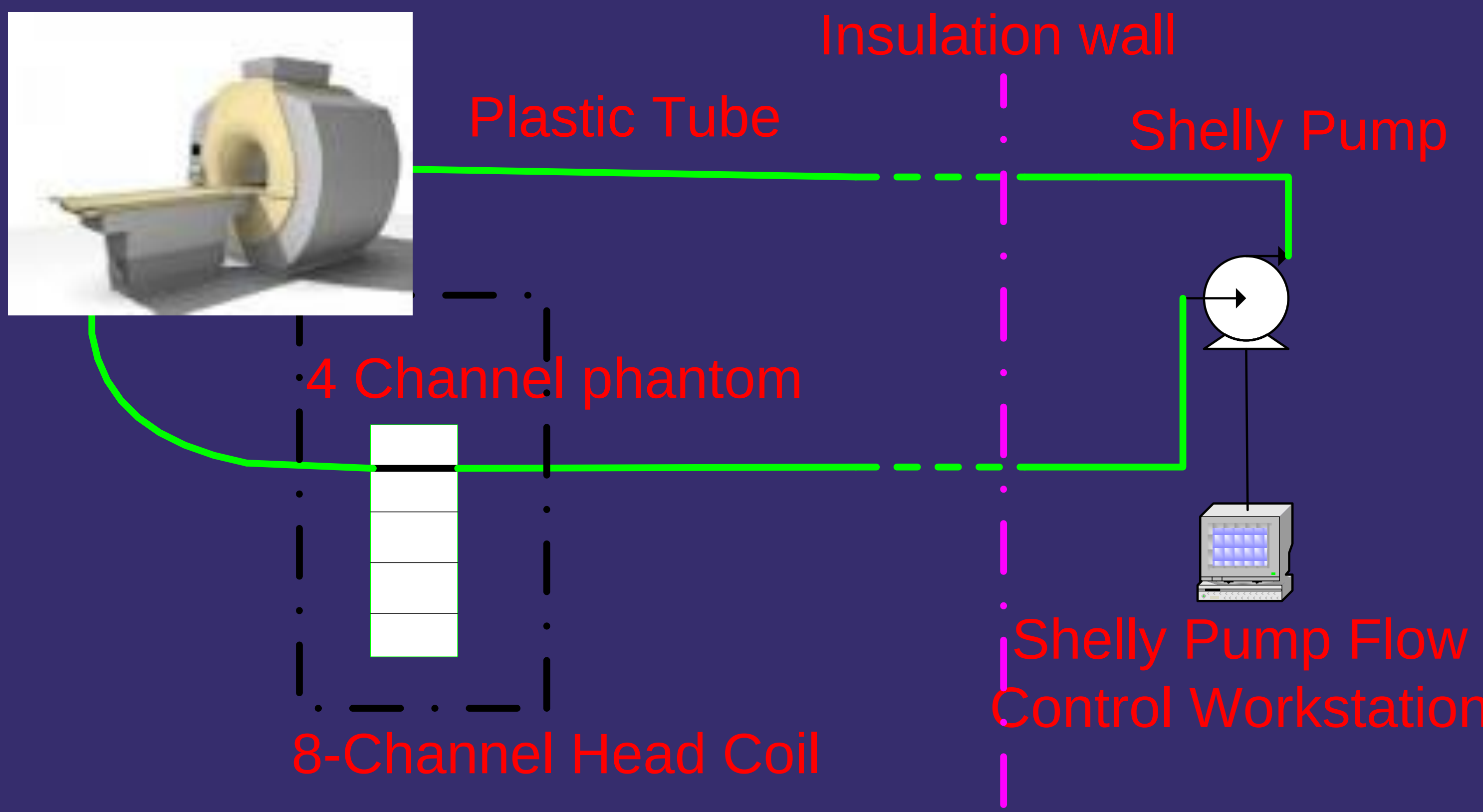
Flow Phantom Diagram

Traditional MRA:



VasSol's Quantitative MRA™



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PCMR Parameters

- Flip Angle 10-15-20
- VENC 10-20
- Number of Excitations (NEX)2-6
- View Per Segment (VPS) 2-16
- Number of Phases 12-24
- Resolutions / FOV

Traditional MRA:

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PCMR parameters

Flow Rate	1 ml/s (60 ml/min)	2ml/s (120 ml/min)	3ml/s (180 ml/min)	4ml/s (240 ml/min)
Venc	10	20	20	20
Number of Excitations	2, 4, 6	2, 4, 6	2,4,6	2,4,6
View per Segment	2, 4, 6, 8	2, 4, 6, 8	2, 4, 6,8	4, 6, 8, 16
Cine Phase	12/24	12/24	12/24	12/24

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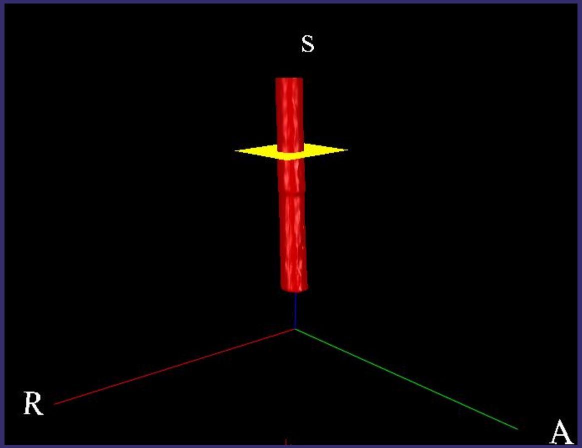
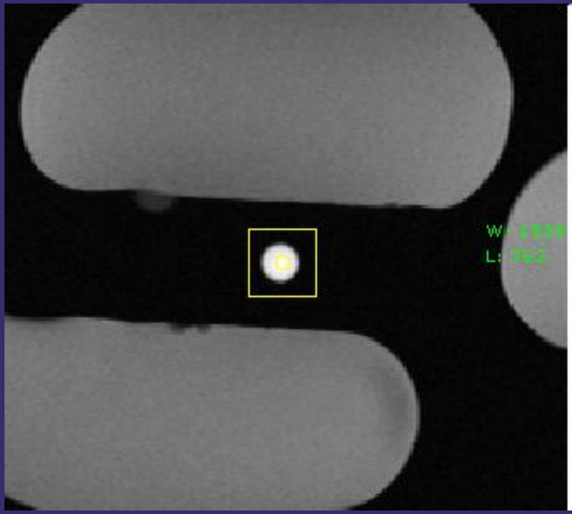
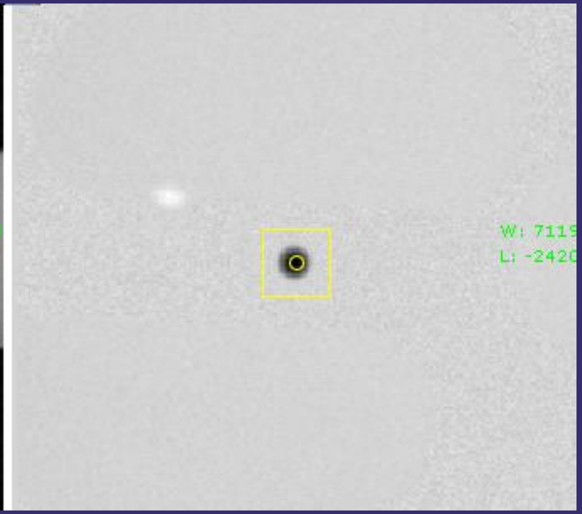
Phantom PCMR Images



