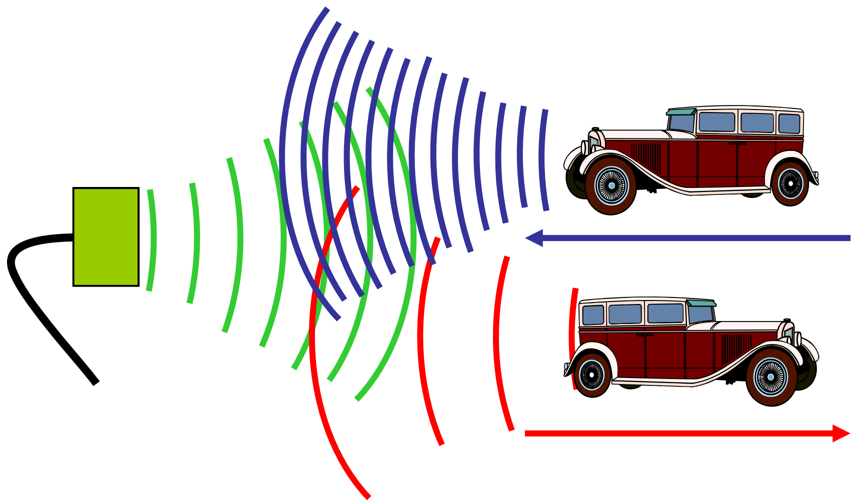
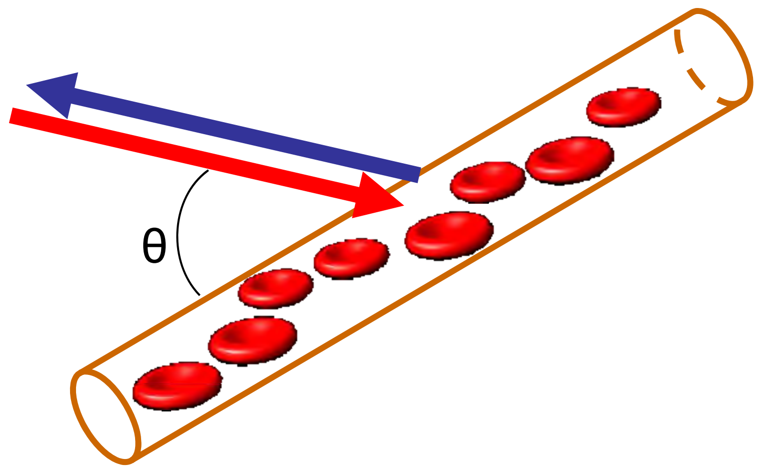
Doppler and Speckle Imaging

Doppler Effect

- **Christian Johann Doppler, 1803-1853, Austria**
- **Doppler Effect**
    - Motion of scatterers imparts a frequency shift in the laser signal
    - Two Doppler shifts (one for each direction



$$f_d = f_s\left(1 \pm 2\frac{v_{sc}}{\lambda_0}\cos\theta\right)$$



- f_d = frequency measured at detector
- f_s = frequency of source
- v_{sc} = velocity of scatterer

