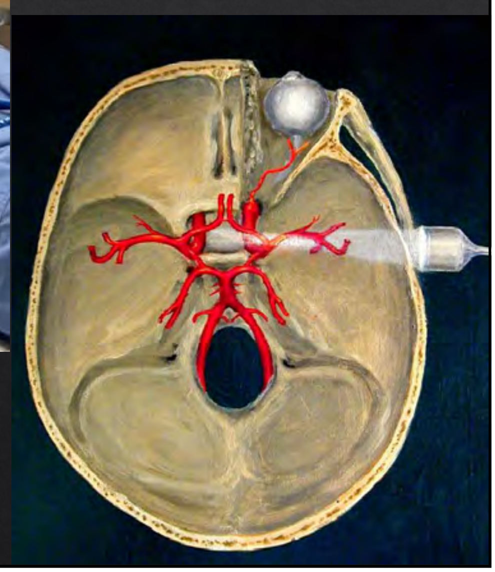
Cerebrovascular Intracranial: Transcranial Doppler

Sarah LaRose Michaud, RVT

Real-time measures of neurovascular function



What is TCD used for?

Common Tests:

- Stenosis and collateral flow
- Vasospasm monitoring
- Emboli Detection aka “HITS” Study
- Emboli Detection with Microbubble Injection
- Vasoreactivity testing with CO_2
- Monitoring Sickle Cell patients
- Brain Death

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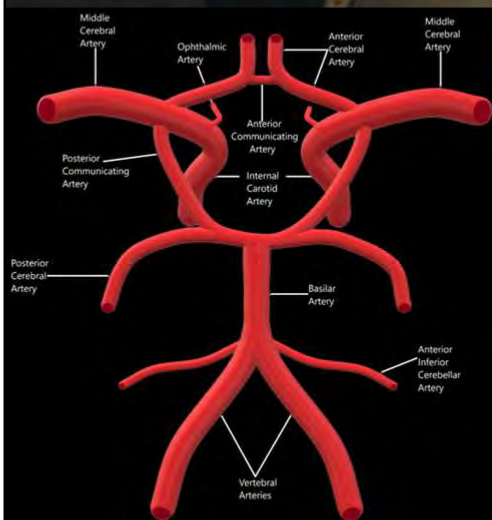
Ancillary Tests:

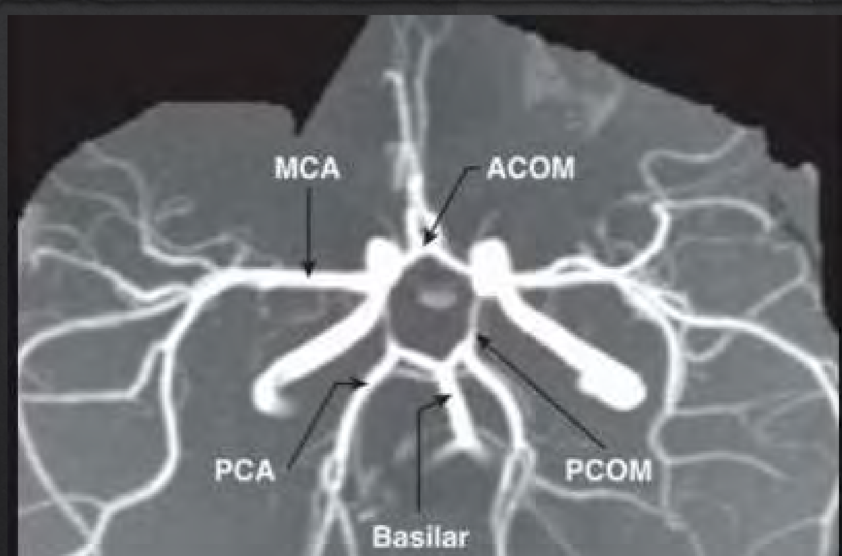
- Dynamic monitoring
  - Subclavian Steal, Head turning (such as for “Bow Hunter’s Syndrome”), Sit-to-Stand, etc
- Evaluation of Arteriovenous Malformations
- Intraoperative monitoring such as during carotid endarterectomy
- Thrombolysis in Acute Ischemic Stroke
- Autoregulation and Neurovascular coupling (research focus)



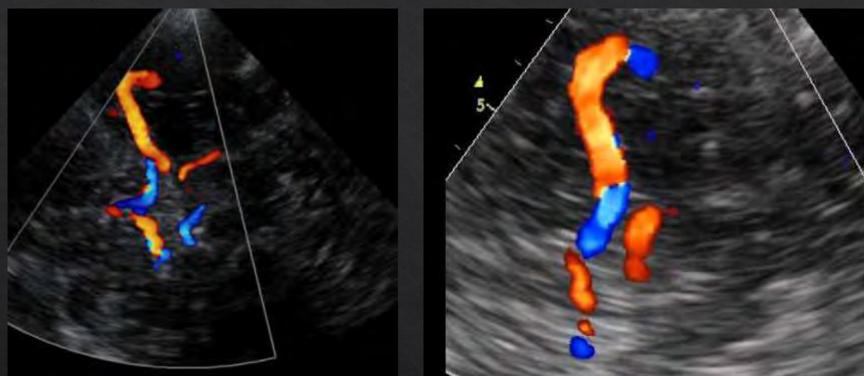
The Circle of Willis

An anastomotic ring at the base of the skull which connects the right and left hemispheres and the anterior and posterior circulations.

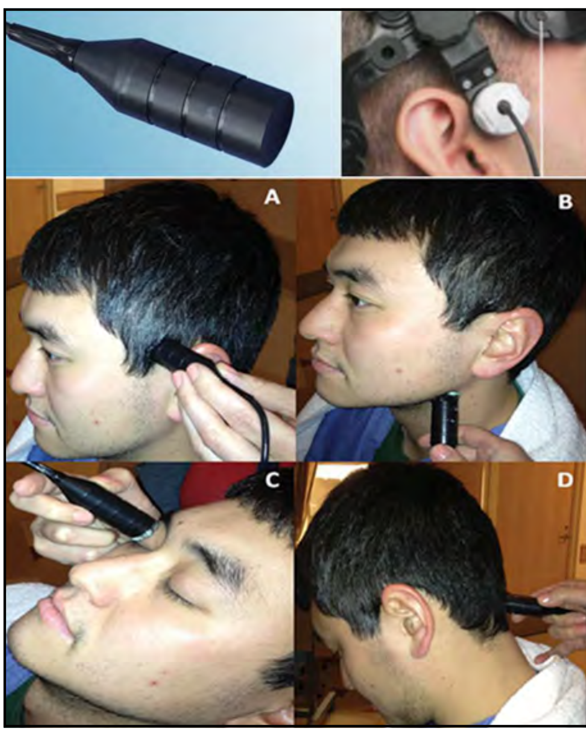
Only about 18-20% of people have a classic Circle



MRA

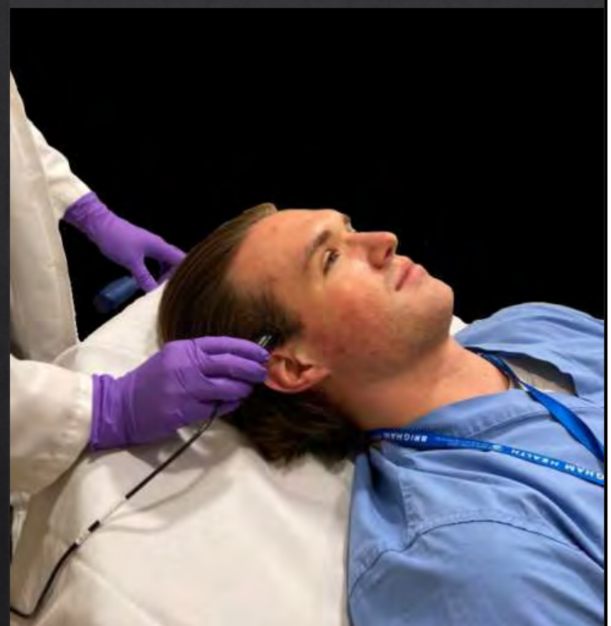


Transcranial Color-Coded Duplex Sonography (TCCS)



- 2 MHz Pulsed Wave Transducer
- Four "bone windows"
- <35% of energy penetrates the skull
- ~10-20% of the population does not have adequate temporal windows

Anchor your arm so you won't drift



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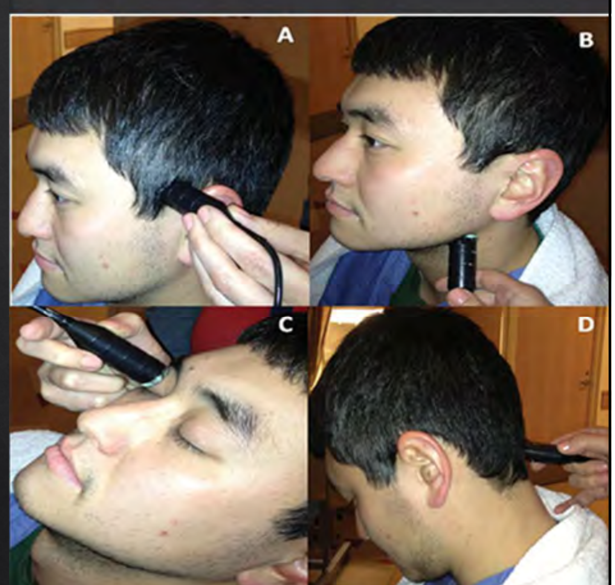


Fig. 2. Four acoustic windows commonly used in transcranial Doppler examination: transtemporal window (**A**), submandibular window (**B**), transorbital window (**C**), suboccipital window (**D**).