3D model from
TOF





Magnitude Image

Phase Image

12 Flow Contours in a Cardiac Cycle

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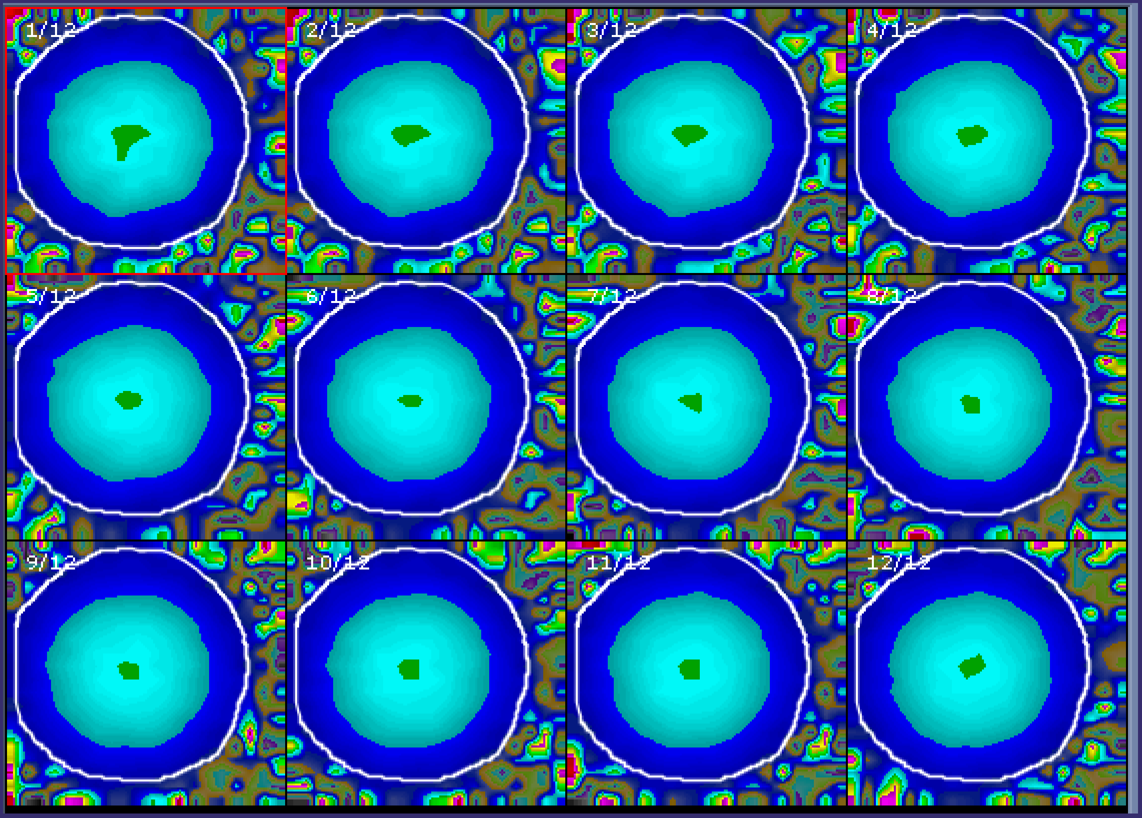

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Phantom results

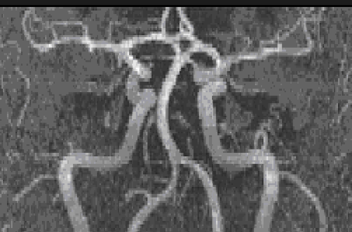
Table 1. Phantom Actual Flow Rate in Comparison with the Flow Rate from PCMR

Flow Rate (mL/min)	**Avg Velocity (cm/s)**	**12 Phases (mL/min)**				**24 Phases (mL/min)**			
		Min	**Max**	**Avg**	**Error (%)**	**Min**	**Max**	**Avg**	**Error (%)**
60	1.99	54.5	57.1	55.58	-7.36	54.7	56.5	55.37	-7.72
120	3.98	113	114	113.5	-5.41	112.1	115.3	113.5	-5.40
180	5.97	173.7	176.3	174.57	-3.01	172.1	175.5	174.0	-3.32
240	7.96	232.2	236.1	233.98	-2.51	218.2	236.8	232.7	-3.04

3. Optimize the protocol parameters with volunteers

- Spatial Resolution
  - Partial volume effect
  - Limited by the hardware
- Slow Flow
  - Eddy current
  - Background Noise
- Temporal resolution
  - Missing phases

Traditional MRA:



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3. Optimize the protocol parameters with volunteers-(Continue)

- Peripheral gating – EKG gating
- Reproducibility
  - The same volunteer on the same scanner
- Inter scanner differences
  - Different magnets, 1.5T, 3T from the same vendor
  - Different scanners from different vendors

