MSc Advanced Neuroimaging Lectures

Ultrasound II

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Learning outcomes

- Describe the **Doppler effect** and its application in **blood flow imaging**
  - Doppler shift
  - Doppler equation
- Understand **Doppler trace** and **Doppler image**
- Key components of a **pulsed** and **continous wave** Doppler systems
- What is **aliasing** and its relation with Doppler measurements
- Common **artefacts of Doppler imaging**
- Basic concepts of **ultrasound safety**
- A glimpse in the state of the art in ultrasound imaging
  - Ultrafast imaging, Contrast agents, Anatomical and functional brain imaging

The Doppler effect

0:00 / 0:29

The waves scattered by a source moving away/towards the transducer, are shifted in frequency when measured at the transducer location

- Doppler shift: $f_r - f_i$
- If moving **towards** $f_r > f_i$, if moving **away** $f_r < f_i$

Doppler equation

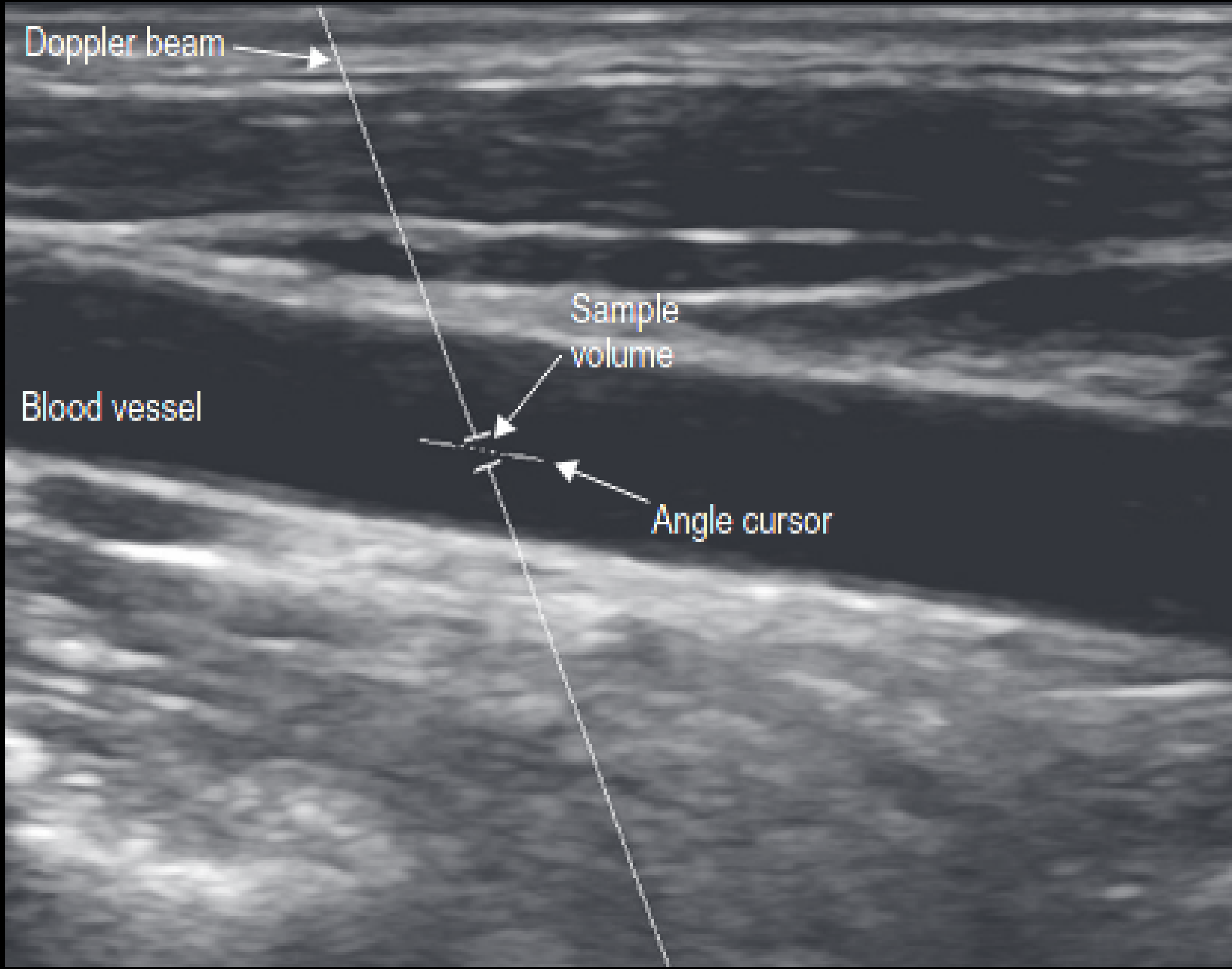
Doppler shift:

$$f_s = f_r - f_i = \frac{2 f_i v}{c} \cos\theta$$

$$v = \frac{c f_s}{2 f_i \cos\theta}$$

Where:

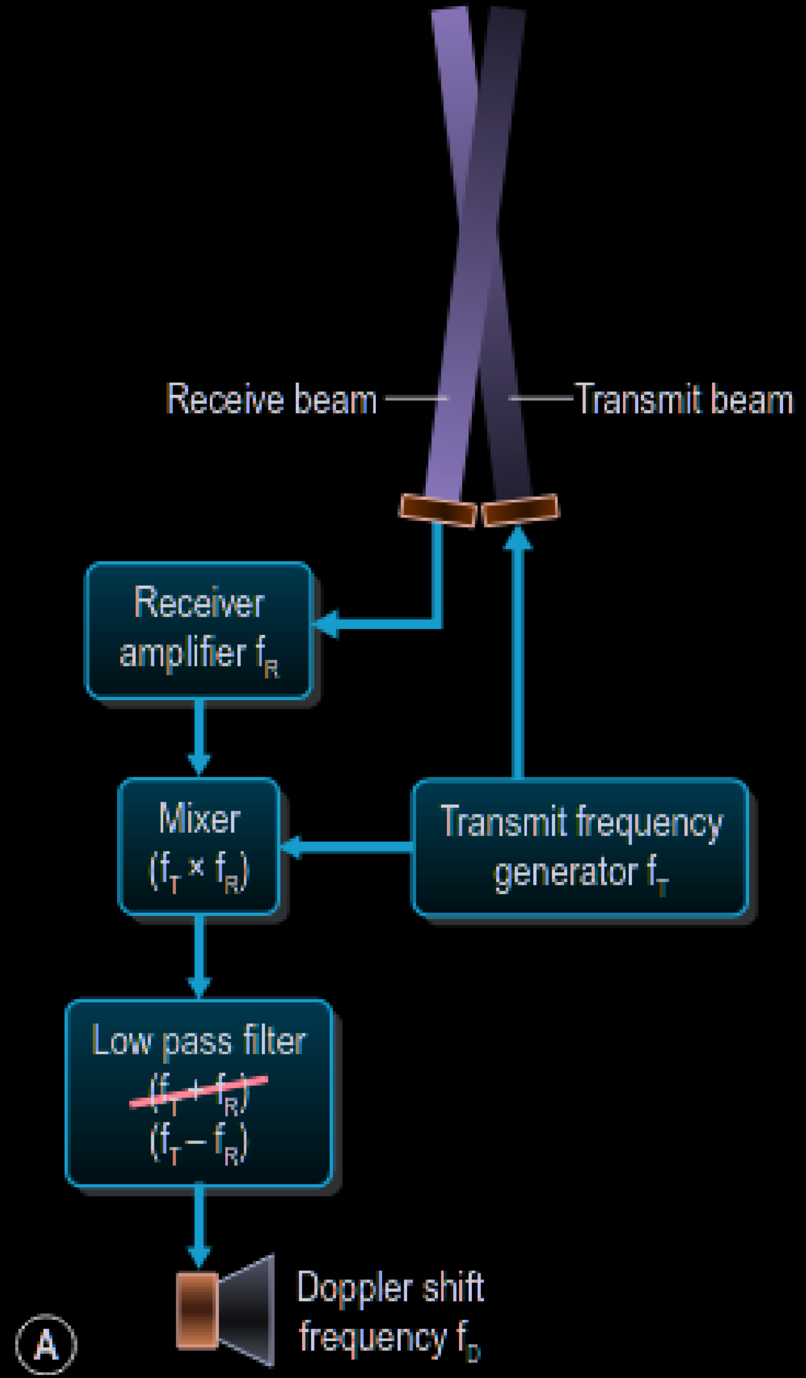
- f_r: received frequency
- f_i: incident frequency
- v: blood velocity
- θ: angle between the beam axis and the vessel
- c: speed of sound