Four Insonation Windows

A – **Temporal:**
- MCA, ACA, PCA (terminal ICA, Acomm, Pcomms)

B – **Submandibular:**
- Distal extracranial ICA

C – **Orbital:**
- OA, Carotid siphon

D – **Suboccipital:**
- VA, Basilar

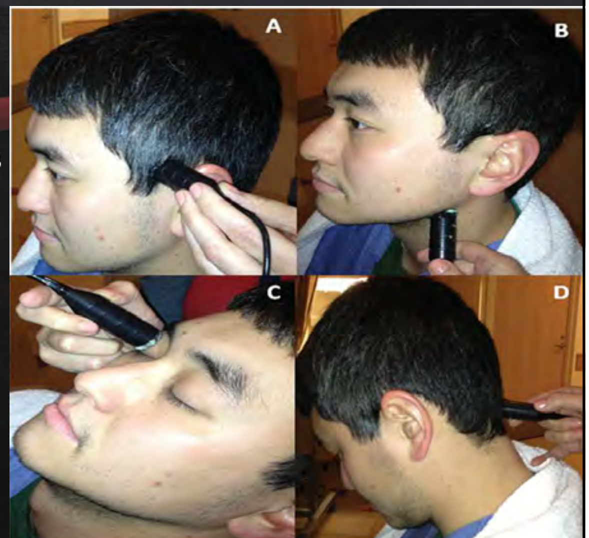
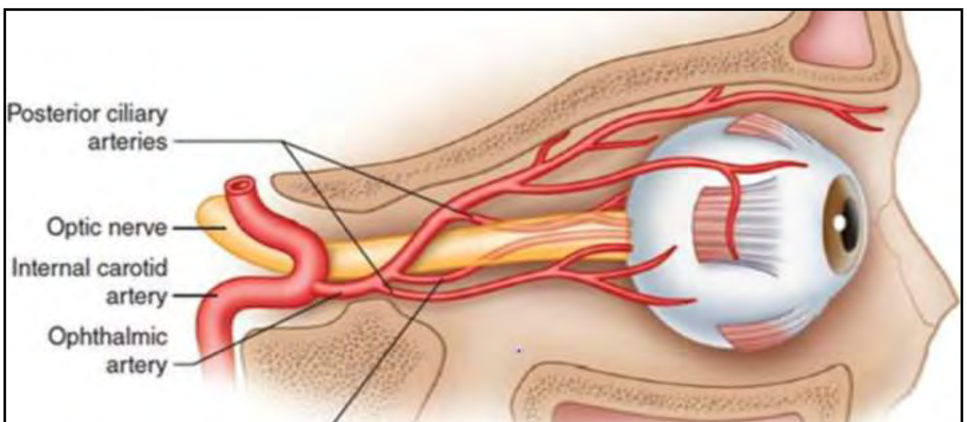
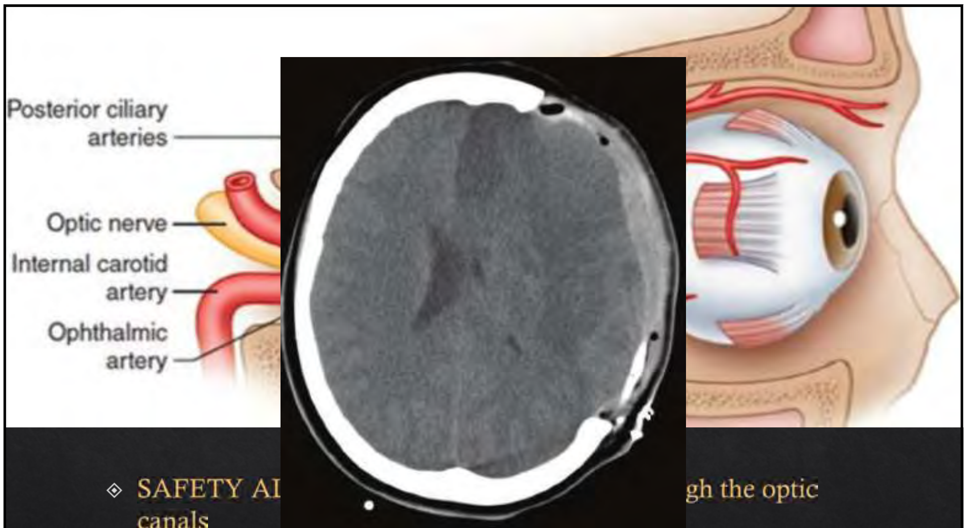


Fig. 2. Four acoustic windows commonly used in transcranial Doppler examination: transtemporal window (A), submandibular window (B), transorbital window (C), suboccipital window (D).



- SAFETY ALERT: The Orbital Window is through the optic canals

Machine power MUST be reduced to 10% of its total possible output



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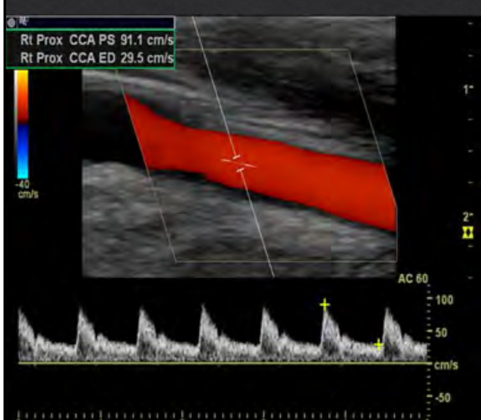
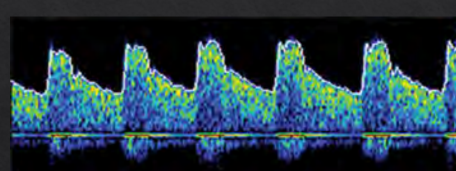
Importance of the Angle of Insonation

Assumed angle of incidence of 0-30°





The Doppler shift: the difference in frequency between the beam transmitted into tissue and the echo produced by reflection from the moving red blood cells.

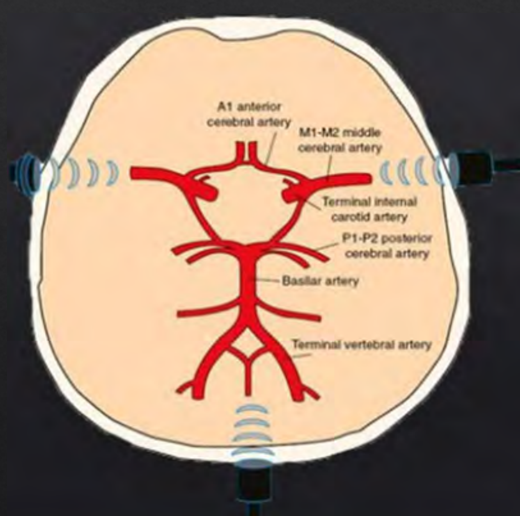
$$V = \frac{c \quad Df}{2\,F_0 \cos\theta}$$

- V = velocity of red blood cell
- C = ultrasound propagation speed in blood (approximately 1570 m/sec)
- Df = Doppler shift frequency (the received frequency)
- f0 = transmitted ultrasound beam frequency
- θ = angle between the ultrasound beam and the direction of red blood cell flow

- Frequency shift is proportional to both the velocity of the moving blood cells and the angle of incidence.

Reflector speed (cm/s) = $\frac{\text{Received frequency x propagation speed}}{\text{2 x transmitted frequency x Cos } \theta}$

- Cos 0° = 1
- Cos 90° = 0



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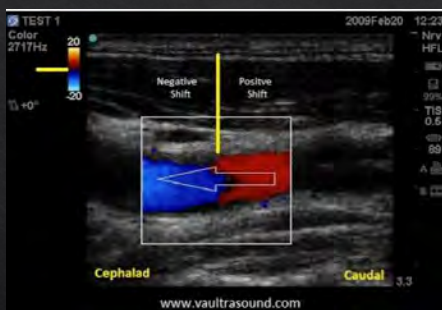
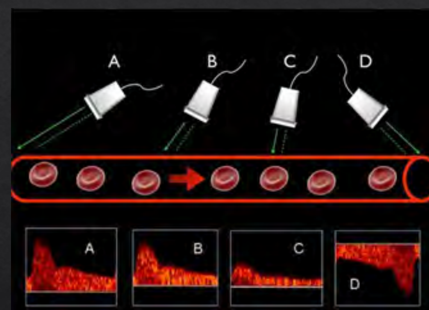
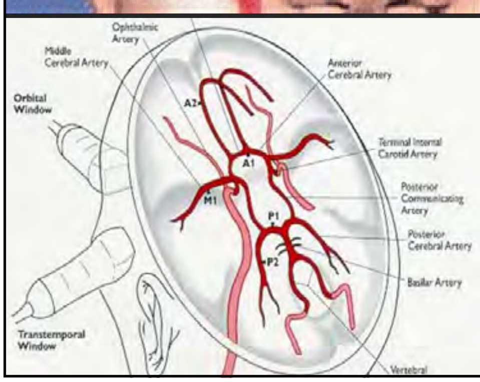




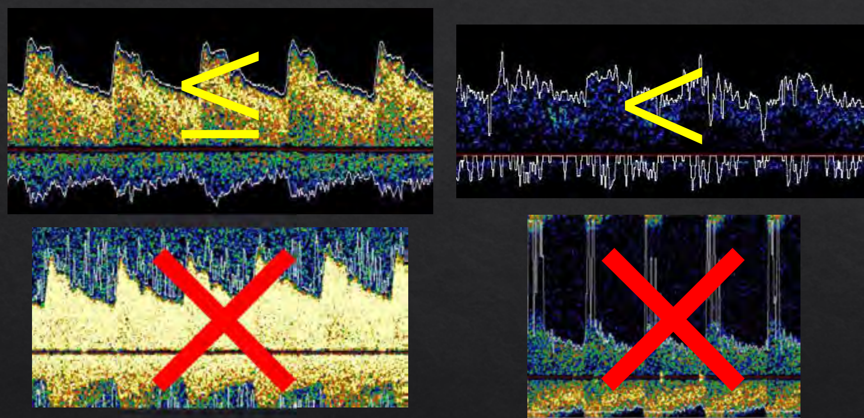
- Angle of insonation is assumed to be 0 - 30°. If > 30° you will lose flow velocity in your measurement. At 90° you will not see any Doppler shift.