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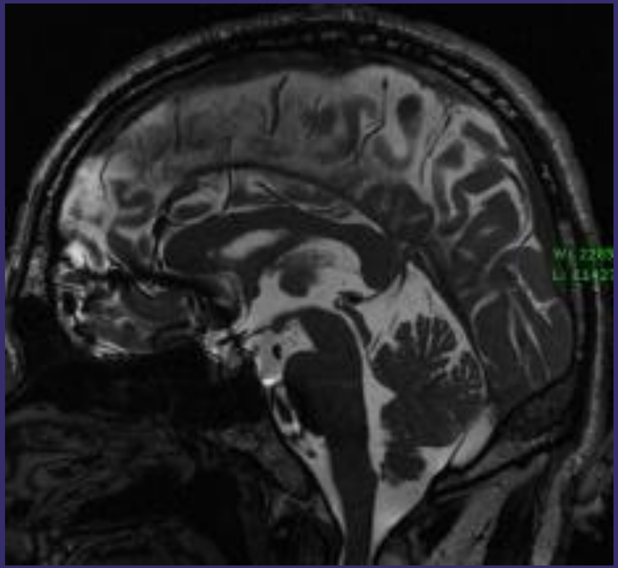
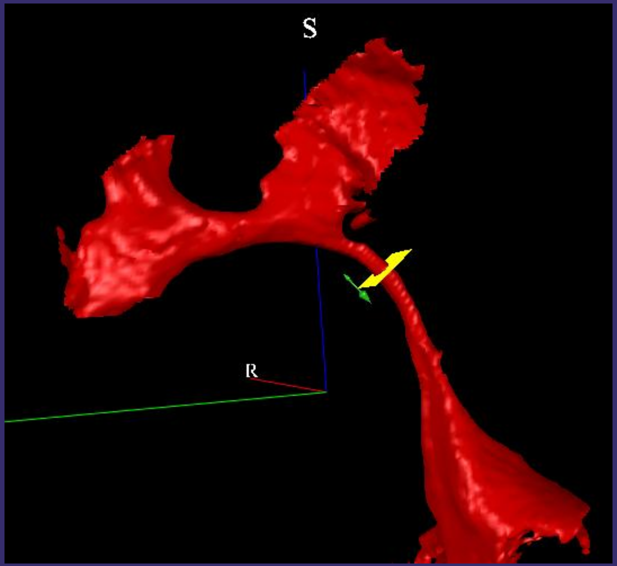
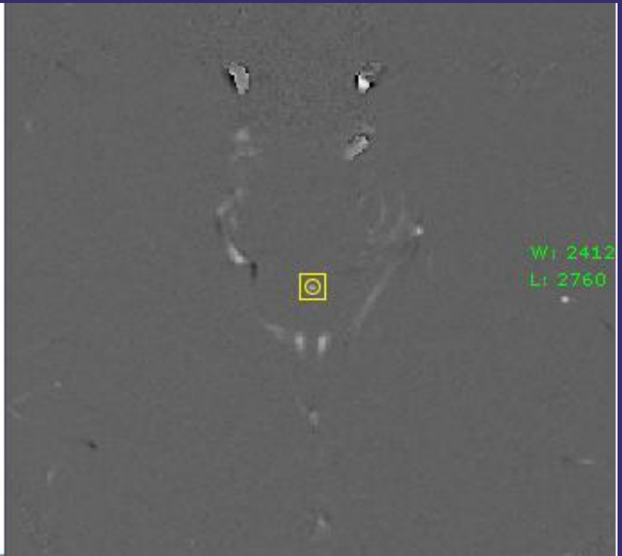
Volunteer Study







Comparison of the Stroke Volume – NPH Patient – Different Scanners

	Stroke Volume- Siemens (µm/cycle)	Stroke Volume- GE (µm/cycle)	Difference
VENC = 10	(+65.8/-59.1) 62.5 (aliasing corrected)	(+106.4/-94.9)100.6	61%
VENC = 20	(+42.8/-53.1) 48	(+90.7/-77.3) 83.8	74%
VENC = 30	(+52.6/-57.3) 54.6	(+121/-76.6) 98.8	81%

Siemens Parameters: FOV =147x147, Matrix 384x384, pixel size=0.38mm x 0.38mm, slice thickness = 3mm

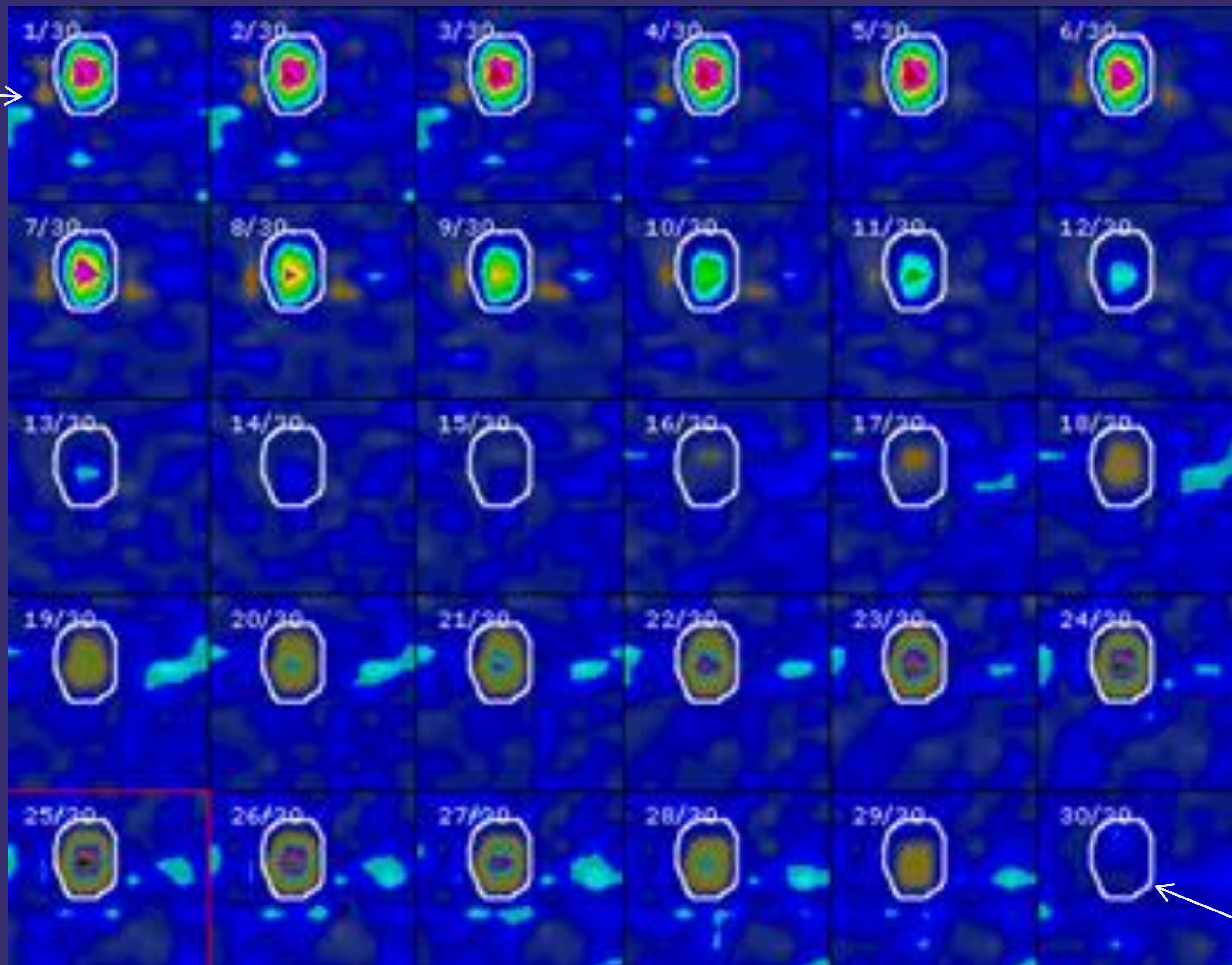
GE Parameters: FOV=240x216, Matrix 256x256, pixel size=0.94mm x 0.84mm, slice thickness = 5mm