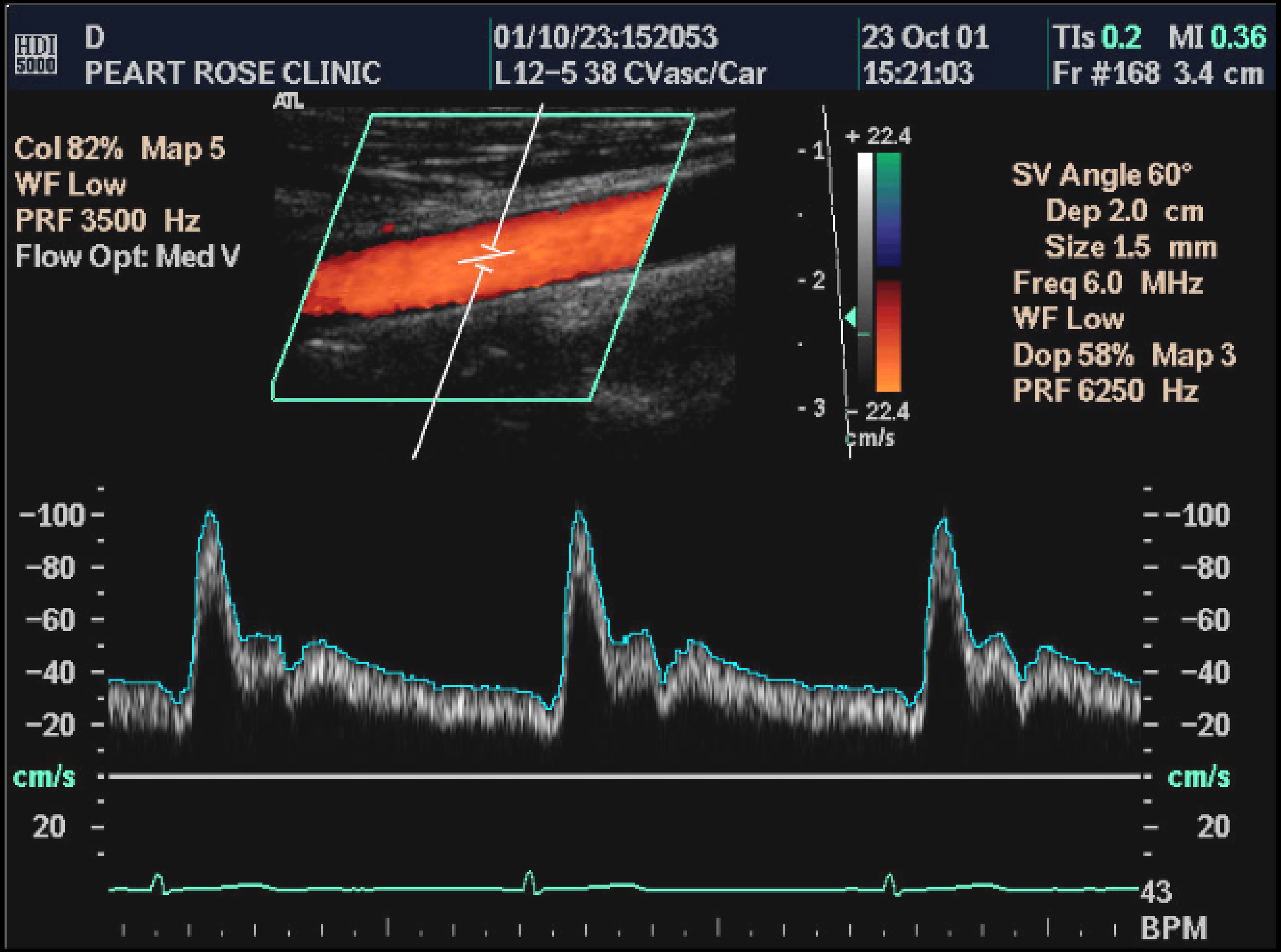
Continous Wave Doppler system

Key steps:

- **Demodulation**: Extracts the Doppler shift (Mixer + Low pass filter)
- **High-pass filter**: Removes static targets (e.g. vessel walls), called "Wall Filter"
- The Doppler Shift is often in the **audible range**! So it can be used to infer diagnostic information (e.g. "listen" to the heart valves)
- The Doppler spectrum can also be shown on the screen



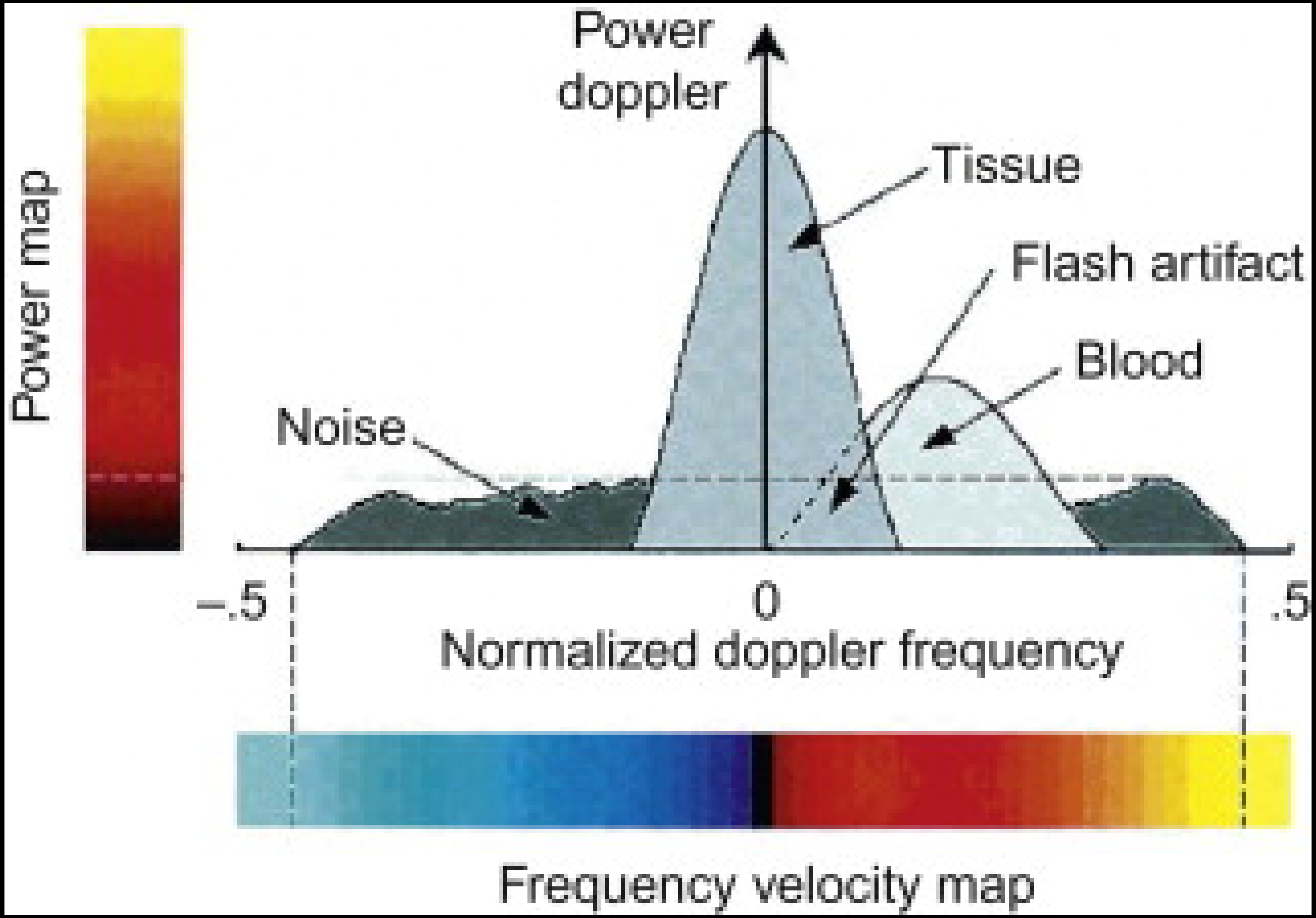
Ultrasound Doppler Imaging



Wall filter

Removes signals with a small or zero Doppler shift, such as vessel walls signal.

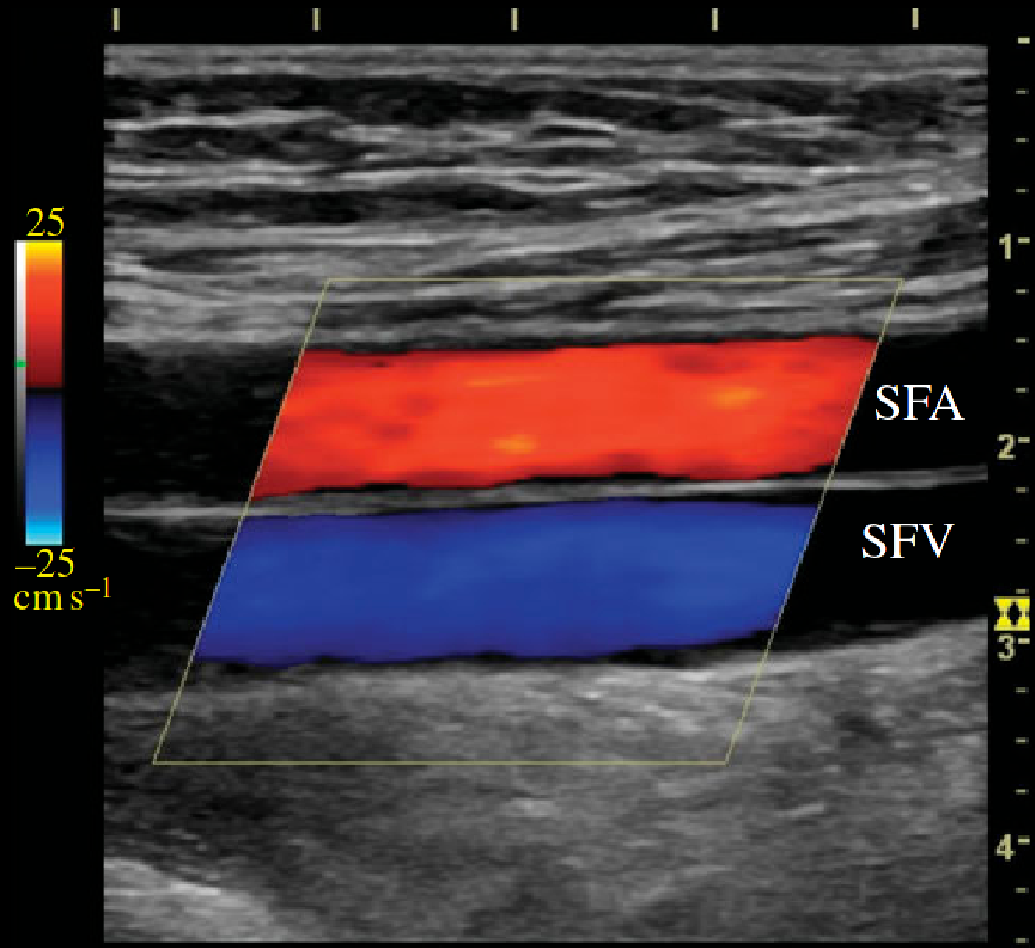
[Szabo, 2014]