Due to vessel orientation, some vessels are impossible to insonate

Saqqur M, Zygun D, Demchuk A. Role of transcranial Doppler in neurocritical care. Crit Care Med. 2007 May

Calculated velocity is always ≤ true velocity



High velocity measurements always warrant further investigation

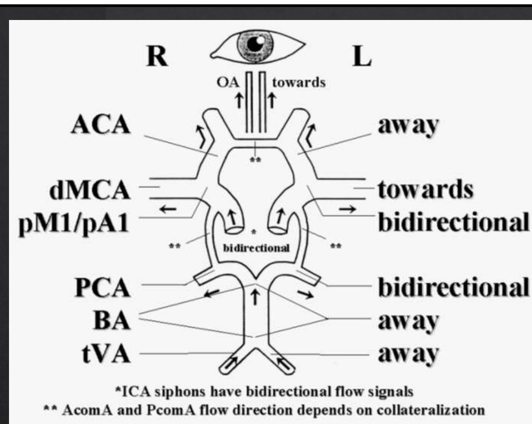
TCD Parameters

- Mean Flow Velocity (time-averaged mean)
  - (MFV = systolic + 2 x diastolic/3)
- Peak Systolic and End Diastolic Velocity
- Pulsatility Index (PI = Vsystole-Vdiastole/Vmean)
- Resistivity Index (RI = PSV-EDV/PSV)

Label	Depth	Mean	Max	PI	RI

Vessel Identification

- Insonation Window, probe angle
- Sample volume depth
- Direction of blood flow (toward or away from transducer)
- Expected flow velocity and pulsatility



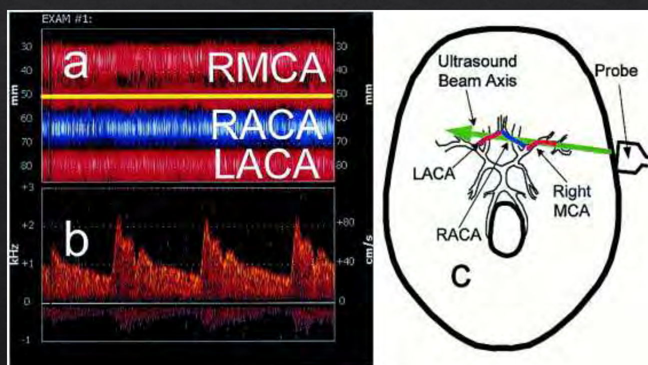
Vessel	Insonation Window	Flow Direction	Depth (mm)	Mean FV (cm/s)
Middle Cerebral (MCA)	temporal	Toward	30-60	40-70
Anterial Cerebral (ACA)	temporal	Away	60-75	35-60
Posterior Cerebral (PCA)	temporal	P1 toward P2 away	55-75	30-55
Terminal ICA	temporal	Toward	60-70	30-50
Distal Extracranial ICA	submandibular	Away	40-60	30-60
Ophthalmic (OA)	orbital	Toward	35-55	15-30
Carotid Siphon	orbital	Bidirectional	55-80	35-60
Vertebral (VA)	suboccipital	Away	60-75	25-50
Basilar (BA)	suboccipital	Away	75-120	30-55

Garami Z. 2017. Transcranial Doppler [PowerPoint Slides].

Vessel Identification

Vessel	Insonation Window	Flow Direction	Depth (mm)	Mean FV (cm/s)
Middle Cerebral (MCA)	temporal	Toward	30-60	55 ± 12
Anterial Cerebral (ACA)	temporal	Away	60-80	50 ± 11
Posterior Cerebral (PCA)	temporal	P1 toward P2 away	60-70	40 ± 10
Terminal ICA	temporal	Toward	55-65	39 ± 9
Ophthalmic (OA)	orbital	Toward	40-60	21 ± 5
Carotid Siphon	orbital	Bidirectional	60-80	47 ± 14
Vertebral (VA)	suboccipital	Away	60-90	38 ± 10
Basilar (BA)	suboccipital	Away	80-120	41 ± 10

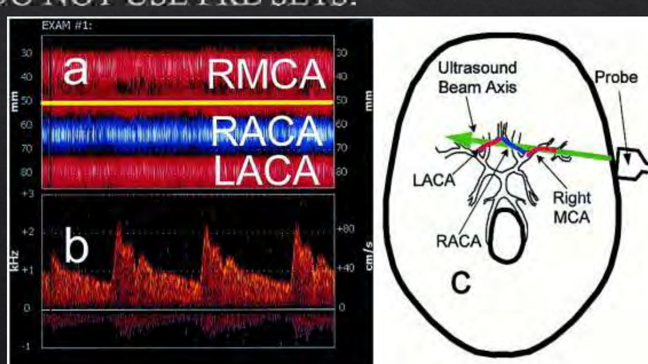
Vessel Identification - Continued



Picture from: Moehring M, Spencer M. Power M-mode Doppler (PMD) for observing cerebral blood flow and tracking emboli. Ultrasound in Medicine and Biology 2002. 28(1):49-57.

Vessel Identification - Continued

- Ability to trace the course of the artery
  - Take pictures in small 2-3mm increments
- Relation of one artery to another (find MCA and then use it as your "Home Base")
- DO NOT USE PRE-SETS!



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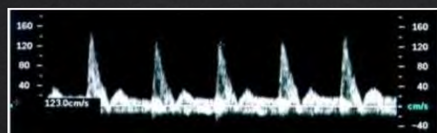
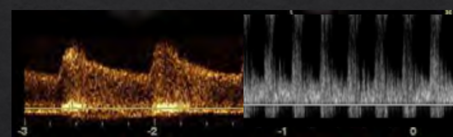
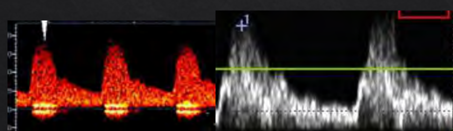


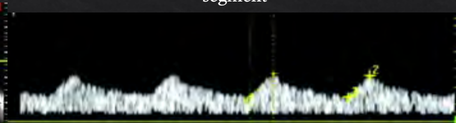
Proximal evidence of increased resistance distally



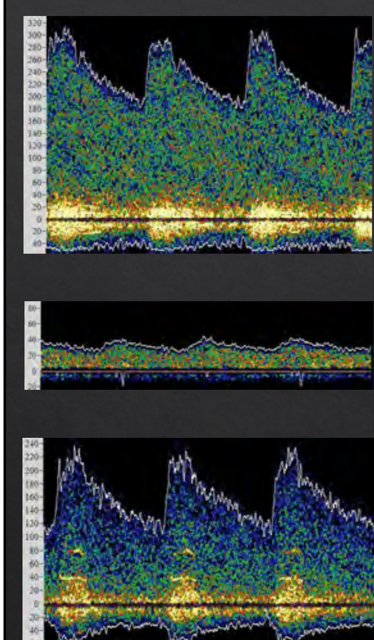
Focal increases in flow velocity within a stenotic segment



Stenotic and Post-stenotic turbulence



Blunted/tardus parvus post-stenotic slowing



Determining Degree of Stenosis

- acceleration of flow velocity through the stenotic segment
- decrease in velocity distal to the stenotic segment (post-stenotic dilation)
- disturbances in flow (i.e., turbulence and murmurs).
- side-to-side differences in mean flow velocity

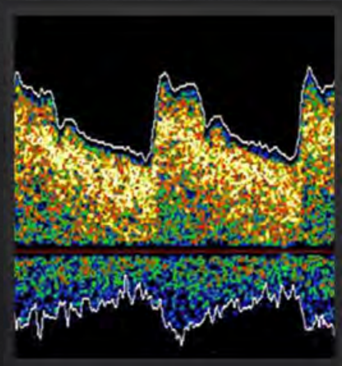
Stenotic Flow Velocity

Vessel	Mean FV	Peak
MCA	>100	>160
ACA	>90	>140
PCA	>55	>85
ICA (siphon)	>90	>135
VA	>60	>90
BA	>65	>100

Degree of Stenosis (in MCA)

	Normal	Mild	Moderate	Severe
Mean	<80	<120	120-140	141-200
Peak	<140	140-209	210-280	>280
MCA/ICA	<3.0	≤ 3.0	3.0 - 5.9	≥ 6.0

Typical Intracranial Hemodynamics



- The brain uses 20-25% of the total blood flow in the body.
- dilated vascular bed
- low resistance waveforms,

  low pulsatility (PI 0.6-1.1)

Pulsatility Index (PI= Vsystole-Vdiastole/Vmean)

- The pulsatility index is the difference between systolic flow velocity and diastolic flow velocity, divided by the time-averaged mean, and is an **estimation of vascular resistance distal to the site of insonation**

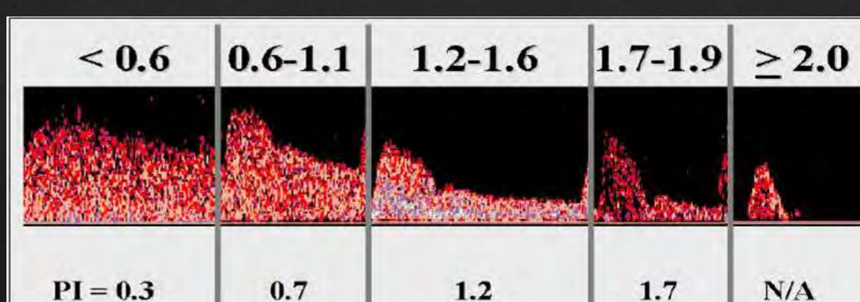
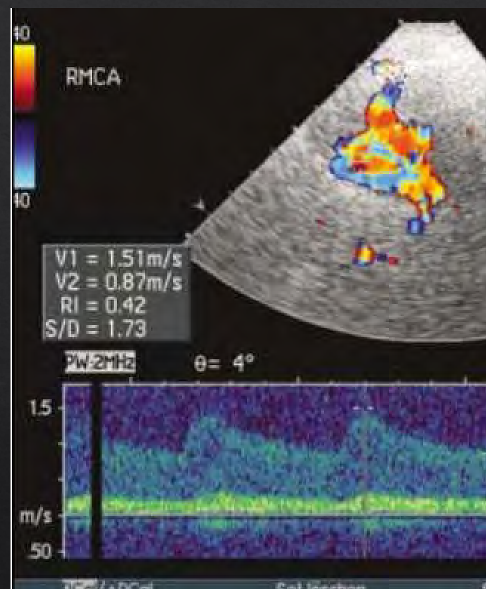


Image from https://slideplayer.com/slide/4898934/ University of Oklahoma Ryan Hakimi **2015 Introduction to Carotid and Transcranial Doppler Ultrasound**

Arteriovenous Malformations and PI

An abnormal tangle of blood vessels connecting arteries and veins, which disrupts normal blood flow and oxygen circulation.