Missing Phases on GE scanner

1st phase

Abrupt change
Between 1st and
the last phase

1-13 Systole
14-30 Diastole



Last phase

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Parameter Changes

- Decrease View Per Segment (VPS)
  - From 8,16 to 2,4
- Increase Phase Number
  - From 30 to 40
- Temporal Resolution
  - Phase#/VPS

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Increase the phase number from 30 to 40 on GE scanner

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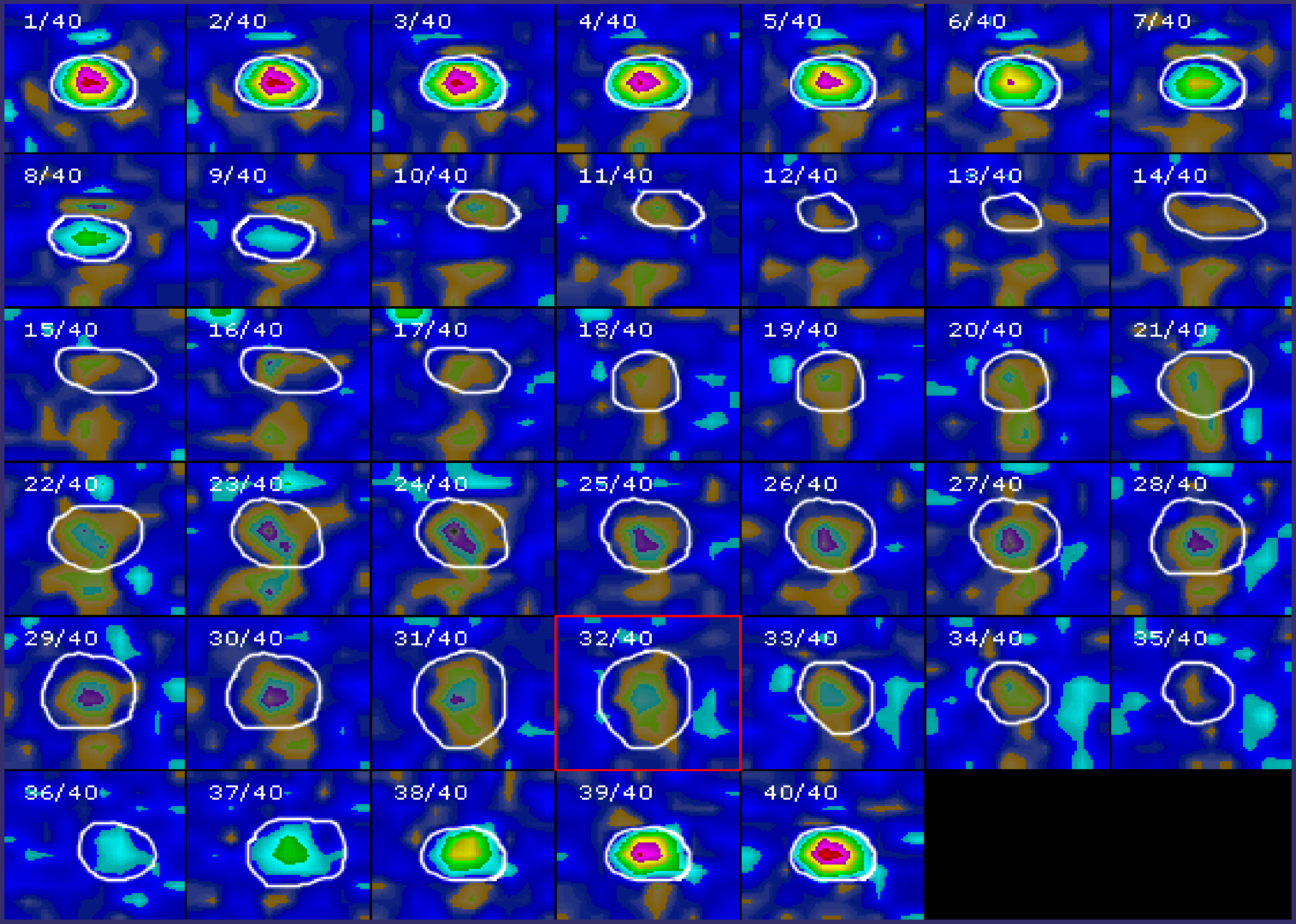

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Stroke Volume Repeatability on GE scanners at UCSD

Same Volunteer

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		Stroke Volume (uL/cycle)			
		GE 3T		**GE 1.5T**	
		VENC =20	VENC =30	VENC = 20	VENC = 30
EKG	1	12.6	10.8	21.3	15.0
	2	16.1	16.1	11.8	13.0
	3	19.6	19.5	14.2	9.3
	AVG	**16.11**	**15.4**	**15.7**	**12.4**
PG	1	17.9	21.8	13.4	18.0
	2	22.2	19.0	17.4	16.3
	3	28.3	22.6	9.1	12.6
	AVG	**22.8**	**21.1**	**13.3**	**15.6**