Color Doppler Ultrasound

- Color coded velocity displayed over the B-Mode image
  - Red for flow dowards transducer
  - Blue for flow away from the transducer
- The color is based on the velocity
- Frame rate is reduced compared to B-Mode imaging
- Approximate calculation of the average frequency (autocorrelation)

[Evans et al., 2011]



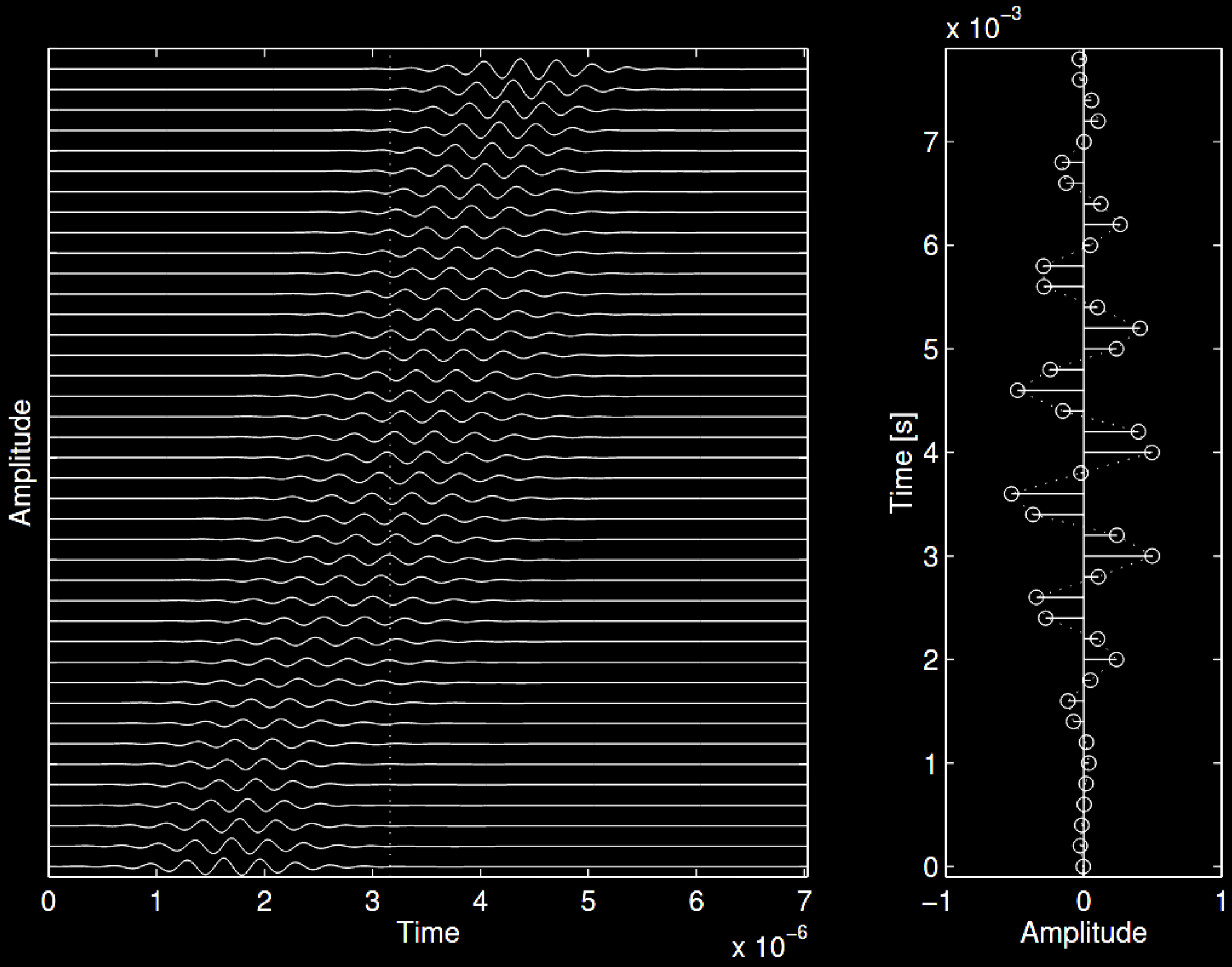
Pulsed Doppler

Send multiple Pulses and record the signal **at a fixed spatial location**

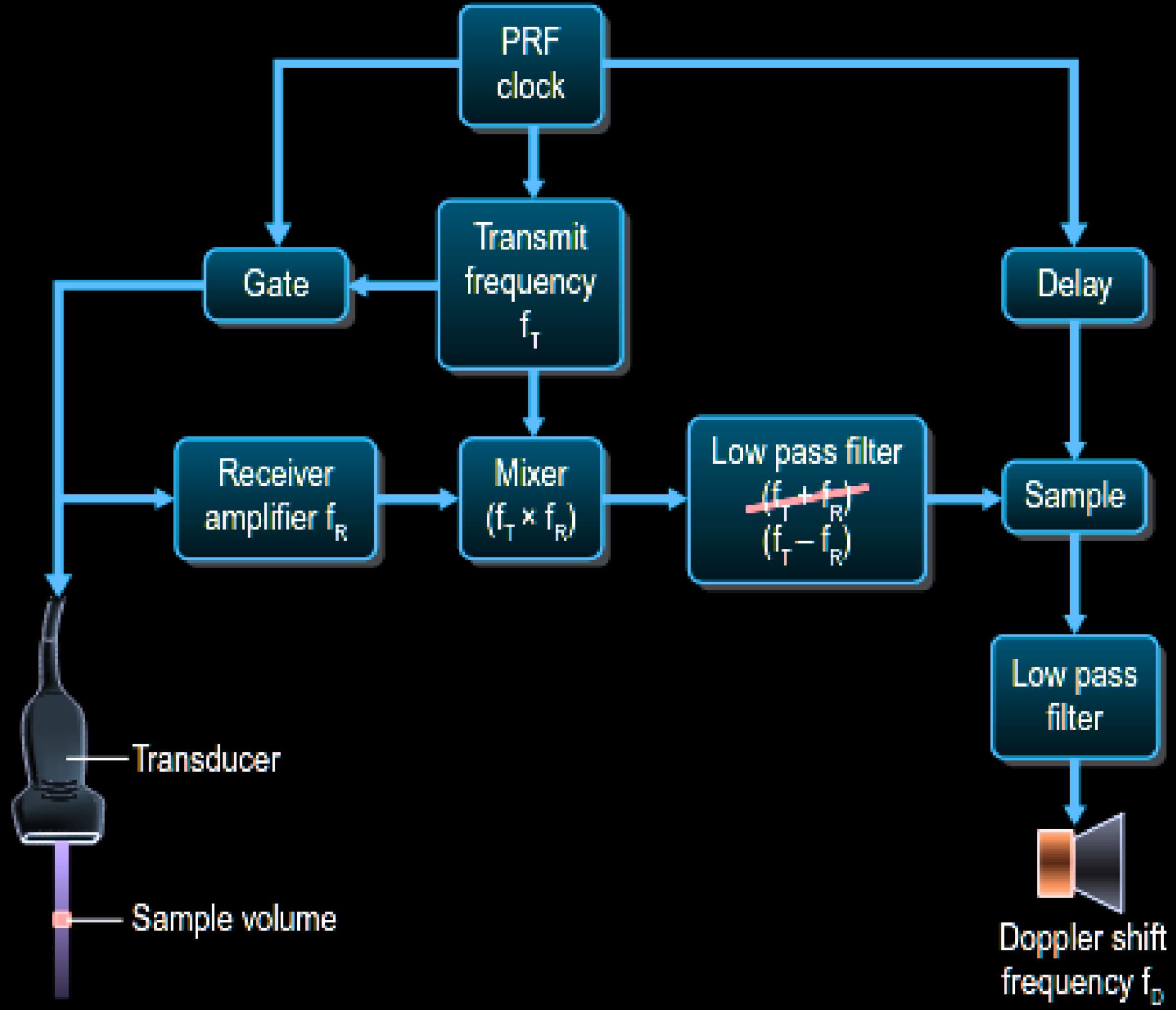
The equation for calculating velocity is the same as the one from the Doppler shift, but **this is not** due to the Doppler effect.

The key parameter is the **Pulse Repetition Frequency (PRF)**

[Jensen, 1995]



Pulsed Doppler System



Artefacts of Doppler Imaging

Much of the artifacts from B-Mode carry on to Doppler imaging.

- Incorrect gain, shadowing, noise, etc..