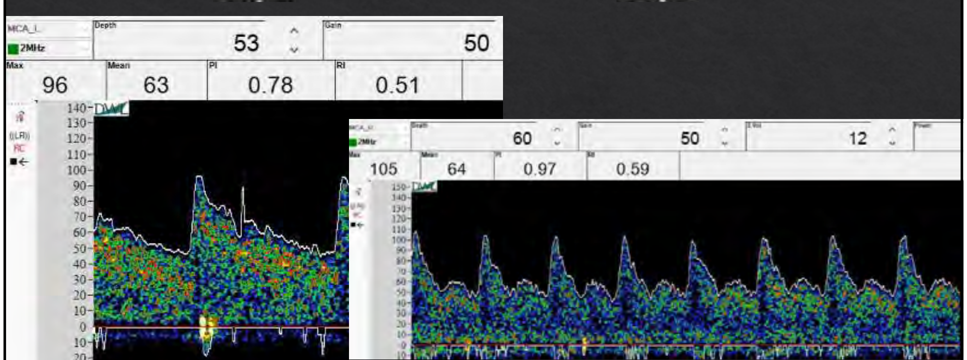
- High velocity, low pulsatility, low resistance
- PI < 0.5



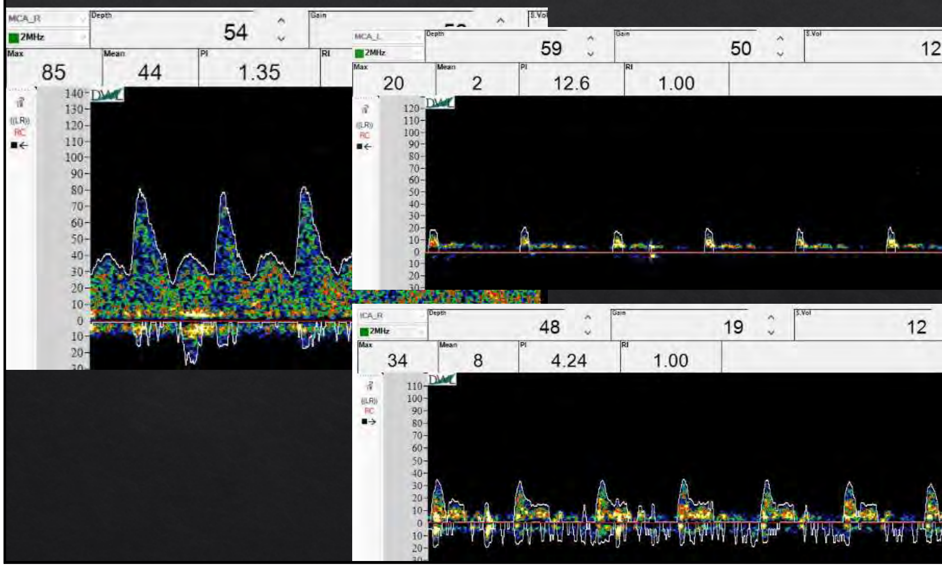
Bartels, E. (2005), Evaluation of Arteriovenous Malformations (AVMs) With Transcranial Color-Coded Duplex Sonography.

Case Study – PI and changes in Waveform shape

Day 0 | Day 6

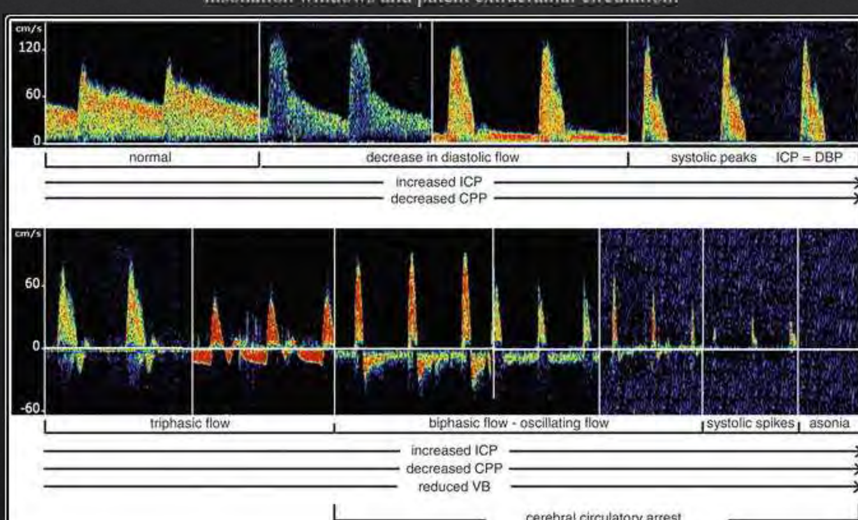


Day 7 Day 8



Brain Death

Small systolic peaks in early systole without diastolic flow or reverberating flow, indicating very high vascular resistance associated with greatly increased intracranial pressure are criteria supportive of the clinical diagnosis of brain death in a patient with adequate insonation windows and patent extracranial circulation.

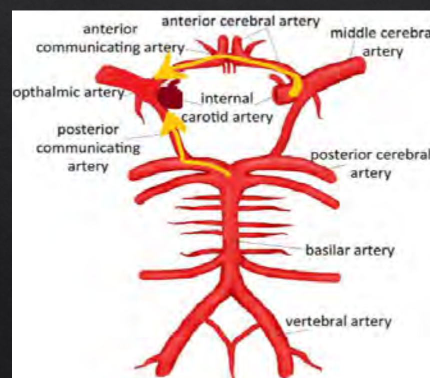


Sawicki M., Wojczal J., Birkenfeld B., Cyrylowski L. (2014) Brain Death Imaging. In: Saba L., Raz E. (eds) Neurovascular Imaging.

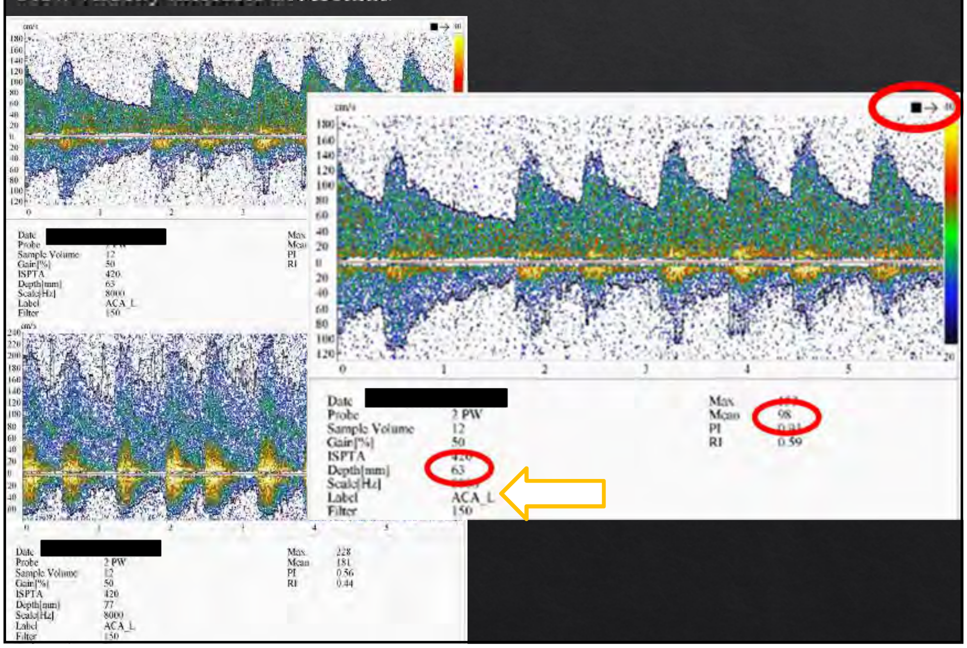
Case Study – Stenosis and Collateral Flow in an 81F with RICA Dissection

- Carotid exam: diminished flow in the RICA with absent diastolic flow, suggesting a more distal occlusion/near occlusion.

- TCD exam: possible cross-collateralization from the Left to the Right through an active Acomm and posterior-to-anterior collateralization through an active Right Pcomm.



Elevated flow velocity in the Left ACA.
Flow velocity increases in Acomm.



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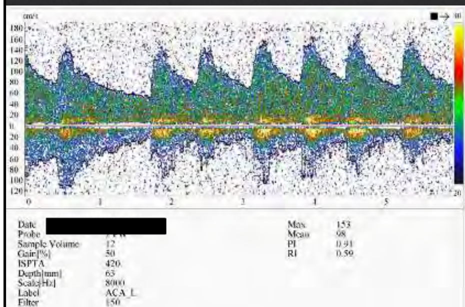
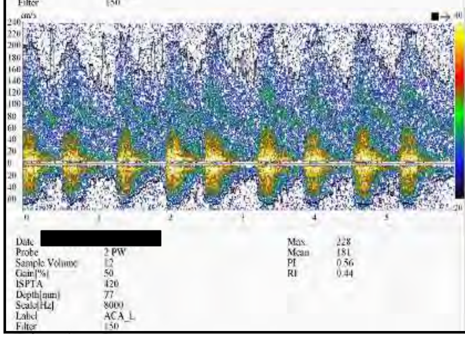
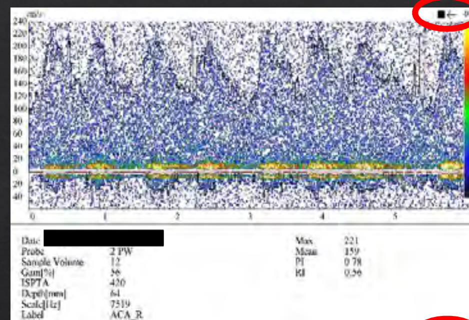
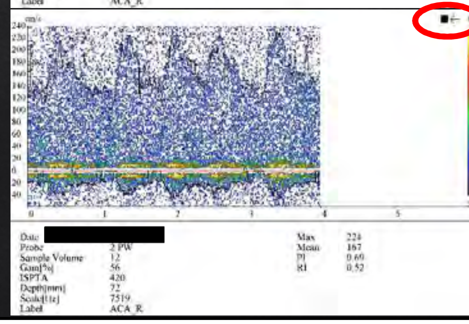