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Stroke Volume Repeatability at UIC- GE Discovery 3T 750 V22

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	NEX/VPS	Phase #	Stroke Volume (µL /cycle)
Volunteer 1	2/2	40	23.1(24.9/-21.3)
	2/4	40	22.4(27.2/-17.6)
Volunteer 2	2/2	40	16.3(21/-11.5)
	2/4	40	19.2(24.5/-13.9)

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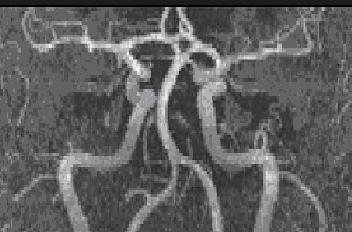
Traditional MRA:



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Stroke Volume Repeatability at Wingsong Hospital - Siemens 3T Verio VB 17 scanner

VENC / Rescan Times		1st Volunteer (µL/cycle)	2nd Volunteer (µL/cycle)	3rd Volunteer (µL/cycle)
Venc =20	1	14.2	2.2	78.9
	2	15.5	1.8	65.5
	3	15.0	1.9	75.3
	4	15.0	1.7	74.3
Mean (±STD)		**14.9(±0.537)**	**1.9(±0.21)**	**73.5(± 5.68)**
Venc =10	1	10.4	1.8	*66.0
	2	13.1	1.9	*66.3
	3	11.3	1.8	*63.5
	4	11.1	1.7	*59.1
Mean (±STD)		**11.5(±1.15)**	**1.8(± 0.081)**	**63.7(± 3.33)**

* Aliasing observed for the 3rd volunteer when Venc =10

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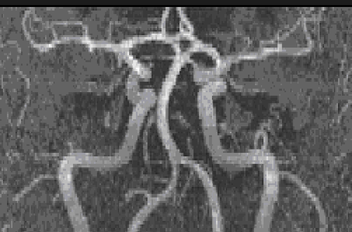

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CSF Flow Difference between GE and Siemens Scanners

Same Volunteer

	Stroke Volume (µL/cycle)	Systolic /Diastolic Volume (µL/cycle)	Net Flow (µL/cycle)	Peak Systolic /Diastolic Velocity (mm/s)	Average Peak Systolic/Diastolic Velocity (mm/s)
Siemens	32.5	32.8/-32.3	0.4	65/-48	37.9/-28.3
GE	42.0	44.3/-39.7	4.5	84/-53	47.3/-20.8
Difference	29%	35%/23%		29%/11%	25%/36%

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3D model, flow contours and waveform with 30 phases - Siemens scanner

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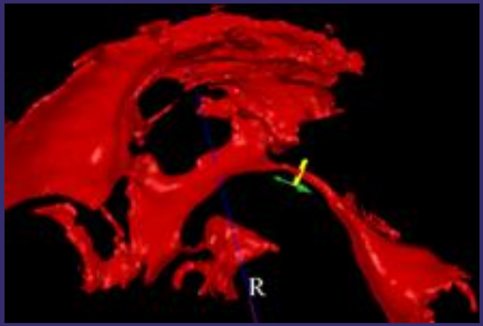

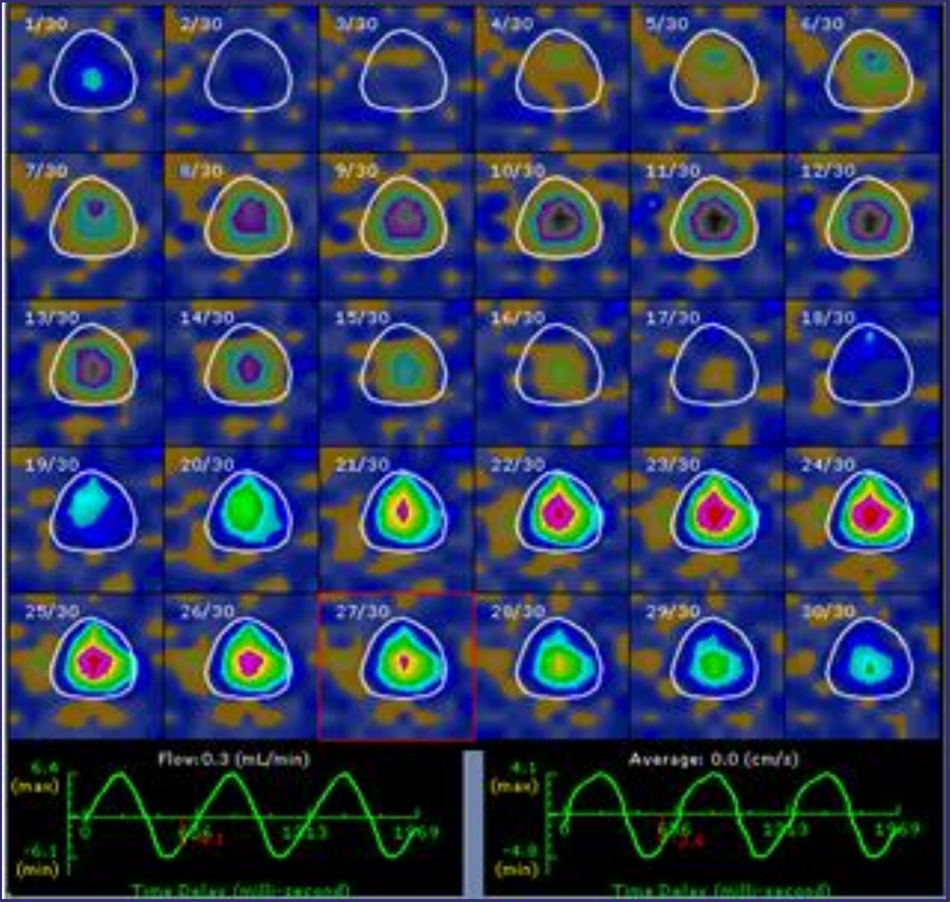

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Flow Contours and waveform with 20 Phase- Siemens scanner