Flash artifacts

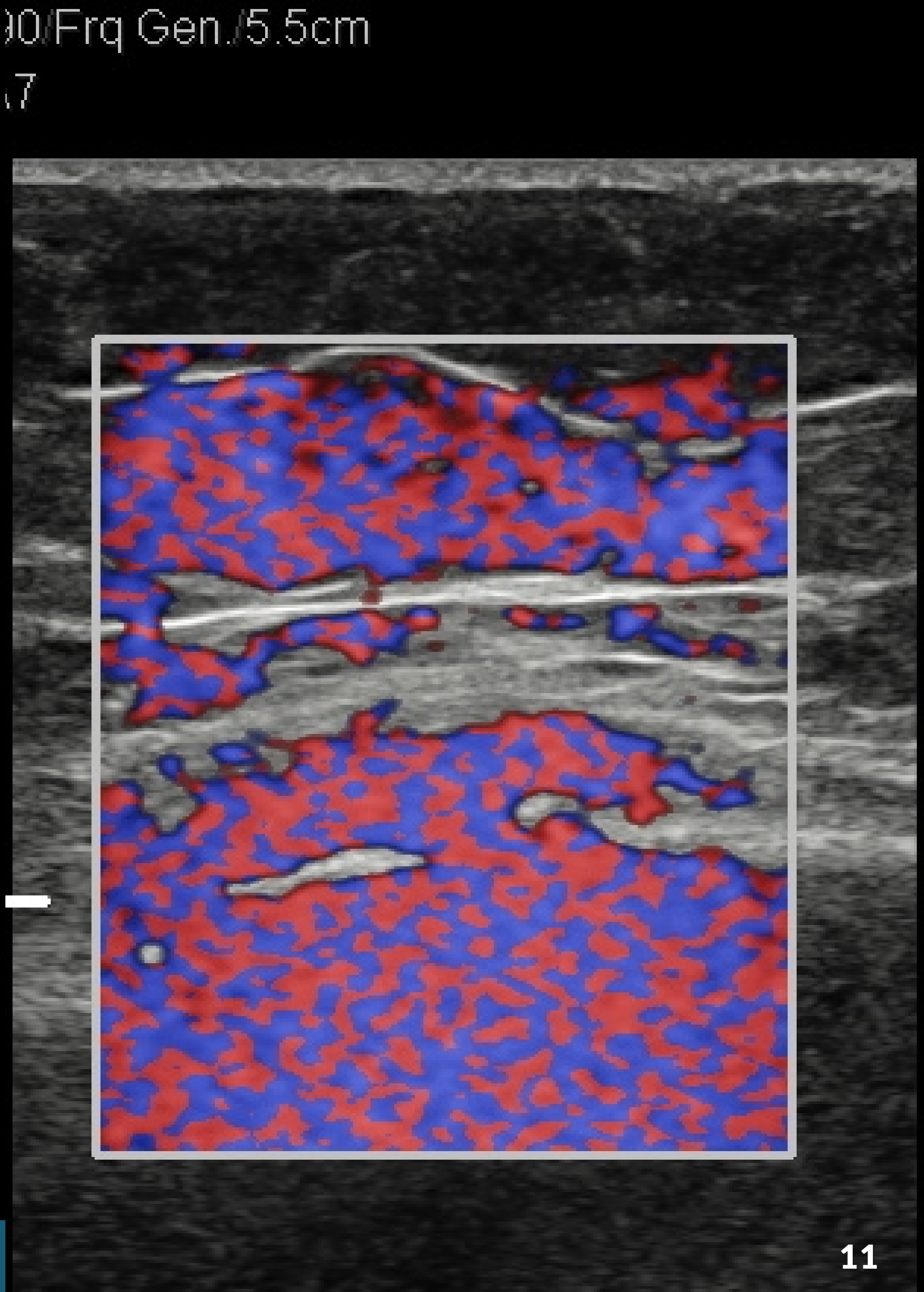
Due to probe motion or rapid vessel motion: ambiguity between source of motion

Colour spilling

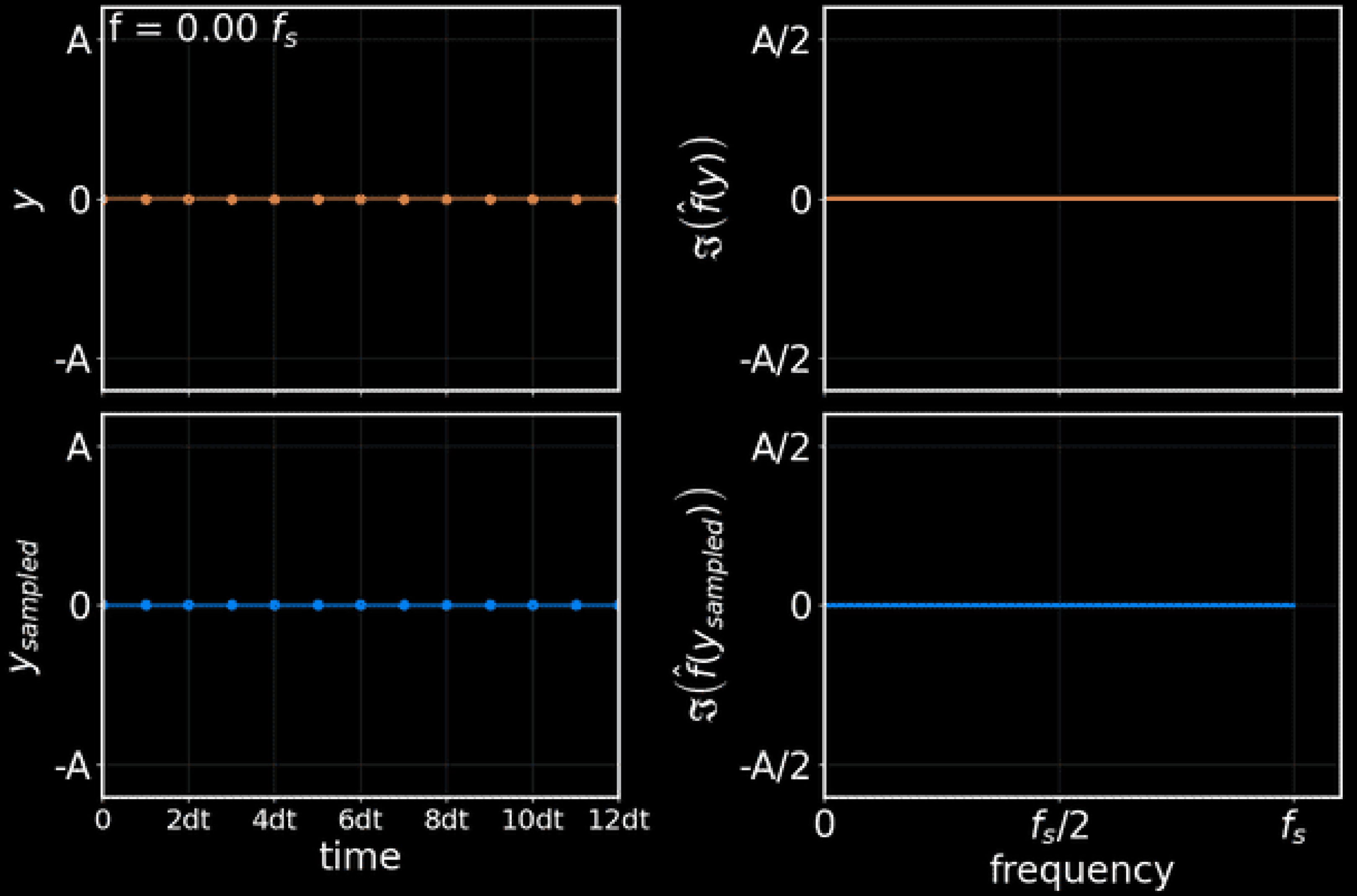
Shows moving targets outside the vessel

Due to the imperfect source localization of ultrasound imaging

[Case courtesy of Dr Balint Botz, Radiopaedia.org, rID: 74358]



Nyquist and Aliasing



Nyquist and Aliasing

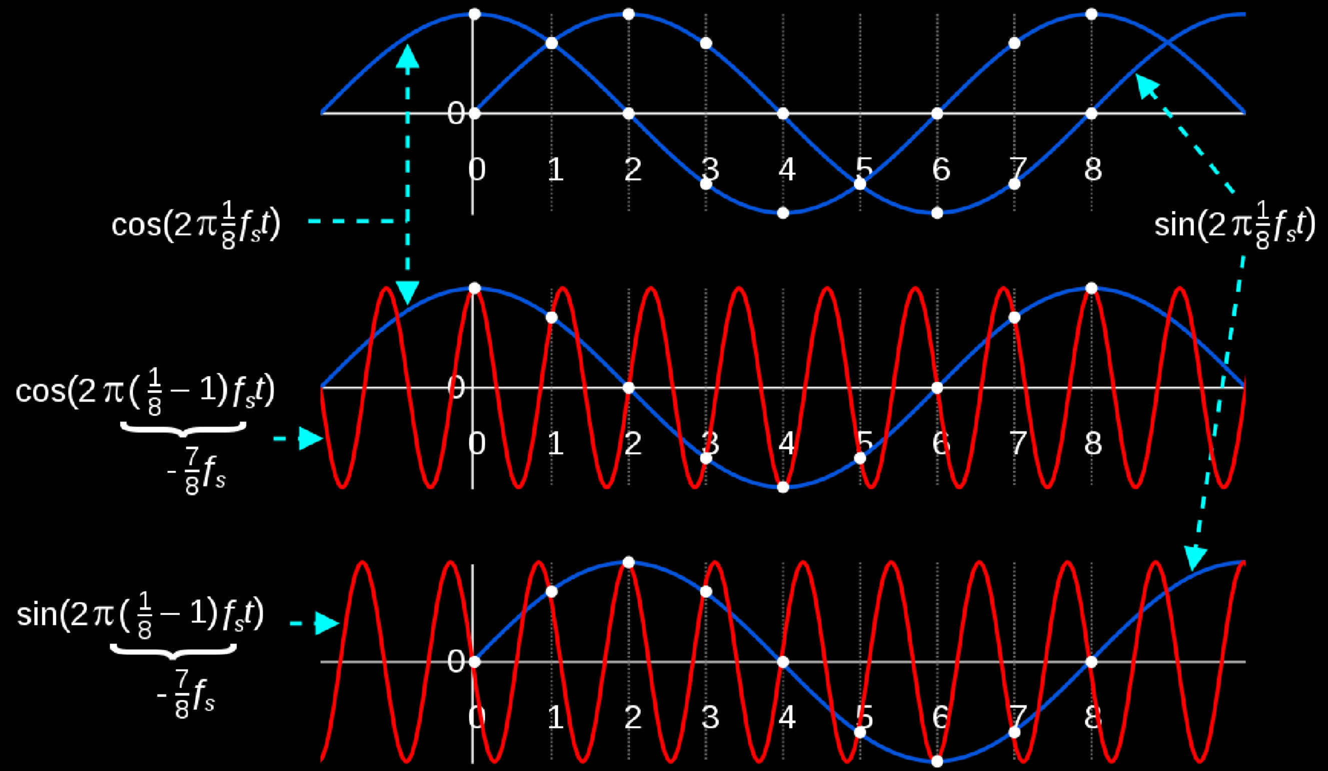
Pulsed Doppler acquisition practically sample a signal