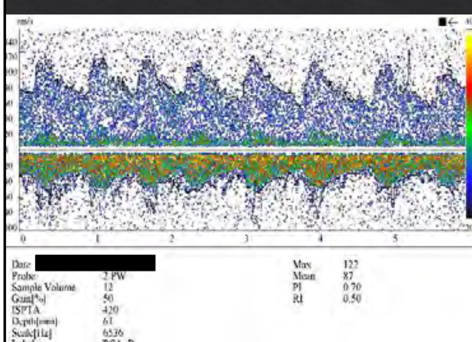


Reversed flow direction and elevated velocity in the Right ACA

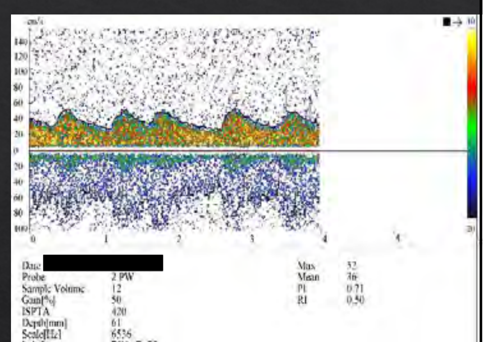




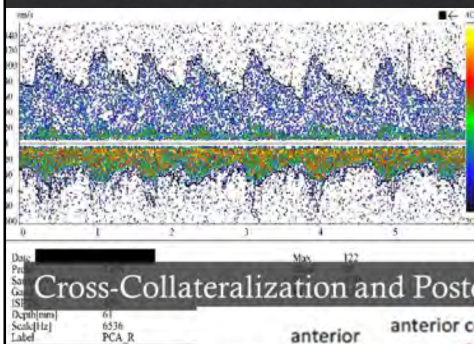
Elevated flow velocity in the Right PCA P1/Pcomm

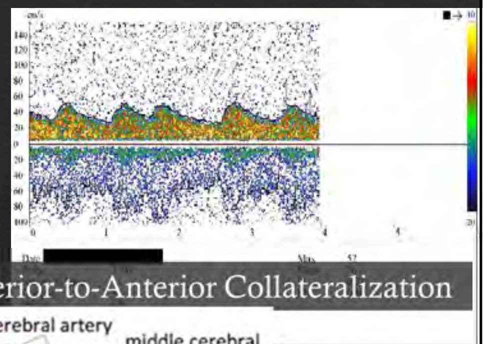


Normal flow velocity in the Right PCA P2 segment

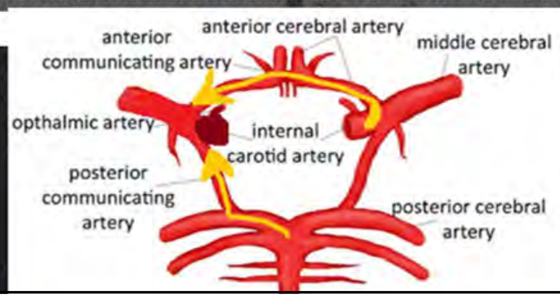


Elevated flow velocity in the Right PCA P1/Pcomm | Normal flow velocity in the Right PCA P2 segment



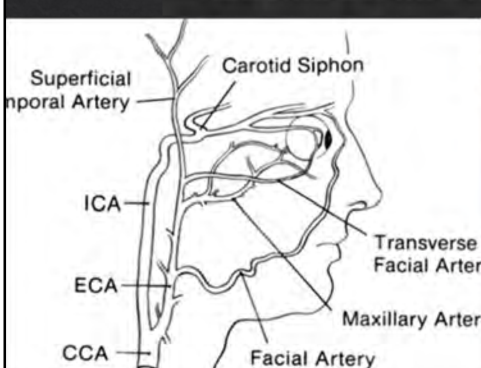


Cross-Collateralization and Posterior-to-Anterior Collateralization



Case Study – Stenosis and Collateral Flow with an Occluded ICA

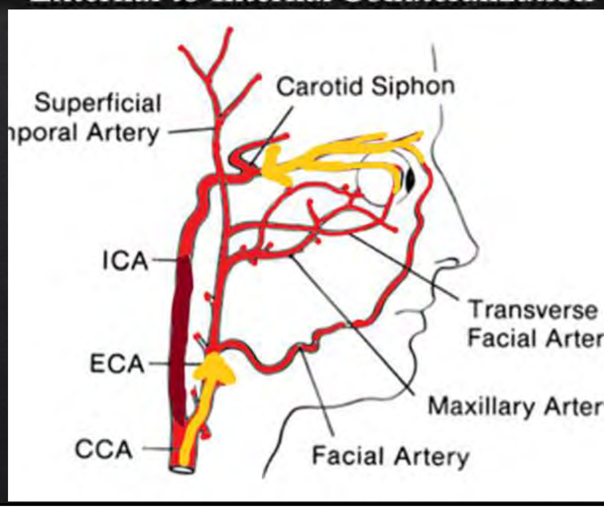
External-to-Internal Collateralization



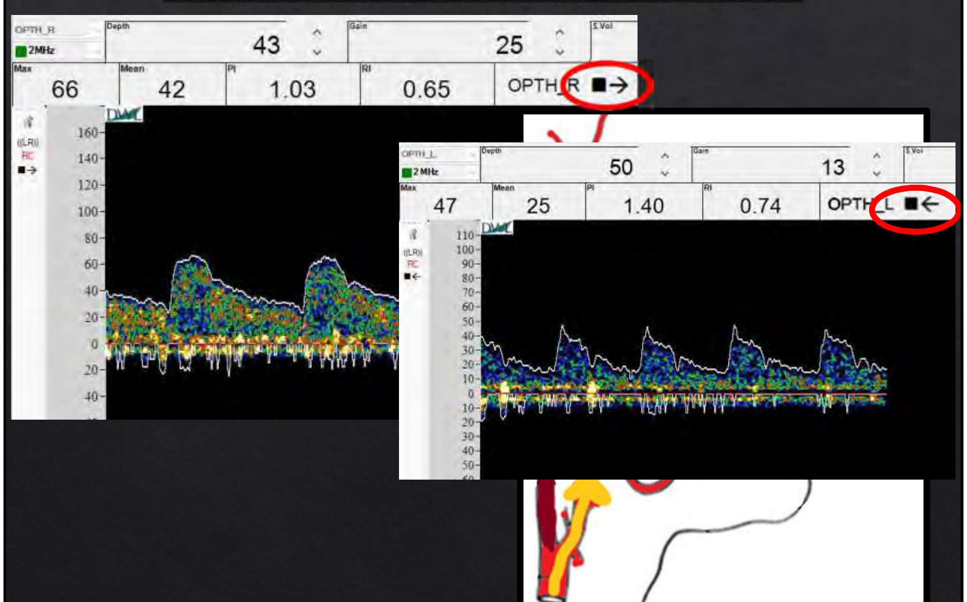
Images from: American Society of Radiologic Technologists

Case Study – Stenosis and Collateral Flow with an Occluded ICA

External-to-Internal Collateralization

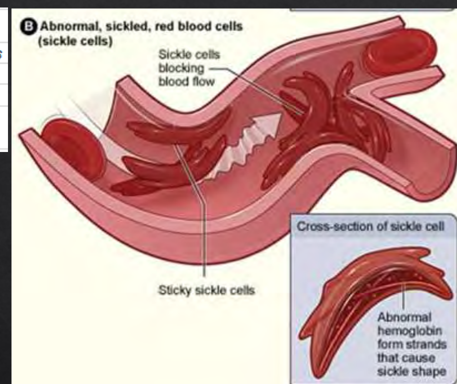


External-to-Internal Collateralization



Sickle Cell Anemia

STOP Study for Sickle Cell Disease			
Note: All values are Mean Flow Velocity (MFV) measurements			
Vessel	Normal	Conditional	Abnormal
distal intracranial ICA & MCA	<170	170-199	>200



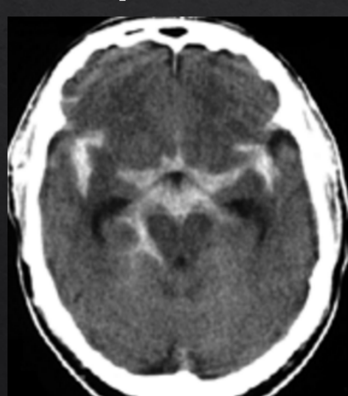
Other abnormal findings include:

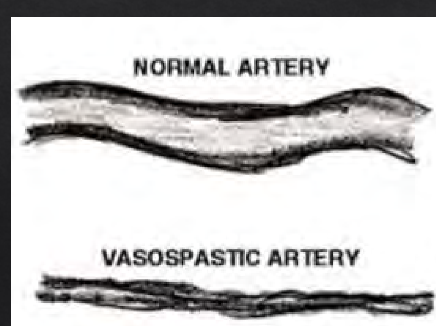
- low FV in MCA (<70cm/s)
- MCA ratio <0.5
- ipsilateral ACA/MCA ratio >1.2
- dampened waveform, turbulence, and musical harmonic murmurs

The National Heart, Lung, and Blood Institute (NHLBI)

Vasospasm and SAH

- SAH is usually from spontaneous aneurysm burst and subsequent bleeding into the subarachnoid space around the Circle of Willis
- 2/3 of aneurysmal SAH develop vasospasm, usually occurring between days 4-10 after bleed
- Daily vasospasm checks of patients post SAH are most common test conducted in most hospital TCD labs





Angiogram
(the Gold Standard)

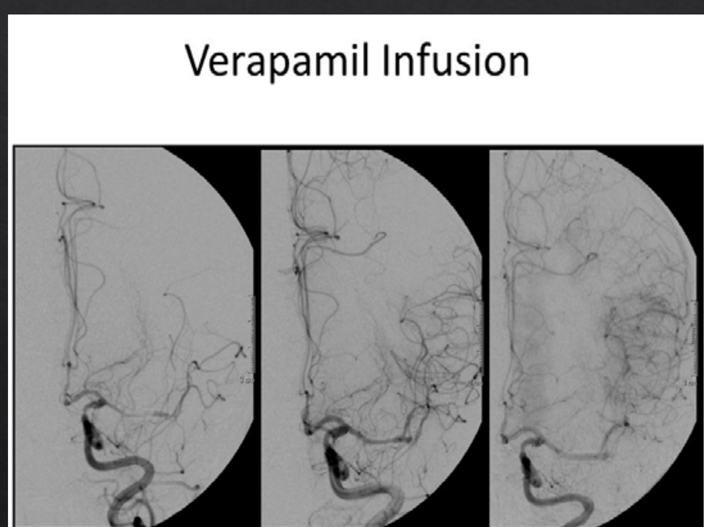
Figure 7.

Cerebral angiogram demonstrates vasospasm.
(A) Vasospasm of the basilar artery (arrow), **(B)** the right vertebral artery (arrow) and **(C)** branches of the left posterior cerebral artery (arrow).
Reproduced with permission from the Oxford University Press, NY, USA.[219]

Computed Tomography Angiography (CTA)

Severe spasm can lead to ischemic stroke.