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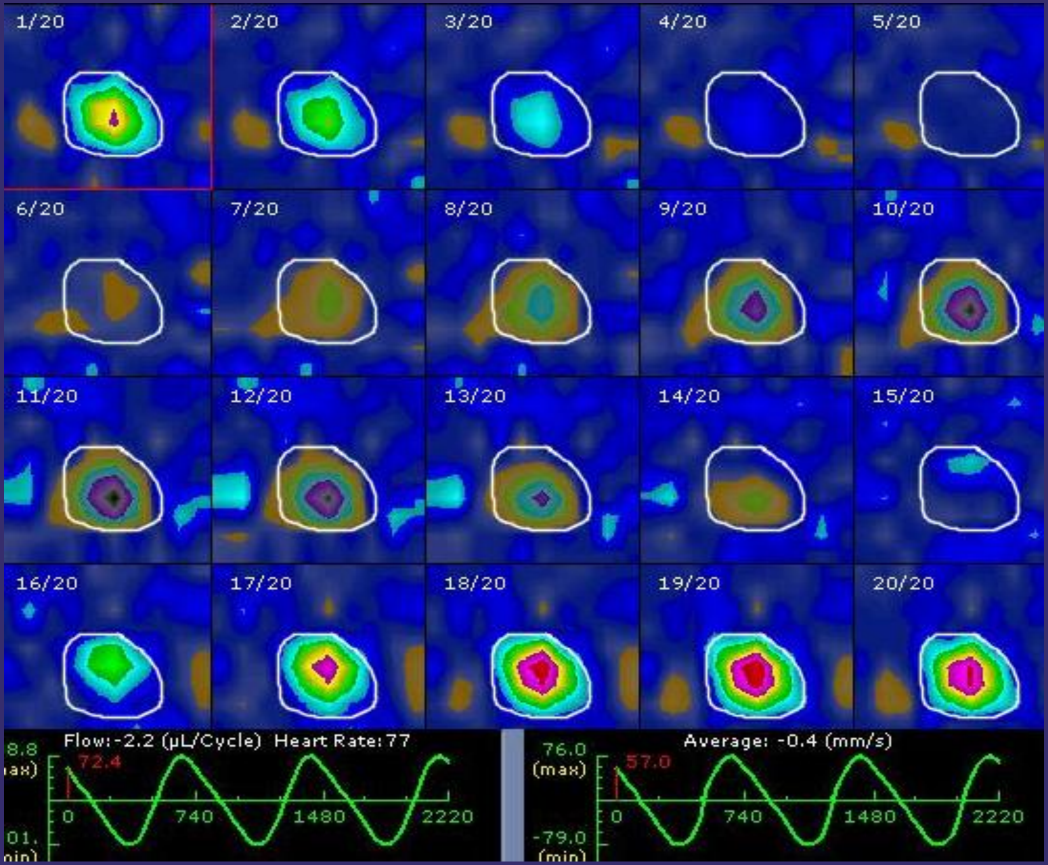

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Suggested CSF PCMR protocol parameters

– GE Scanner:
  - Phase = 40, NEX = 2, VPS = 2
  - Flip angle =20, VENC = 20
  - Matrix 256 x 256, FOV/PFOV = 120/120
  - Thickness = 4mm.
– SIEMES Scanner:
  - Phase = 30, NEX = 2-4, VPS = 2-5,
  - Flip angle =20, VENC = 20
  - Matrix 256 x 256, FOV/PFOV = 120/120
  - Thickness =4mm.

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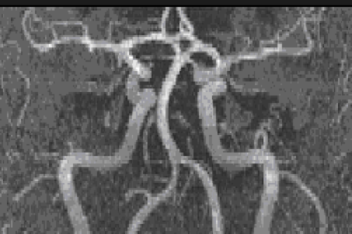
4. Problems and Further Work

- ♦ Pulstile slow flow phantom
  - – Smaller diameters
- ♦ Boundary Extraction Algorithms
  - – Robust
  - – Accurate
- ♦ Background Noise Suppression
  - – Increase SNR
- ♦ Repeatability
  - – Further optimize the protocols
  - – On other scanners – such as Philips and Toshiba

Traditional MRA:



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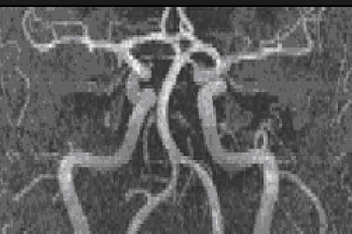
Boundary Inconsistence

Traditional MRA:



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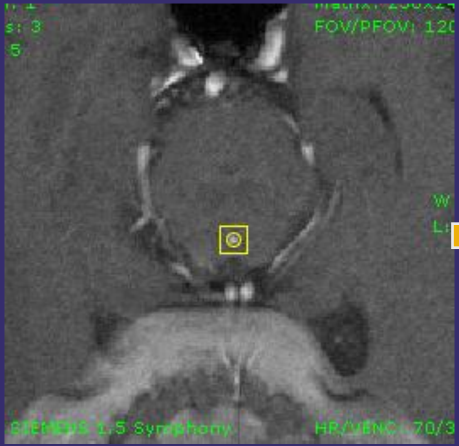