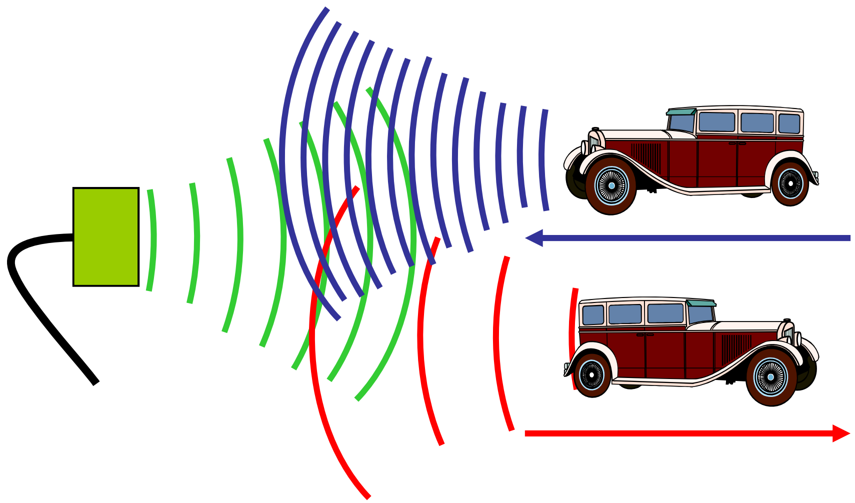
Doppler Effect

- **Doppler Effect**

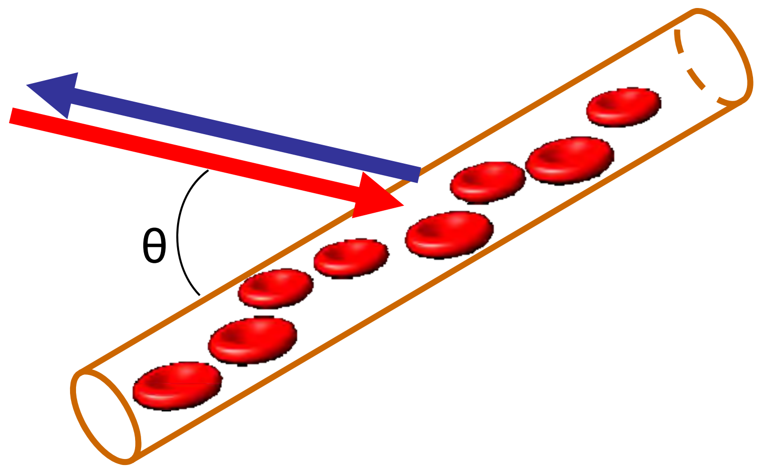
$$f_d = f_s\left(1 \pm 2\frac{v_{sc}}{\lambda_0}\cos\theta\right)$$

$$\Delta f = f_d - f_s$$

$$v_{sc} = \Delta f \frac{\lambda}{2\cos\theta}$$

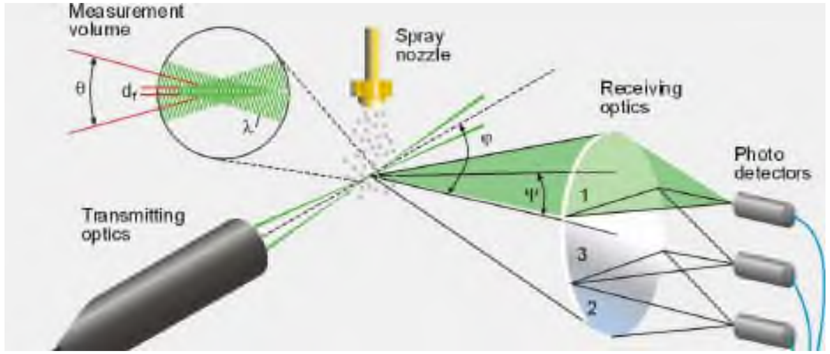


- Δf is typically measured by heterodyne detection
  - A sample of the source light is combined with the scattered light and the beat frequency of the two is measured.