Intra-Arterial –Spasmolysis: direct infusion of a vasodilator to the site of spasm



TCD Diagnosis of Vasospasm

- Increases in Mean Flow Velocity, evidence of turbulence, Lindegaard Ratio

TCD Criteria for Vasospasm

Note: All values are Mean Flow Velocity (MFV) measurements

Vessel	Possible	Probable	Presumed/Definite
ICA (intracranial)	80	125	200
MCA	120	150	>200
ACA	100	130	>150
PCA	80	120	>160
VA	60	80	105
BA	75	85	140

- Lindegaard Ratio – vasospasm vs hyperemia

LR = highest MFV in MCA/ highest MFV in EICA

LR < 3.0 indicates NO vasospasm
LR > 3.0 – 6.0 indicates mild vasospasm
LR > 6.0 indicates severe vasospasm

- Daily TCD exams to monitor for development of vasospasm
- highest **mean flow velocities** written in a flow chart for the care team to easily track changes from day to day.
- Major changes from one day to the next prompt the care team to send patients for subsequent tests: CTA and Angiography.

Daily TCD Monitoring: **maximal Mean Flow Velocities (MFV) and Lindegaard Ratios (LR=MFV MCA / MFV EICA)**

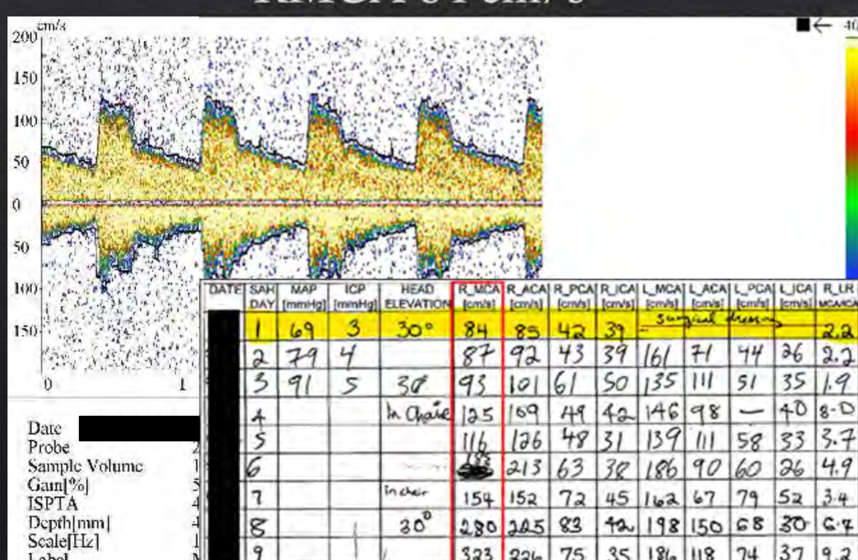
These values are preliminary. The final report will be available in EPIC and the raw TCD waveforms can be viewed in Centricity.

DATE	SAH DAY	MAP [mmHg]	ICP [mmHg]	HEAD ELEVATION	R_MCA [cm/s]	R_ACA [cm/s]	R_PCA [cm/s]	R_ICA [cm/s]	L_MCA [cm/s]	L_ACA [cm/s]	L_PCA [cm/s]	L_ICA [cm/s]	R_LR MCA/ICA	L_LR MCA/ICA	examiner

Case Study – SAH and Vasospasm Progression

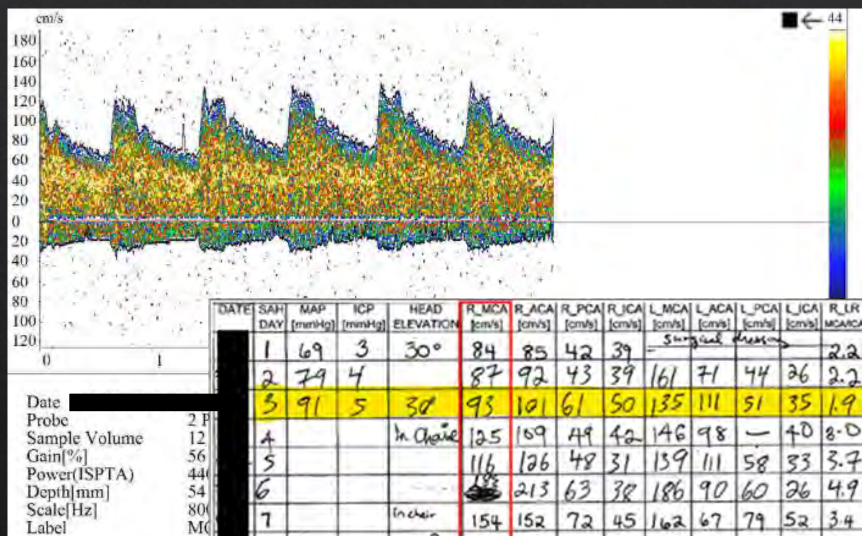
- 53M was doing yard work when he suddenly slumped to the ground and became unresponsive.
- Smoker, no prior medical history, but positive family history of ruptured cerebral aneurysms
- Found to have SAH from a ruptured 9mm LMCA aneurysm
- EVD was placed and he had craniotomy for clipping of the burst aneurysm, plus 2 other aneurysms that were found incidentally
- Serial TCDs showed progressively increasing MFVs.

Post Bleed Day 1: highest MFV in RMCA 84 cm/s



DATE	SAH DAY	MAP [mmHg]	ICP [mmHg]	HEAD ELEVATION	R_MCA [cm/s]	R_ACA [cm/s]	R_PCA [cm/s]	R_ICA [cm/s]	L_MCA [cm/s]	L_ACA [cm/s]	L_PCA [cm/s]	L_ICA [cm/s]	R_LR MCA/ICA	L_LR MCA/ICA
[redacted]	1	69	3	30°	84	85	42	39	surgical dressing →				2.2	/
	2	79	4		87	92	43	39	161	71	44	26	2.2	6.2
	3	91	5	30°	93	101	61	50	135	111	51	35	1.9	3.9
	4			In Chair	125	169	49	42	146	98	—	40	8.0	3.7
	5				116	126	48	31	139	111	58	33	3.7	4.2
	6				183	213	63	38	186	90	60	26	4.9	7.2
	7			In chair	154	152	72	45	162	67	79	52	3.4	3.1
	8			30°	280	225	83	42	198	150	68	30	6.7	6.6
	9				323	226	75	35	186	118	74	37	9.2	5.0
	10		6		306	239	109	50	183	144	112	44	6.1	4.2

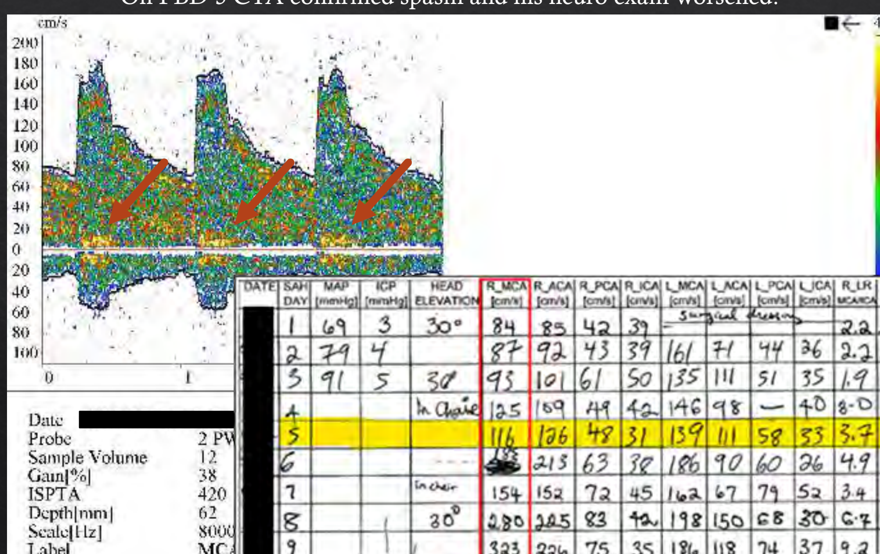
PBD 3: RMCA 93 cm/s



DATE	SAH DAY	MAP [mmHg]	ICP [mmHg]	HEAD ELEVATION	R_MCA [cm/s]	R_ACA [cm/s]	R_PCA [cm/s]	R_ICA [cm/s]	L_MCA [cm/s]	L_ACA [cm/s]	L_PCA [cm/s]	L_ICA [cm/s]	R_LR MCA/ICA	L_LR MCA/ICA
[redacted]	1	69	3	30°	84	85	42	39	Surgical dressing				2.2	
[redacted]	2	79	4		87	92	43	39	161	71	44	26	2.2	6.2
[redacted]	3	91	5	30°	93	101	61	50	135	111	51	35	1.9	3.9
[redacted]	4			In Chair	125	109	49	42	146	98	—	40	3.0	3.7
[redacted]	5				116	126	48	31	139	111	58	33	3.7	4.2
[redacted]	6			---	[illegible]	213	63	38	186	90	60	26	4.9	7.2
[redacted]	7			In chair	154	152	72	45	162	67	79	52	3.4	3.1
[redacted]	8			30°	280	225	83	42	198	150	68	30	6.7	6.6
[redacted]	9				323	226	75	35	186	118	74	37	9.2	5.0
[redacted]	10		6		306	239	109	50	183	144	112	44	6.1	4.2

PBD 5: RMCA 116 cm/s

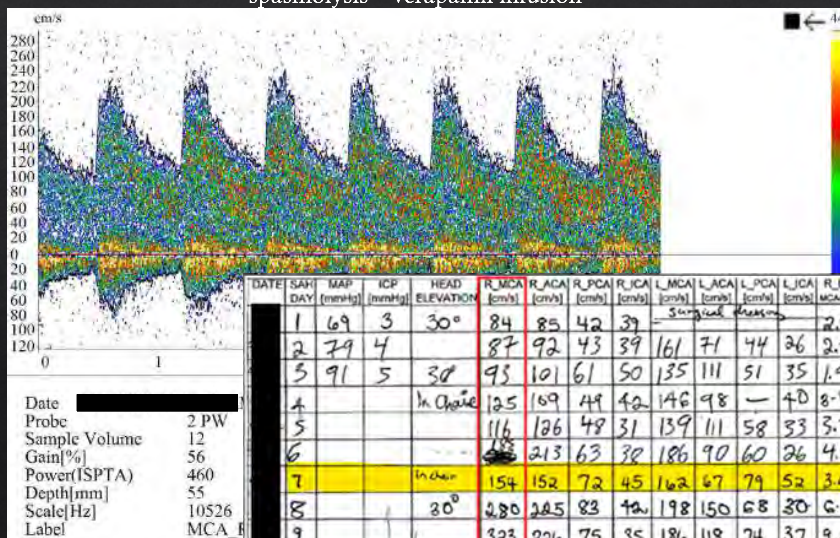
On PBD 5 CTA confirmed spasm and his neuro exam worsened.