There's a trade-off between PRF and maximum detectable velocity

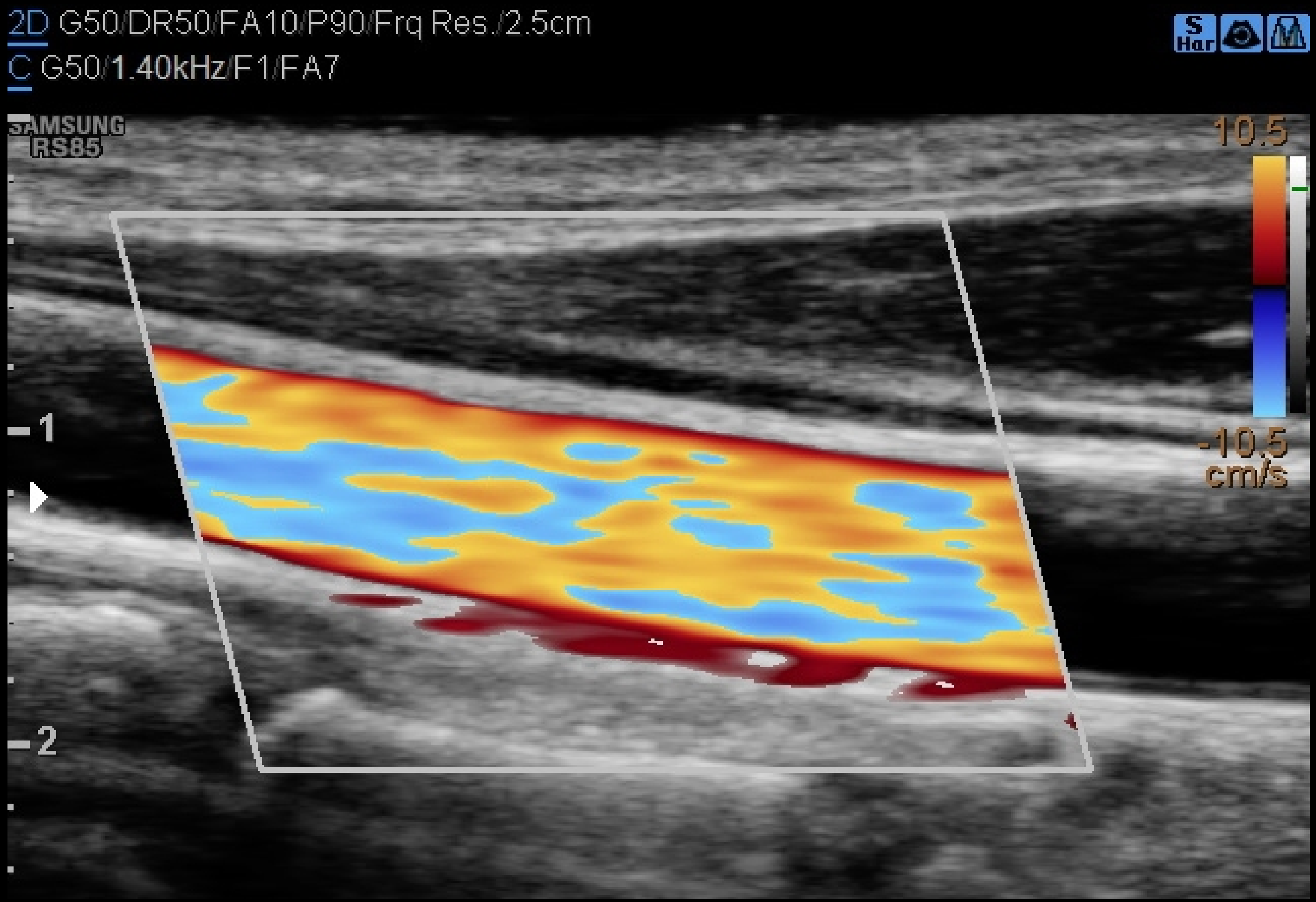
Maximum PRF is bounded by the time of arrival of the last echo

Aliased frquencies "wrap back" to the opposite side of the spectrum

- High positive velocities $\rightarrow$ negative velocities



Aliasing artefacts



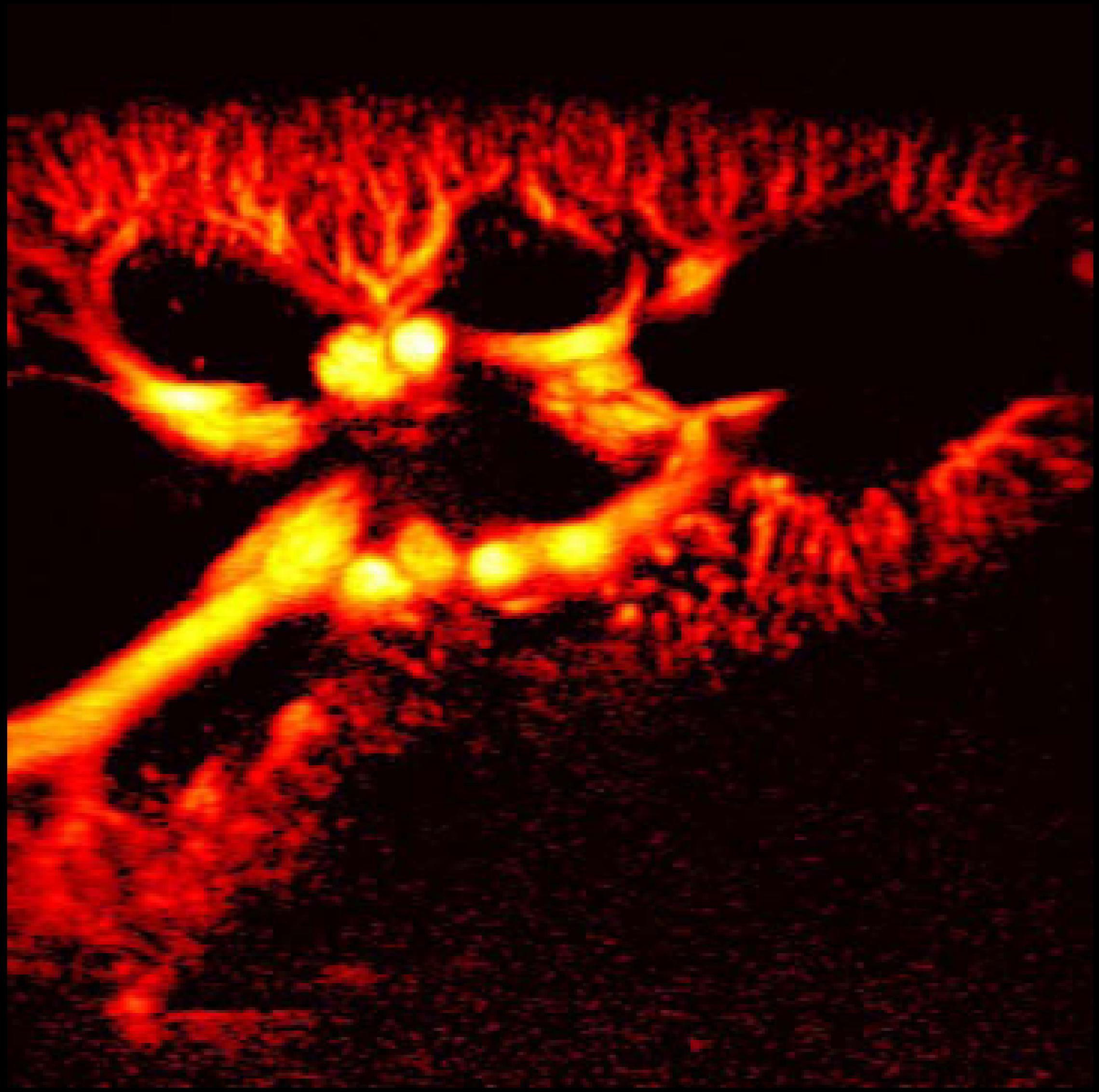
[Case courtesy of Dr Balint Botz, Radiopaedia.org, rID: 64786]

Power Doppler imaging

Discards velocity information and only shows the power of the Doppler signal

- Increased sensitivity (e.g. smaller vessels become detectable)
- Helps to visualize complex geometries
- Can't distinguish between veins and arteries

[Stanziola et al, 2018]