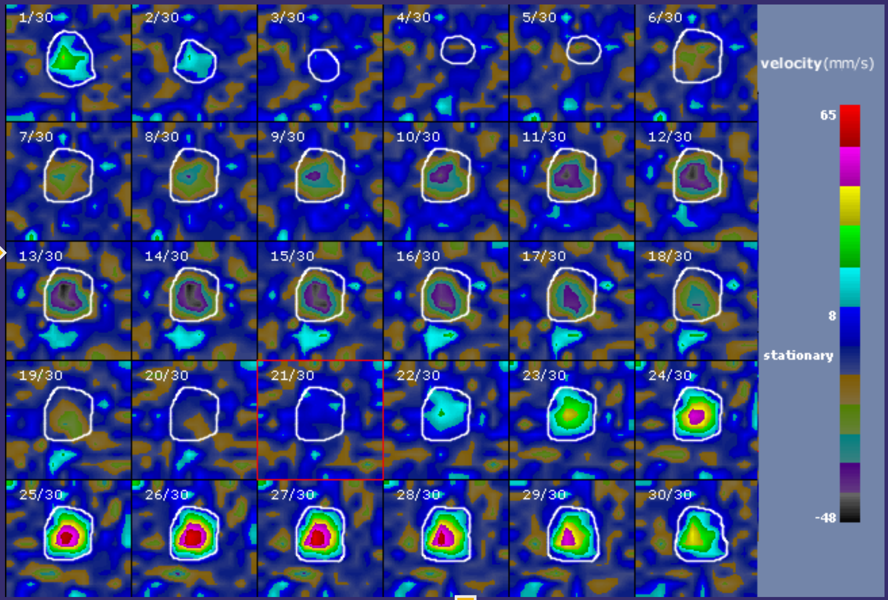

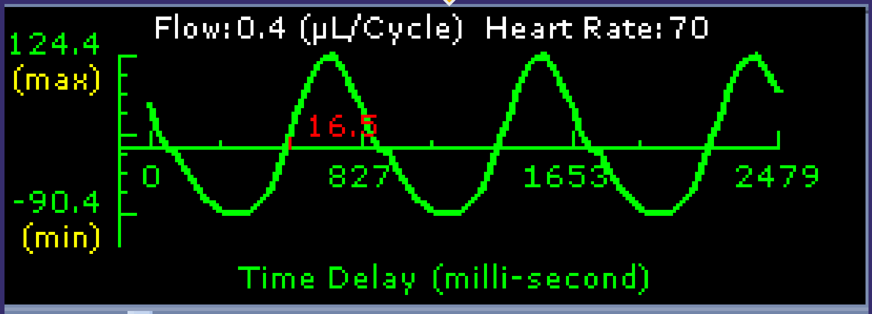

Hyperdynamic CSF flow Model

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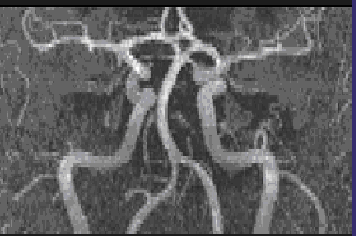

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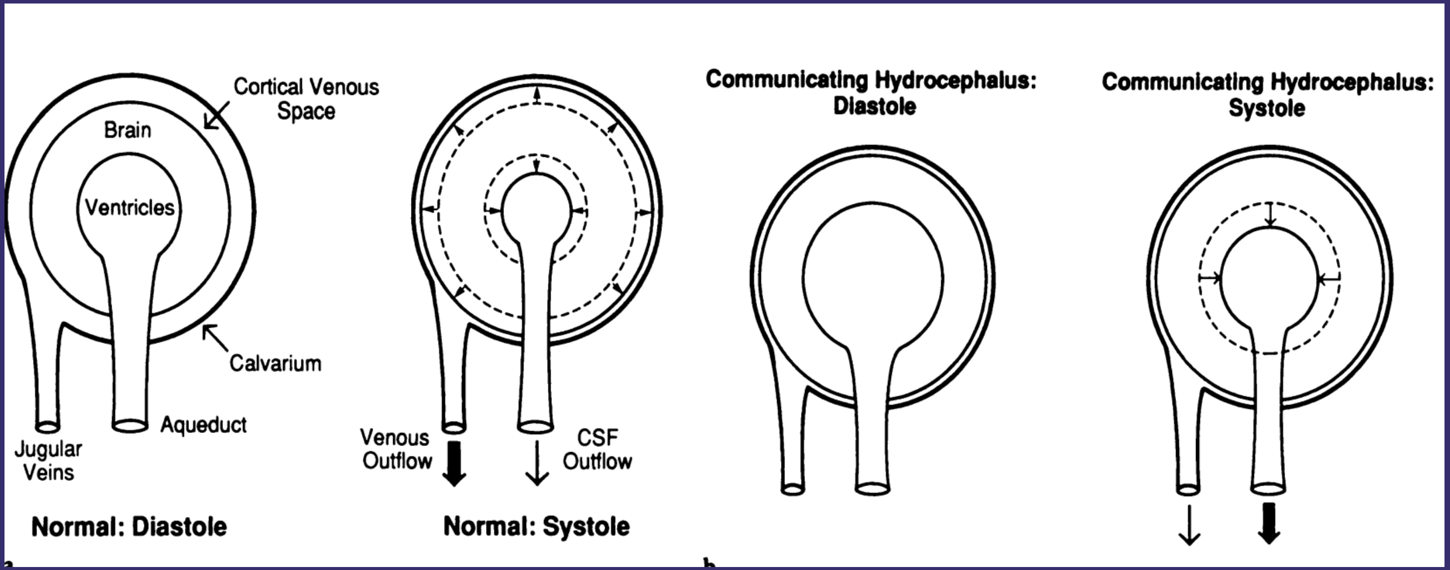

Copy of Figure 5 of Bradley, Radiology1991

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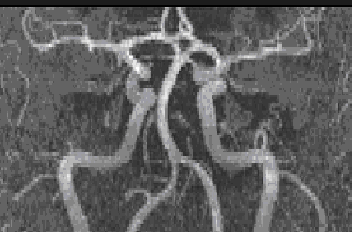
Cerebrospinal fluid pulse pressure and intracranial volume-pressure relationships

J Neurol Neurosurg Psychiatry. Aug 1979; 42(8): 687–700.

Traditional MRA:



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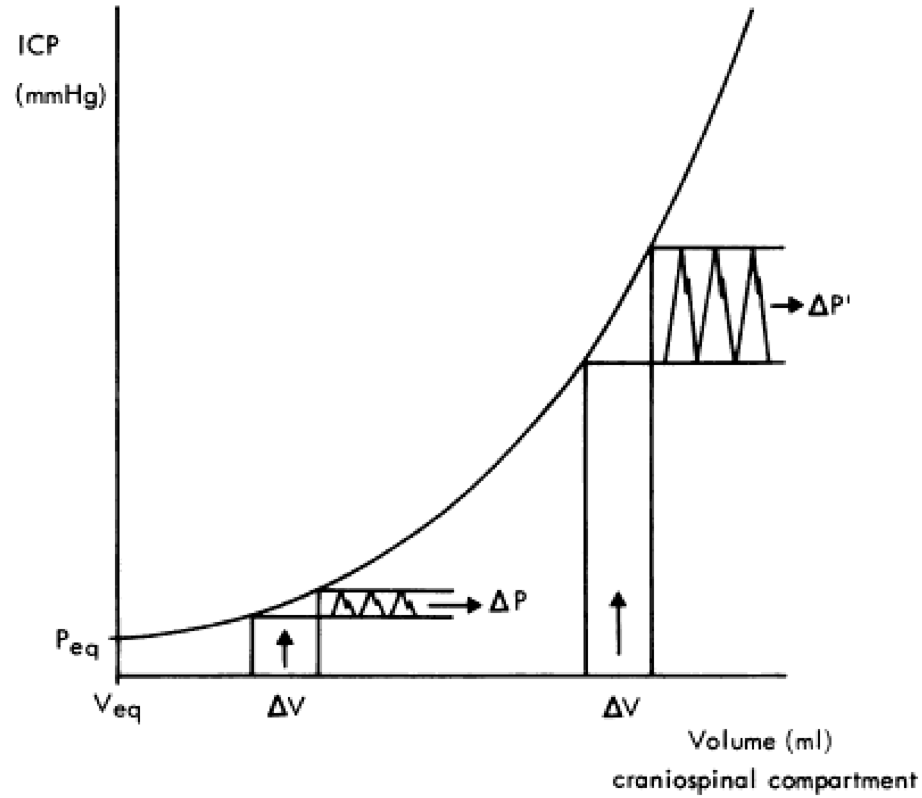