DATE	SAH DAY	MAP [mmHg]	ICP [mmHg]	HEAD ELEVATION	R_MCA [cm/s]	R_ACA [cm/s]	R_PCA [cm/s]	R_ICA [cm/s]	L_MCA [cm/s]	L_ACA [cm/s]	L_PCA [cm/s]	L_ICA [cm/s]	R_LR MCA/ICA	L_LR MCA/ICA
[redacted]	1	69	3	30°	84	85	42	39	Surgical dressing				2.2	
[redacted]	2	79	4		87	92	43	39	161	71	44	26	2.2	6.2
[redacted]	3	91	5	30°	93	101	61	50	135	111	51	35	1.9	3.9
[redacted]	4			In Chair	125	109	49	42	146	98	—	40	3.0	3.7
[redacted]	5				116	126	48	31	139	111	58	33	3.7	4.2
[redacted]	6			---	[illegible]	213	63	38	186	90	60	26	4.9	7.2
[redacted]	7			In chair	154	152	72	45	162	67	79	52	3.4	3.1
[redacted]	8			30°	280	225	83	42	198	150	68	30	6.7	6.6
[redacted]	9				323	226	75	35	186	118	74	37	9.2	5.0
[redacted]	10		6		306	239	109	50	183	144	112	44	6.1	4.2

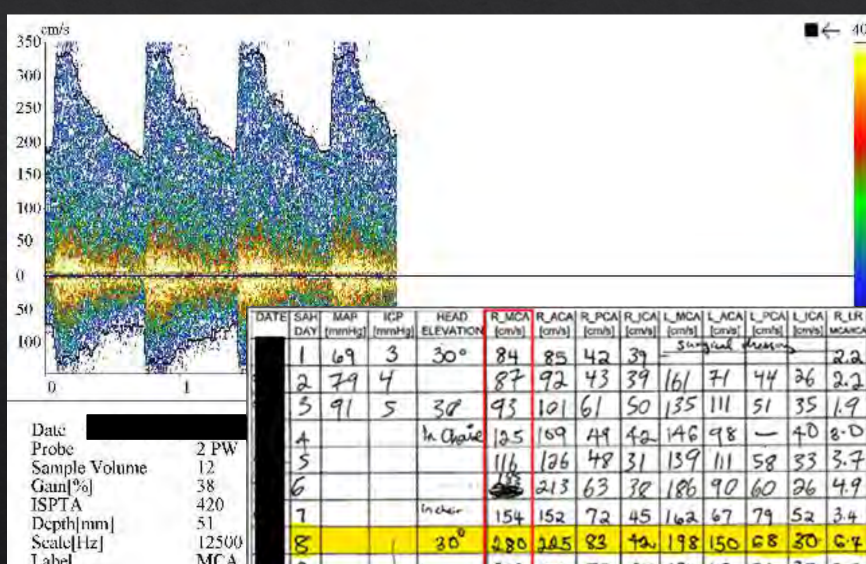
PBD 7: RMCA 154 cm/s

Angio on PBD 7 also confirmed spasm and he was treated with direct IA spasmolysis – verapamil infusion



DATE	SAH DAY	MAP [mmHg]	ICP [mmHg]	HEAD ELEVATION	R_MCA [cm/s]	R_ACA [cm/s]	R_PCA [cm/s]	R_ICA [cm/s]	L_MCA [cm/s]	L_ACA [cm/s]	L_PCA [cm/s]	L_ICA [cm/s]	R_LR MCA/ICA	L_LR MCA/ICA
[redacted]	1	69	3	30°	84	85	42	39	surgical dressing				2.2	
	2	79	4		87	92	43	39	161	71	44	26	2.2	6.2
	3	91	5	30°	93	101	61	50	135	111	51	35	1.9	3.9
	4			In Chair	125	109	49	42	146	98	—	40	8.0	3.7
	5				116	126	48	31	139	111	58	33	3.7	4.2
	6				[illegible]	213	63	32	186	90	60	26	4.9	7.2
	7			In chair	154	152	72	45	162	67	79	52	3.4	3.1
	8			30°	280	225	83	42	198	150	68	30	6.7	6.6
	9				323	226	75	35	186	118	74	37	9.2	5.0
	10		6		306	239	109	50	183	144	112	44	6.1	4.2

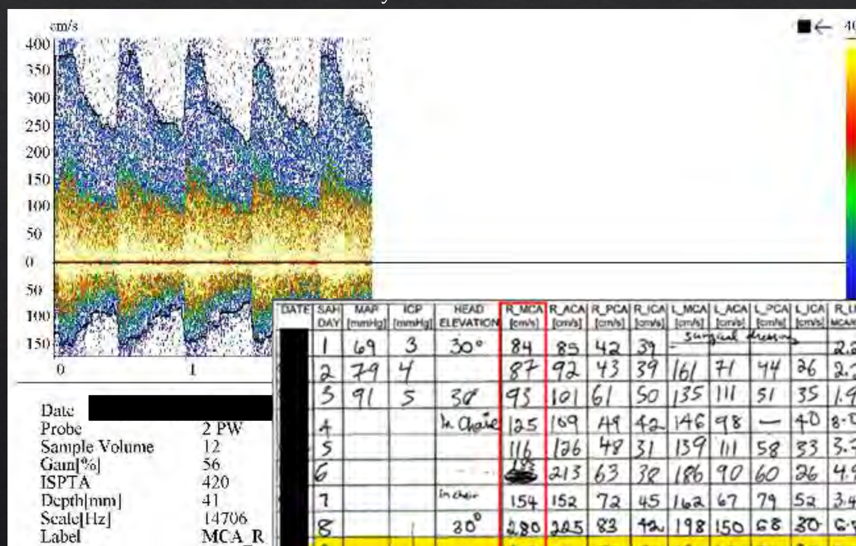
PBD 8: RMCA 280 cm/s



DATE	SAH DAY	MAP [mmHg]	ICP [mmHg]	HEAD ELEVATION	R_MCA [cm/s]	R_ACA [cm/s]	R_PCA [cm/s]	R_ICA [cm/s]	L_MCA [cm/s]	L_ACA [cm/s]	L_PCA [cm/s]	L_ICA [cm/s]	R_LR MCA/ICA	L_LR MCA/ICA
[redacted]	1	69	3	30°	84	85	42	39	surgical dressing				2.2	
	2	79	4		87	92	43	39	161	71	44	26	2.2	6.2
	3	91	5	30°	93	101	61	50	135	111	51	35	1.9	3.9
	4			In Chair	125	109	49	42	146	98	—	40	8.0	3.7
	5				116	126	48	31	139	111	58	33	3.7	4.2
	6				[illegible]	213	63	32	186	90	60	26	4.9	7.2
	7			In chair	154	152	72	45	162	67	79	52	3.4	3.1
	8			30°	280	225	83	42	198	150	68	30	6.7	6.6
	9				323	226	75	35	186	118	74	37	9.2	5.0
	10		6		306	239	109	50	183	144	112	44	6.1	4.2