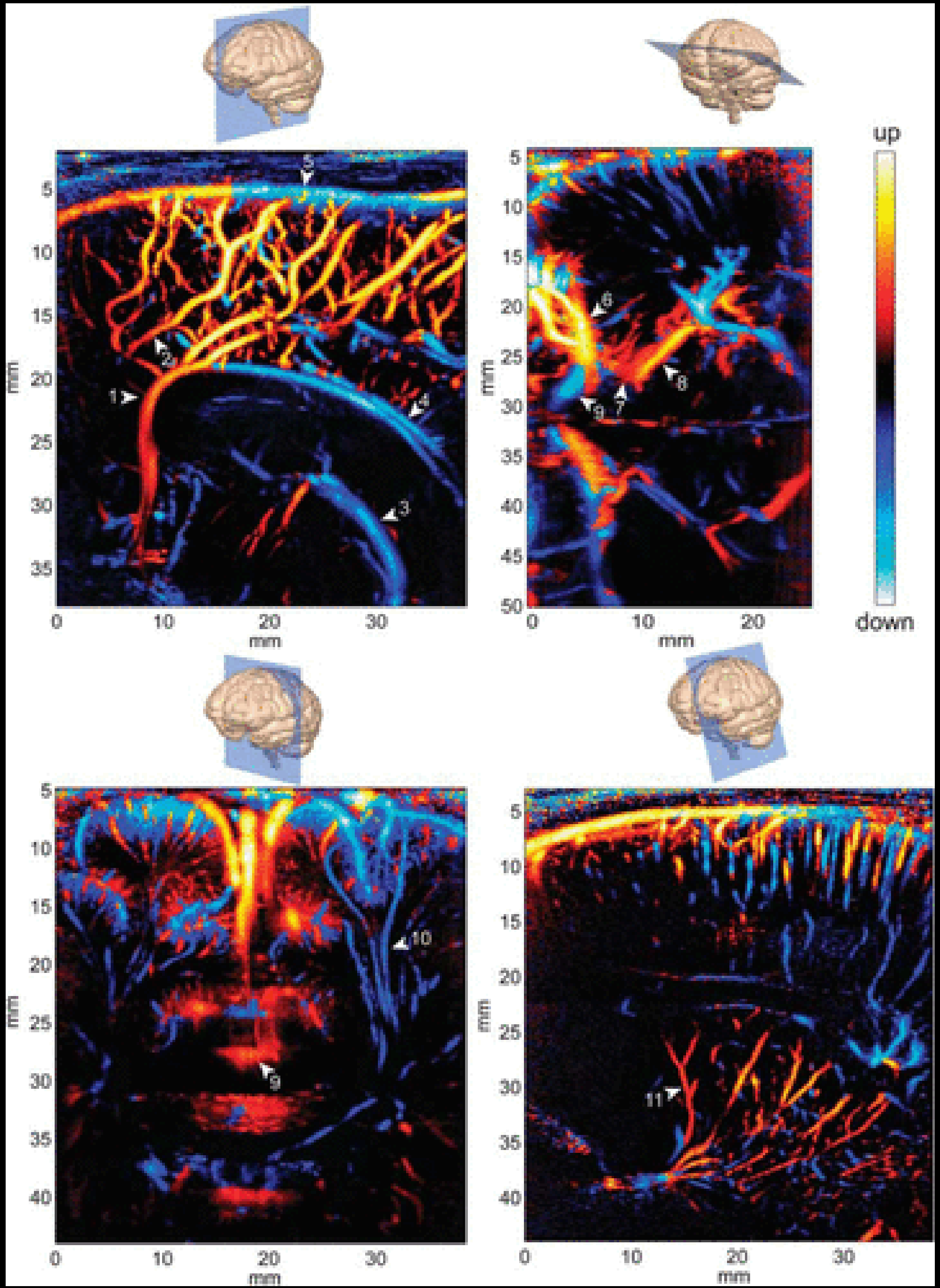


Applications

Vascular imaging of the neonatal brain

In vivo mapping of the full vasculature dynamics based on Ultrafast Doppler

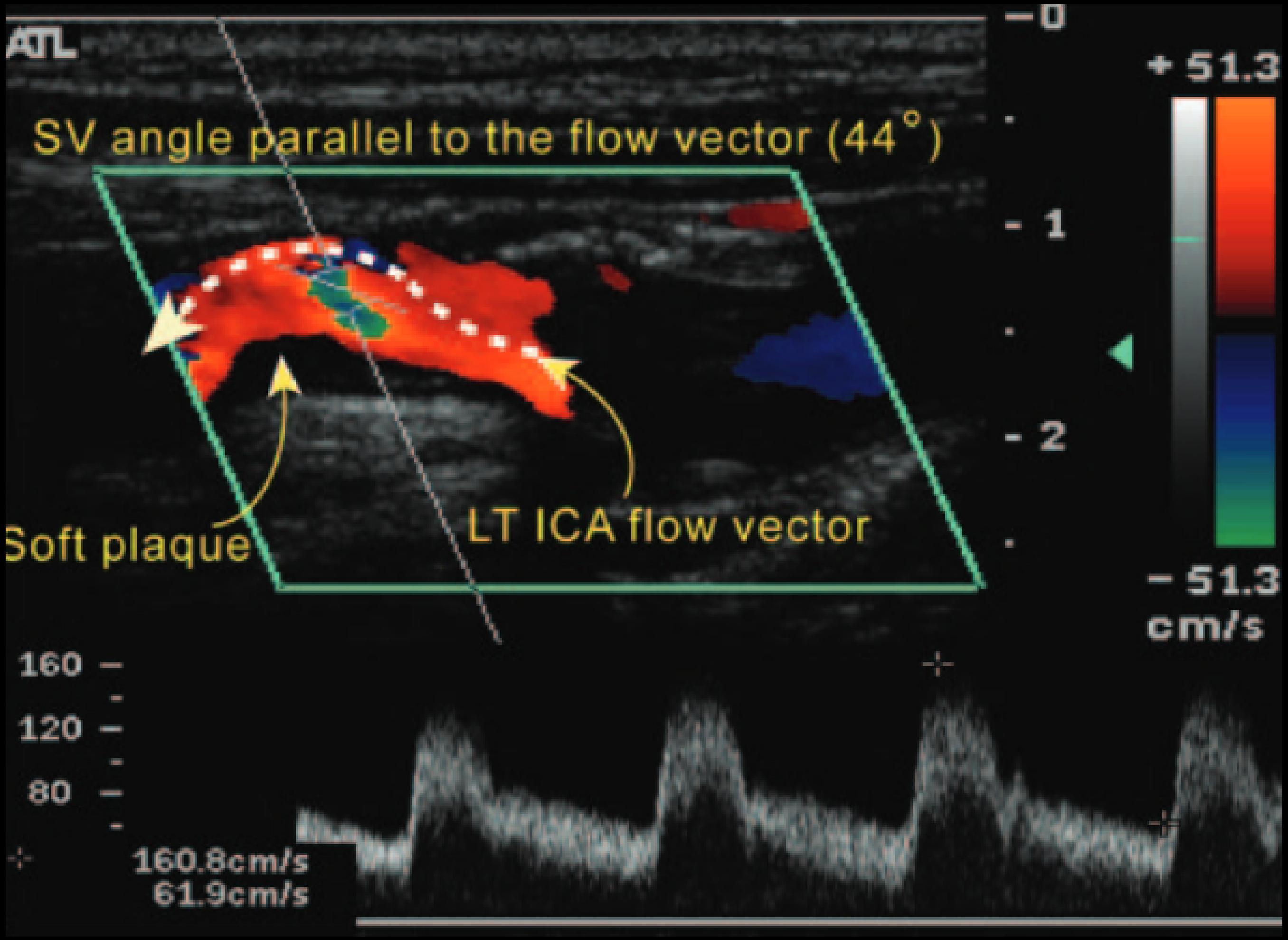
[Demene et al, 2020]



Examination of the Carotid Arteries

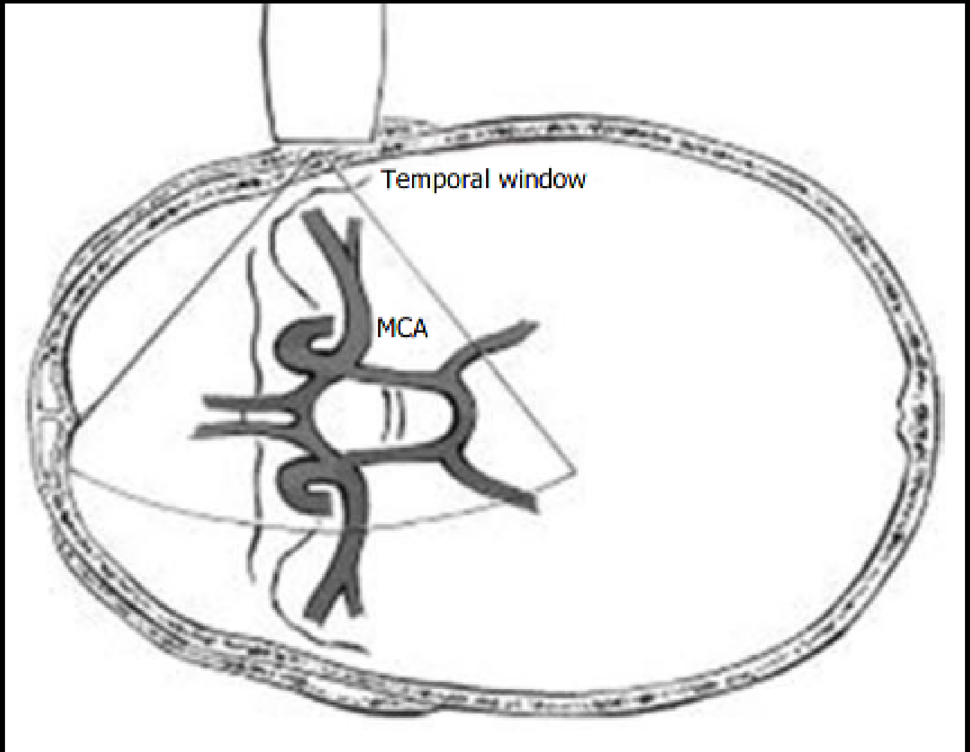
Evidence of carotid atherosclerotic plaques