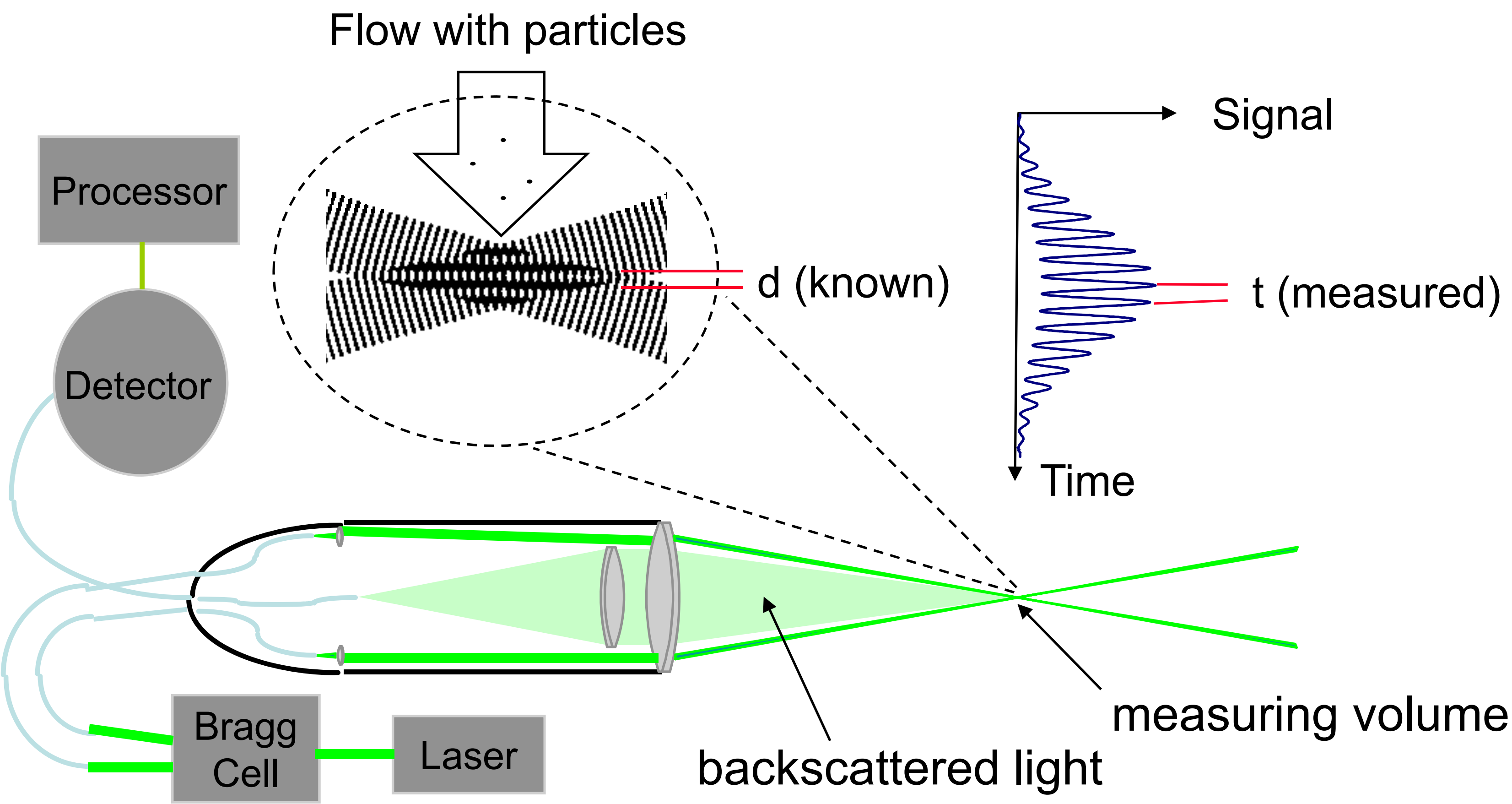


Laser Doppler velocimetry (LDV)

- **Invented by Yeh and Cummins in 1964**
- **Velocity measurements in Fluid Dynamics (gas, liquid)**
  - Up to 3 velocity components
- **Advantages**
  - Non-intrusive measurements (optical technique)
  - Absolute measurement technique (no calibration required)
  - Very high accuracy
  - Very high spatial resolution due to small measurement volume
- **Limitations**
  - Tracer particles are required



Laser Doppler velocimetry (LDV)



Velocity = distance/time

Laser Doppler velocimetry (LDV)

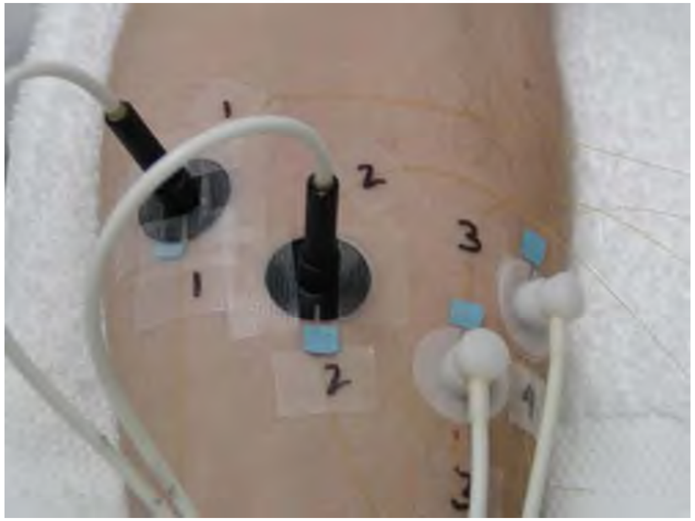
- **Applications of LDV**
  - Laminar and turbulent flows
  - Investigations on aerodynamics
  - Supersonic flows
  - Turbines, automotive etc.
  - Liquid flows
  - Surface velocity and vibration measurement
  - Hot environments (flames, plasma etc.)
  - Velocity of particles
  - ...etc., etc., etc.