Fig. 1 *The CSF pulse pressure is a pressure response (ΔP) to the transient increase in intracranial blood volume during a cardiac cycle (ΔV). The exponential shape of the intracranial volume–pressure curve explains why the CSF pulse pressure increases with rising intracranial pressure (ICP). Abbreviations defined in Table 1.*

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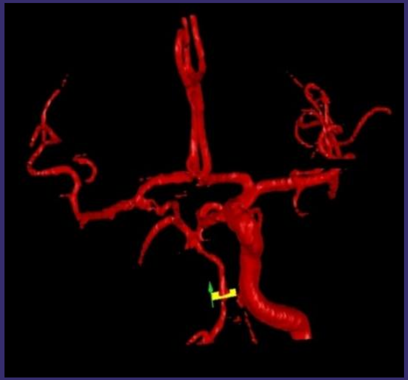
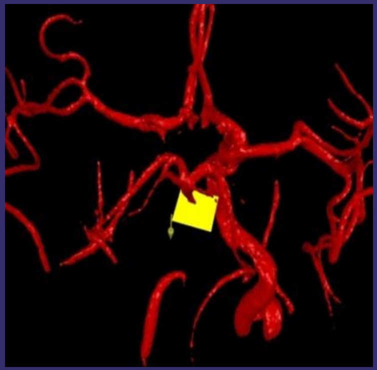
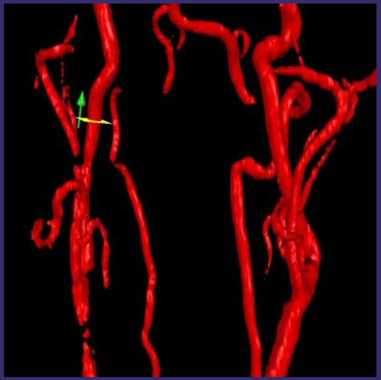
QMRA (NOVA) Applications



Basilar Stenosis



Basilar Oclussion



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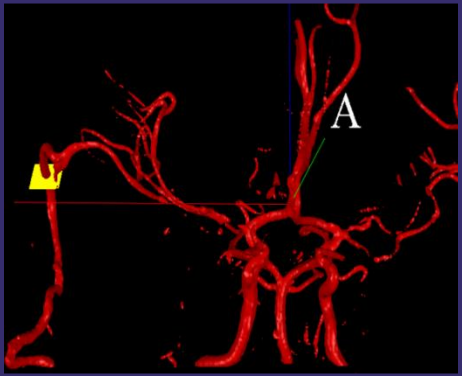


EC-IC Bypass

FDA approved

Accurate and non-invasive

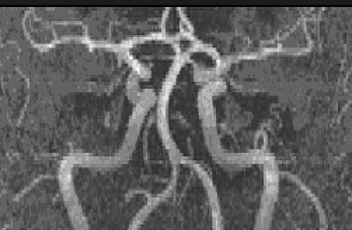
Improve the diagnosis and management of cerebrovascular patients

Easy to use and fit in the clinical workflow

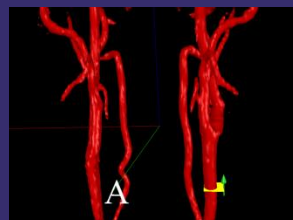
Thousands patients benefited each year around the world

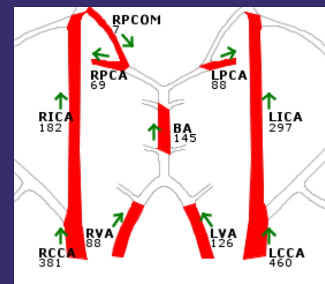
Combination of Artery, Vein and CSF → ICP ?

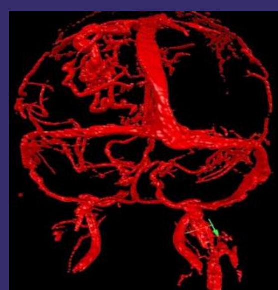
Traditional MRA:

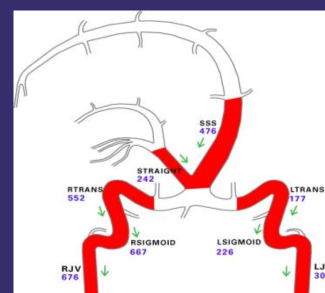


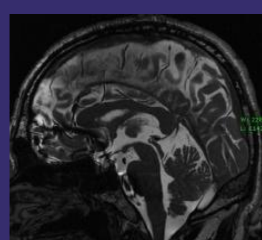
VasSol's Quantitative MRA™

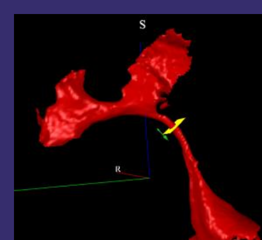












Intracranial Pressure (ICP)

VasSol nova

5. Summary - Quantitative Flow Assessment

- Review of important factors in PCMR imaging
- PCMR protocol parameters are optimized and validated for CSF flow measurement at the aqueduct
  - In vitro with phantom study
  - In vivo with volunteers
- Reproducibility of the stroke volume on different scanners
- Problems and future's work.

Traditional MRA:

VasSol's
Quantitative MRA™

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Traditional MRA:

VasSol's Quantitative MRA™

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Traditional MRA:

VasSol's Quantitative MRA™

Thank you!