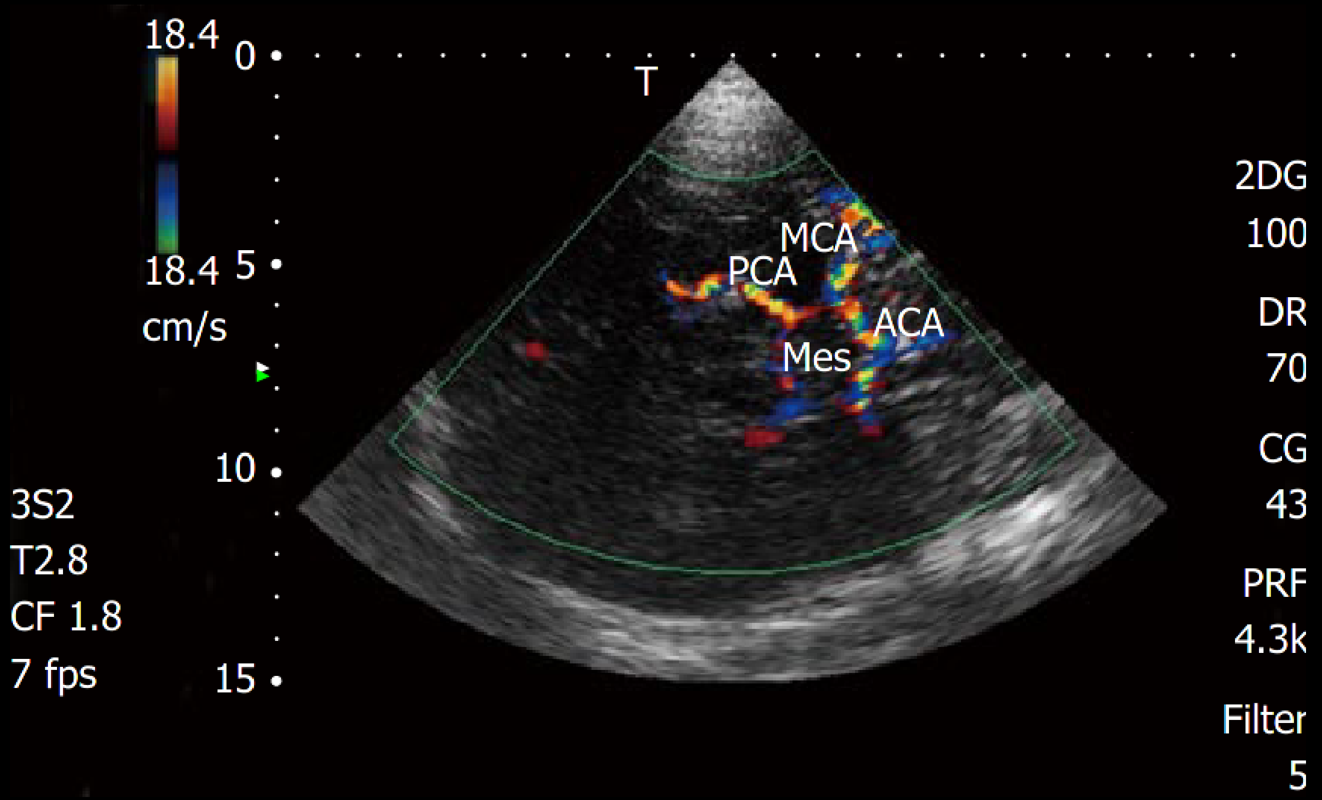
[Tahmasebpou et al, 2005]



Transcranial Doppler

Evidence of carotid atherosclerotic plaques [Tahmasebpou et al, 2005]





Safety

Ultrasound safety

- Ultrasound is generally a safe diagnostic tool
- However, it does generate biological effects, and the number of scans is increasing

Key safety practice

- Only perform a scan if it is clinically required
- Minimize scanning time, but acquire all information needed for a diagnosis
- Use Doppler mode after finding the target region, minimize the size of the colour box
- Take notice of the Thermal and Mechanical index and adjust exposure accordingly (more on this later)
- Keep the scanner in good working conditions

At risk groups and tissues

Embryo during first trimester

- Heat is a teratogen, temperature rises are limited (<1.5 $^\circ$C)
- Kinetics of biochemical processes are heat dependent but poorly understood $\rightarrow$ caution

Foetus during second-third trimesters

- Bone ossification occurs $\rightarrow$ localised heating due to absorption and heat conduction into soft tissue (neurological tissue particularly sensitive)

Foetus when mother has a fever

Neonate

- Developing brain is at risk from temperature increases
- Imaging heart may expose pleural tissue $\rightarrow$ risk of capillary rupture

The eye

- Cornea, lens and vitreous body are unperfused tissues $\rightarrow$ thermal conduction is the only means of dissipating heat $\rightarrow$ potentially large temperature rises

Mechanical index (MI)

Ultrasound may produce **cavitation**, creating gas bubbles or pockets that can grow over time

$$\mathrm{MI} = \mathrm{peak}(P)/\sqrt{f}$$

- **Sonoporation**: Generation of pores in cell membranes using ultrasound, allowing for transferin of nucleic acid material
- **Inertial cavitation**: violent collapse or change in size of the bubble, causes very high, localized an increase of pressure and temperature, induces shear stress damage

Rough safety guidelines

- **MI $>$ 0.3:** Potential minor damages to the neonatal lung
- **MI $>$ 0.7**: Demonstrated risk of cavitation using constrast agents, theorectical risk of cavitation without

Thermal index: (TI)

Rough estimate of the temperature increase caused by acoustic energy transformed into thermal energy

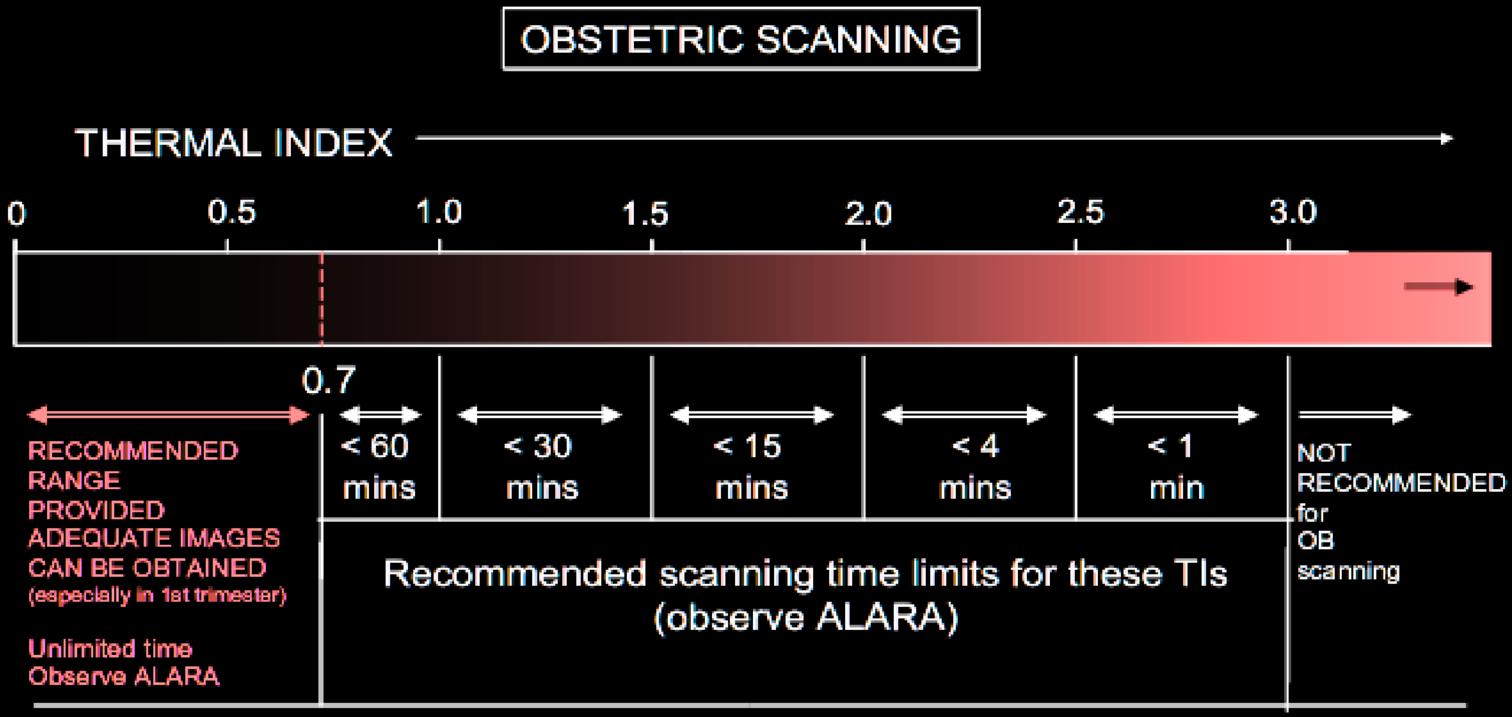
$$\mathrm{TI} = W_{in}/W_{1^\circ C}$$

TI depends on the region being scanned

- TIS for soft tissue
- TIC for bones next to the skin surface and cranium
- TIB for bones

The eye is very sensitive to high TI

[Guidelines for the safe use of diagnostic ultrasound equipment]