Measurement of flow field around a 1:5 scale car model in a wind tunnel (Photo courtesy of Mercedes-Benz, Germany)

Measurement of flow around a ship propeller in a cavitation tank

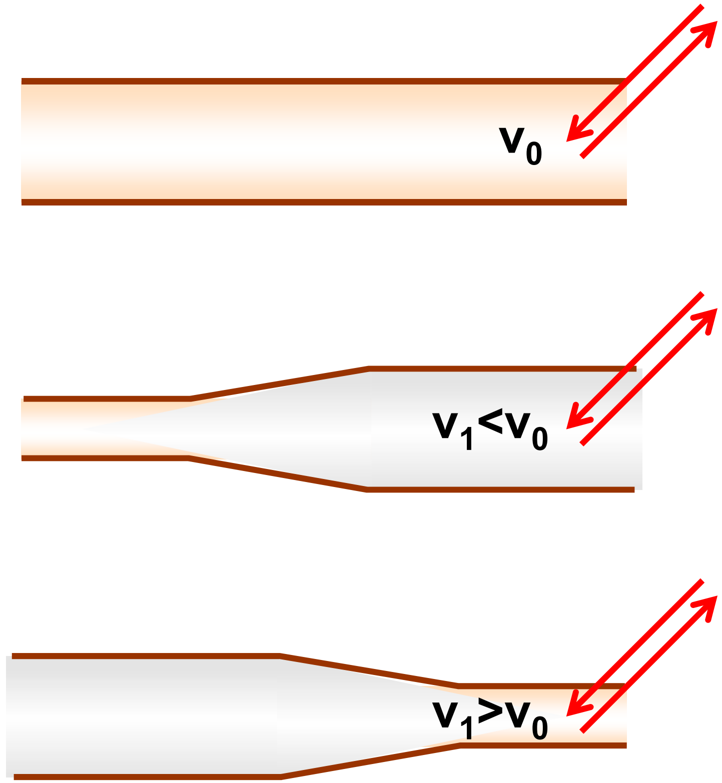
Laser Doppler flowmetry (LDF)

- **In medical applications, Doppler predominantly used to measure blood flow velocity → laser Doppler flowmetry (LDF)**
  - Microvascular blood flow and perfusion
- **Advantages of LDF technique**
  - Measurements can be made through the skin or into an artery using a fiber-optic catheter
  - Highly sensitive
  - Responsive to local blood perfusion
  - Versatile and easy to use for continuous real-time monitoring.
  - Non-invasive and non-contact (unlike Ultrasound)
  - Does not disturb the normal physiological state of the microcirculation
  - The small dimensions of the probes have enabled it to be employed in experimental and clinical environments not readily accessible using other techniques.



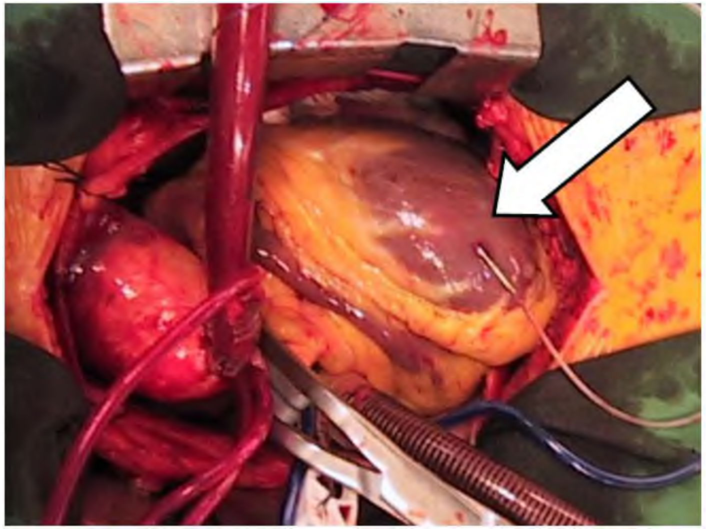
Laser Doppler flowmetry (LDF)

- **Limitations**
  - Currently LDF does not give an absolute measure of blood perfusion
- **Velocity change**
  - Slower blood flow can mean that there is a restriction “upstream” from the point of measurement.
  - Faster blood flow can mean that an artery is constricted at the site of measurement.