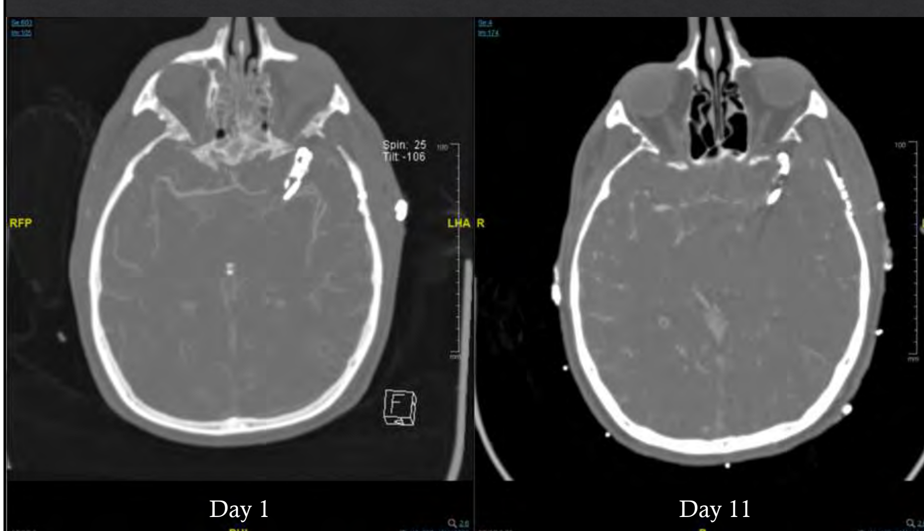
PBD 9: RMCA 323 cm/s

Post-bleed day 9 – scaled maxed out



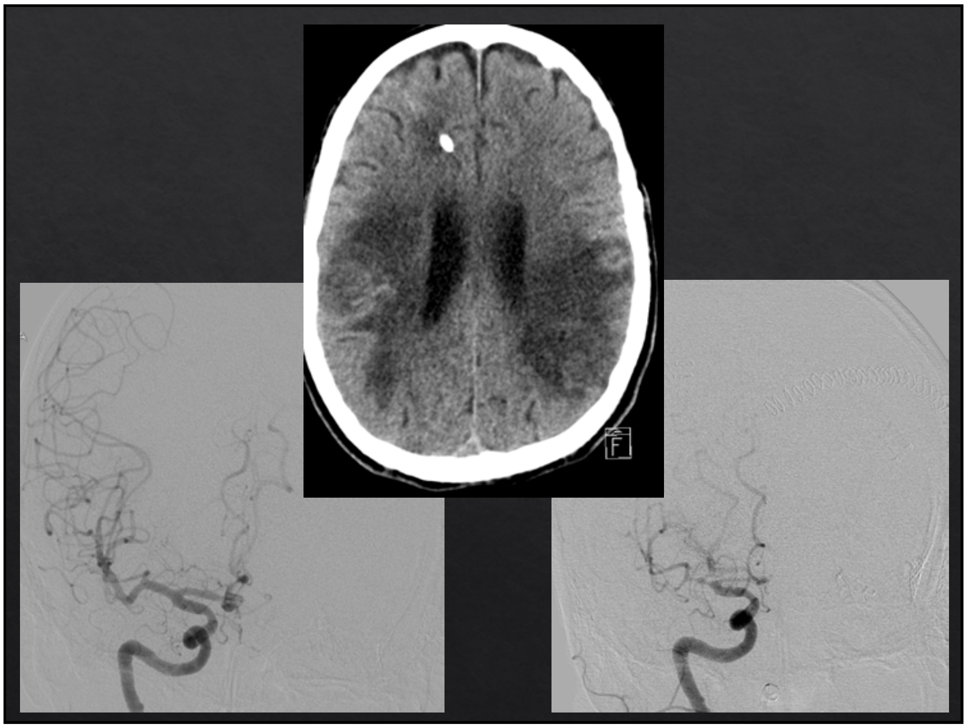
DATE	SAH DAY	MAP [mmHg]	ICP [mmHg]	HEAD ELEVATION	R_MCA [cm/s]	R_ACA [cm/s]	R_PCA [cm/s]	R_ICA [cm/s]	L_MCA [cm/s]	L_ACA [cm/s]	L_PCA [cm/s]	L_ICA [cm/s]	R_LR MCA/ICA	L_LR MCA/ICA
[redacted]	1	69	3	30°	84	85	42	39	← surgical dressing →				2.2	/
	2	79	4		87	92	43	39	161	71	44	26	2.2	6.2
	3	91	5	30°	93	101	61	50	135	111	51	35	1.9	3.9
	4			In chair	125	109	49	42	146	98	—	40	8.0	3.7
	5				116	126	48	31	139	111	58	33	3.7	4.2
	6			- - -	[illegible]	213	63	38	186	90	60	26	4.9	7.2
	7			In chair	154	152	72	45	162	67	79	52	3.4	3.1
	8			30°	280	225	83	42	198	150	68	30	6.7	6.6
	9				323	226	75	35	186	118	74	37	9.2	5.0
	10		6		306	239	109	50	183	144	112	44	6.1	4.2

CTA on PBD1 vs PBD11



Day 1

Day 11

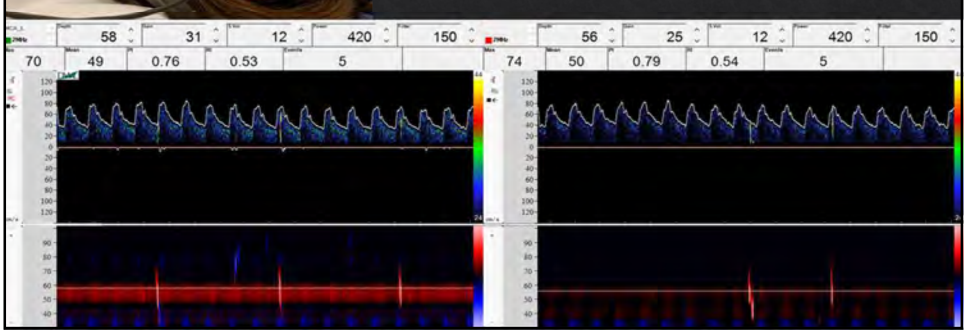


Emboli Detection

- Ischemic stroke, TIA, asymptomatic high-grade stenosis
- Microbubble Test for PFO diagnosis

Monitor "downstream" from the obstruction

Turn down gain enough to allow visualization of embolic signals



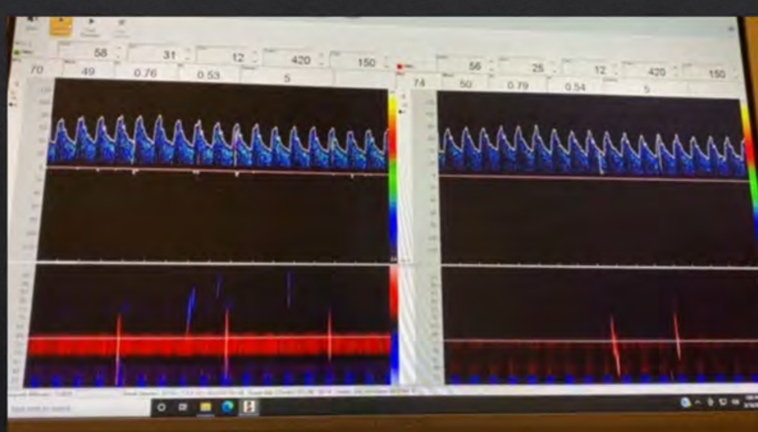
Emboli Detection

Microembolic Signals (MES) aka High Intensity Transient Signals (HITS)

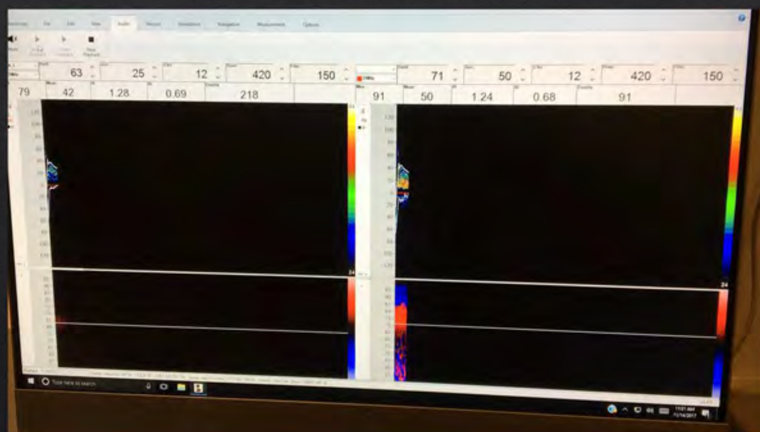
- Random occurrence during cycle
- Brief duration (<0.1 second)
- High intensity (>3dB over background)
- Primarily unidirectional signals
- Audible component

Garami Z. 2017. Transcranial Doppler [PowerPoint Slides].

Emboli Detection

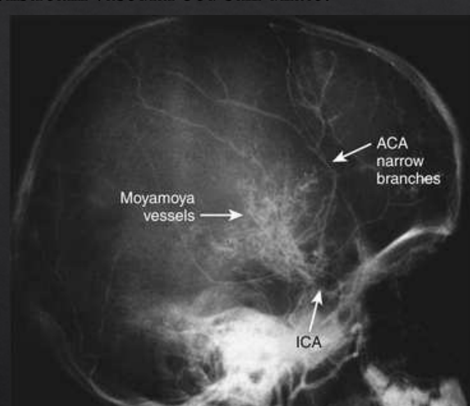


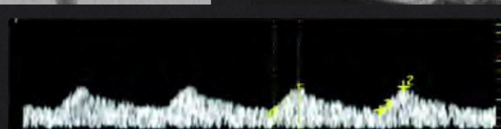
Emboli Detection



Cerebral Vasoreactivity Testing (CVR)

Vascular Reserve: Can the downstream vascular bed still dilate?





Picture from Neupsy Key https://neupsykey.com/surgical-treatment-of-moyamoya-disease-in-adults/#f0010

CVR Testing Method

6-Minute Recording of MCA velocity in response to changes in end tidal pCO2

- 2 min normal room air
- 2 min 8% CO2, 21% O2, 71% N2
- 2 min normal air hyperventilation

Breath-holding is another common method

Cerebral Vasoreactivity Testing (CVR)

CO2 reactivity (CO2R): the percent change in mean flow velocity per mmHg change in end-tidal pCO2

$$CO2R = \frac{a}{v_{am}} x\,100\%$$

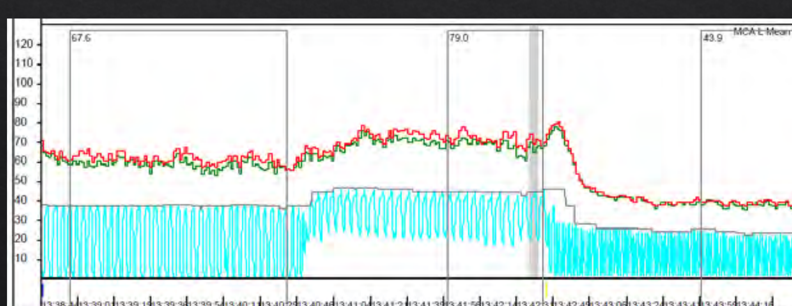
a = slope calculated from the formula y = ax + b

v_{am} = arithmetic mean velocity of all data points in the diagram

$$\left(v_{am} = \frac{\sum v_{0-n}}{n}\right)$$

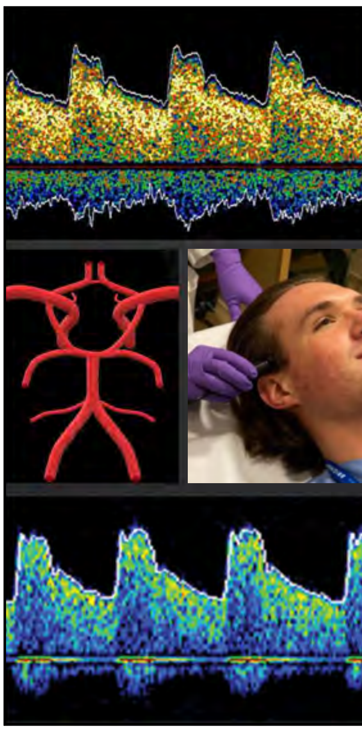
Vasomotor Range (VMR): the total percent range of the velocity change relative to baseline

$$VMR = \frac{v_{hypo} - v_{hyper}}{v_{norm}} x\,100\,\%$$



Limiting the Limitations

- Dedicate TCD techs in your lab
- Same tech performing serial measurements
- Speak to EEG lab techs about putting T3 and T4 leads a little higher to avoid obstructing window in patients where tests overlap
- Track the course of each vessel, take many pictures
- DO NOT USE PRE-SETS!



An Essential Tool for Neurovascular Assessment

- Inexpensive
- Repeatable
- Non-invasive
- Real-time
- Portable

- Localize source of obstruction and embolization
- Aid in treatment evaluation and planning

References

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