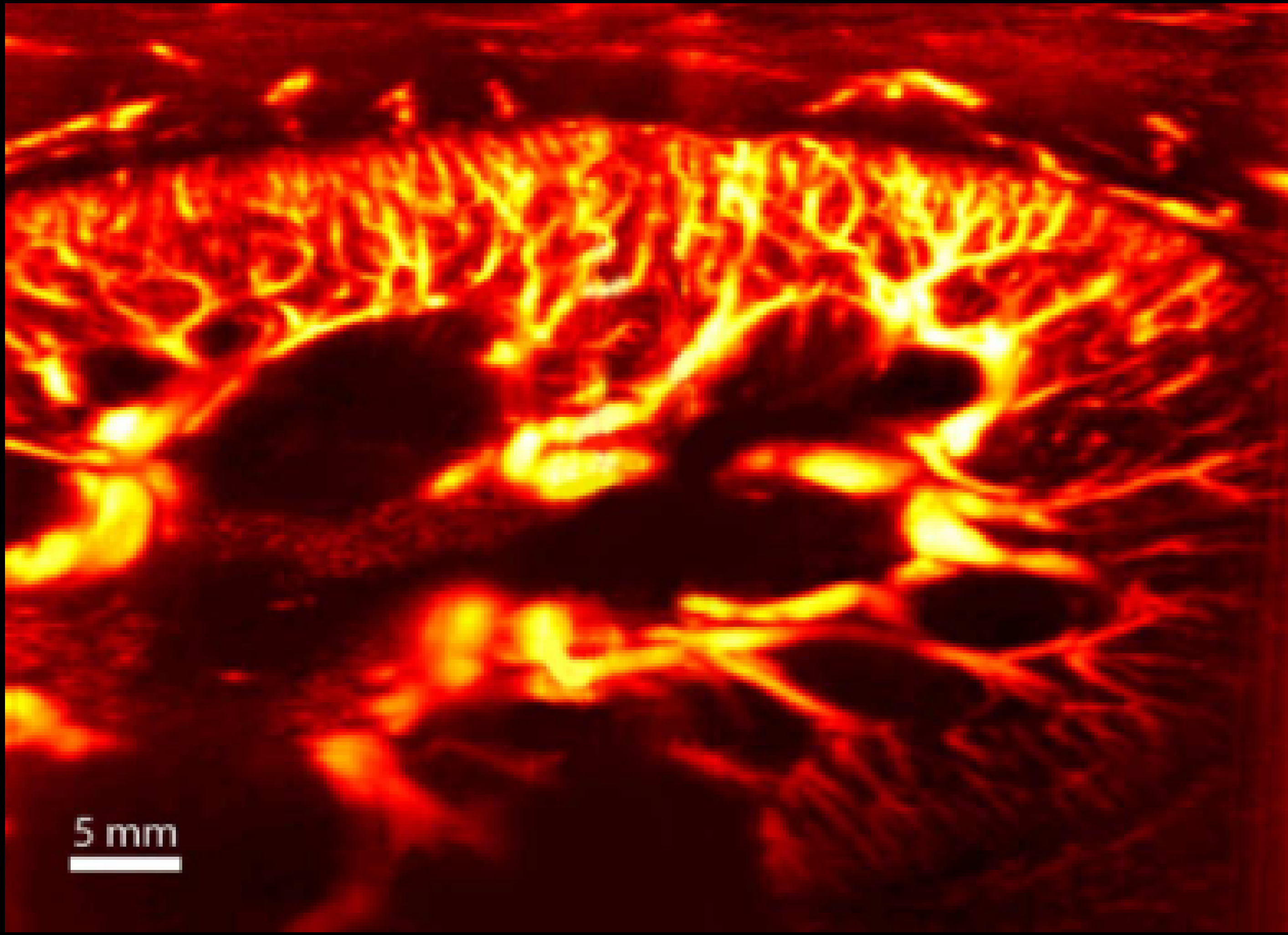
Additional material

Ultrafast ultrasound

Uses **Plane/Diverging waves** instead of line-by-line imaging

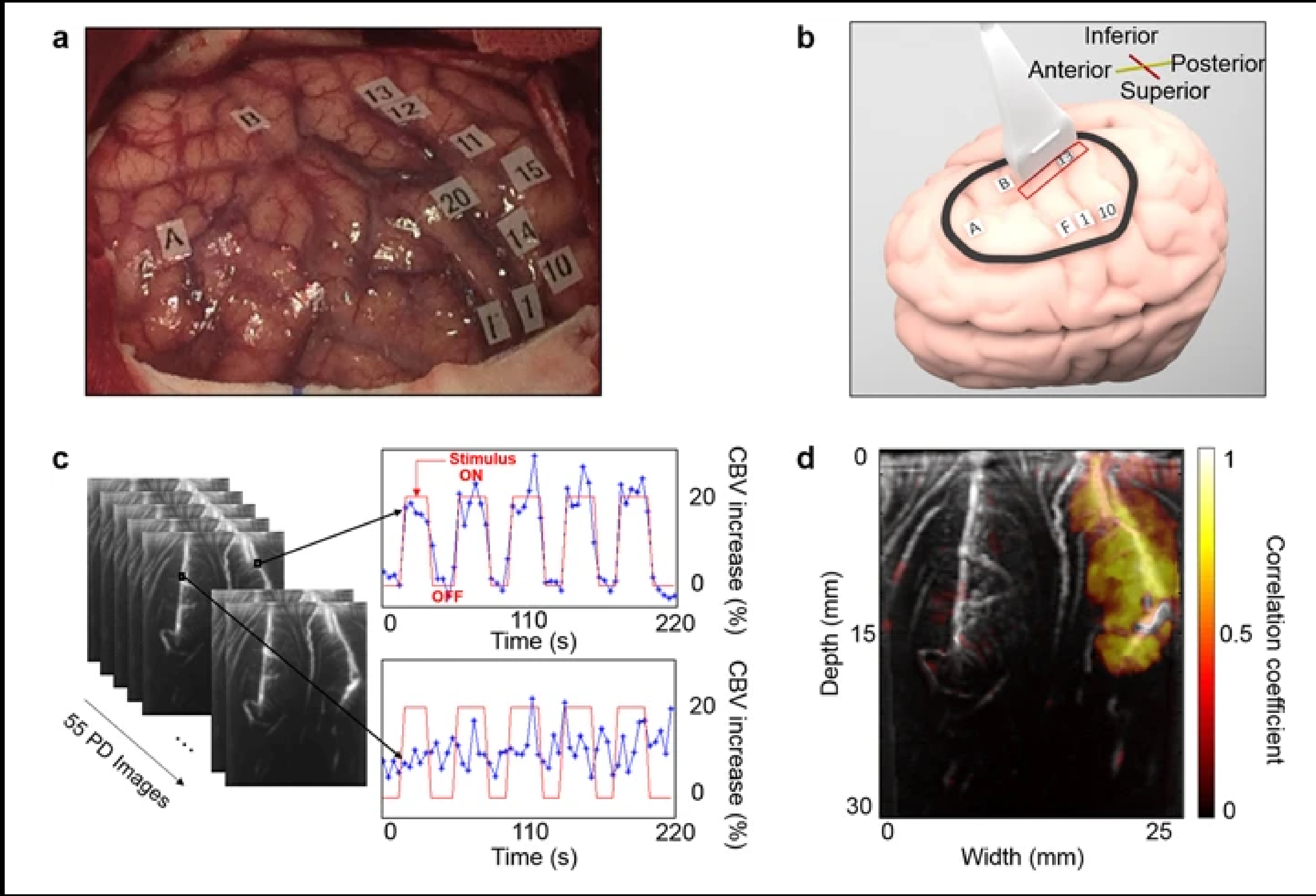
- Frame rate improvements $\times 100$ (up to 5000 fps)
- Used to estimate viscoelastic properties of the arterial wall (track shear waves)
- New avenues for studying fast-moving events (e.g. cardiac imaging)
- High increase on Power Doppler sensitivity

[Demene et al., 2015]



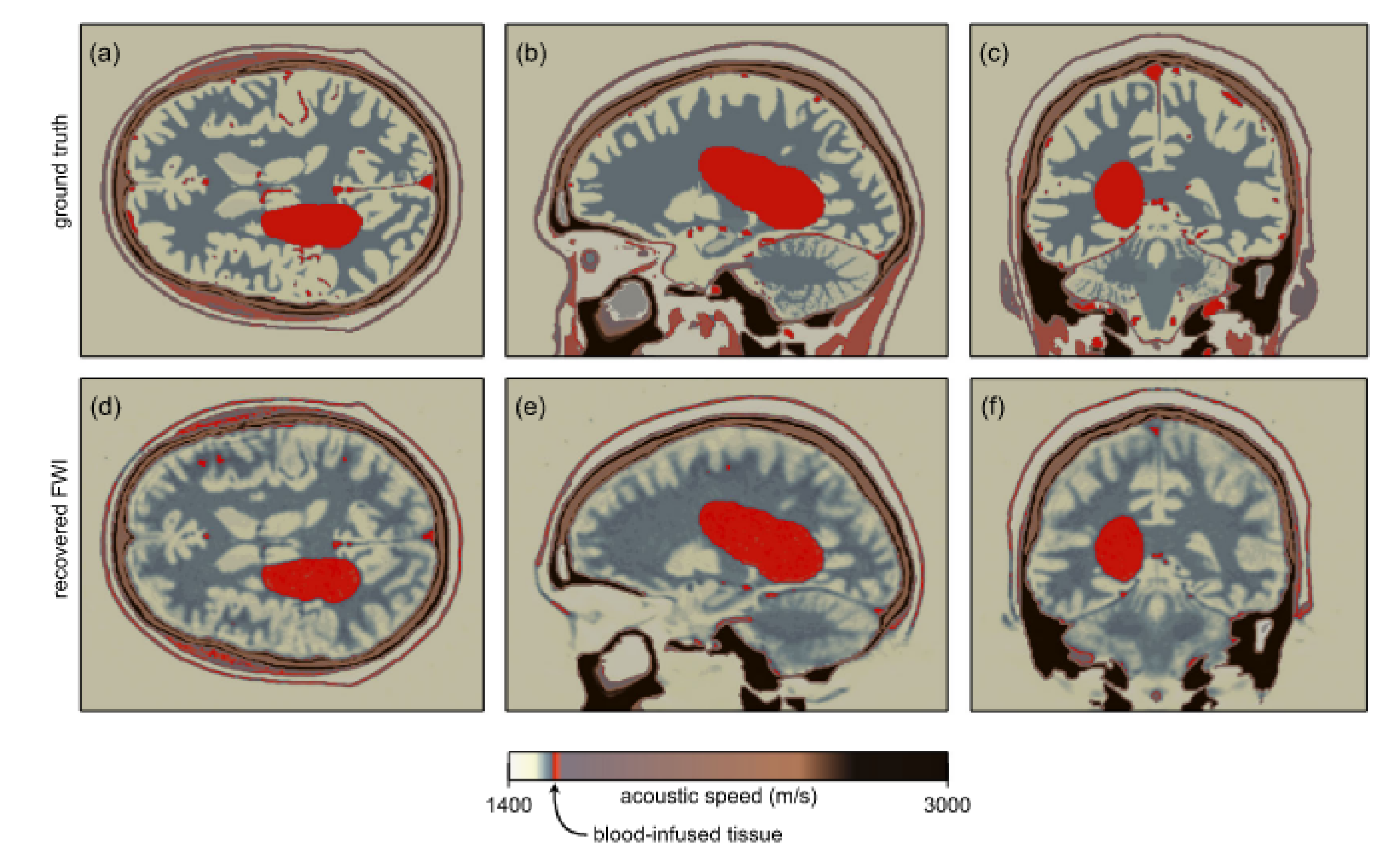
Functional ultrasound imaging of the brain

Correlates power doppler measurements with brain activity.



Full wave inversion

Uses a more complex physical model (wave equation) to reconstruct acoustic material properties



Super resolution

Uses microbubbles contrast agents

Tracks individual microbbules to delineate vessels (and micro vessels!)

[Errico et al., 2015]