Laser Doppler flowmetry (LDF)

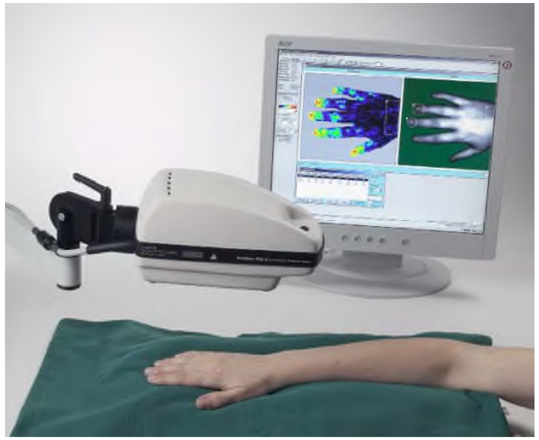
- **Applications of LDF**
  - Post-operative monitoring of free tissue transfer
    - Monitoring and quick recognition of disruption of flap perfusion reduces the flap failure.
    - (Burn depth assessment)
  - Allergy patch testing, skin diseases research
  - Gastroenterology
    - To assess blood flow of the gastric mucosa and disorders or to measure the effect of treatment intervention
  - Cerebral Blood Flow
    - To assess of cerebral blood in head injury patients
  - Pharmacology Trials
    - To assess the effects of topical or systemic vasoactive drugs on tissue blood flow
  - Tooth Vitality Testing
    - To assess the blood flow pulsation in the pulp capillaries
  - Laboratory animal studies
    - For ocular, cerebral, cutaneous, auricular, splanchnic, and renal blood flow

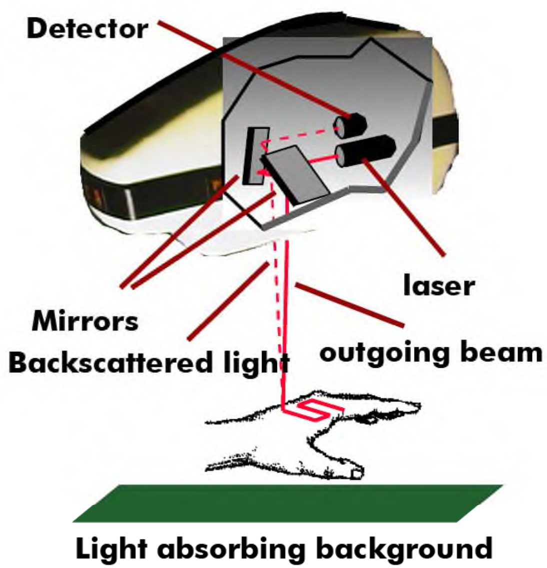


LDF measurements on the heart muscle during surgery

Laser Doppler imaging (LDI)

- **Laser Doppler blood flow imaging system for non-invasive mapping of blood flow in skin**
  - Low power laser beam scans the tissue recording measurement spots.
  - In the tissue, the laser light is scattered and changes wavelength when it hits moving blood cell (Doppler shift).
  - A fraction of the backscattered light is detected by a photo detector and the data is recorded and processed by software.
- **Perfusion image**
  - [concentration of moving blood cell] x [mean velocity of these blood cells]
  - The concentration is related to the magnitude of the Doppler signal
  - Velocity is related to the frequency shift



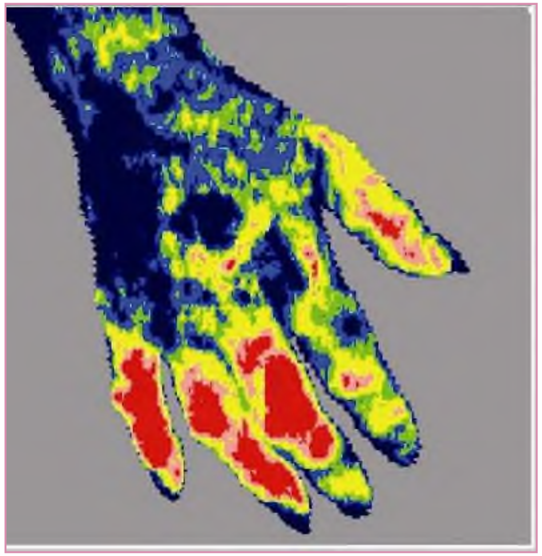


Laser Doppler imaging (LDI)

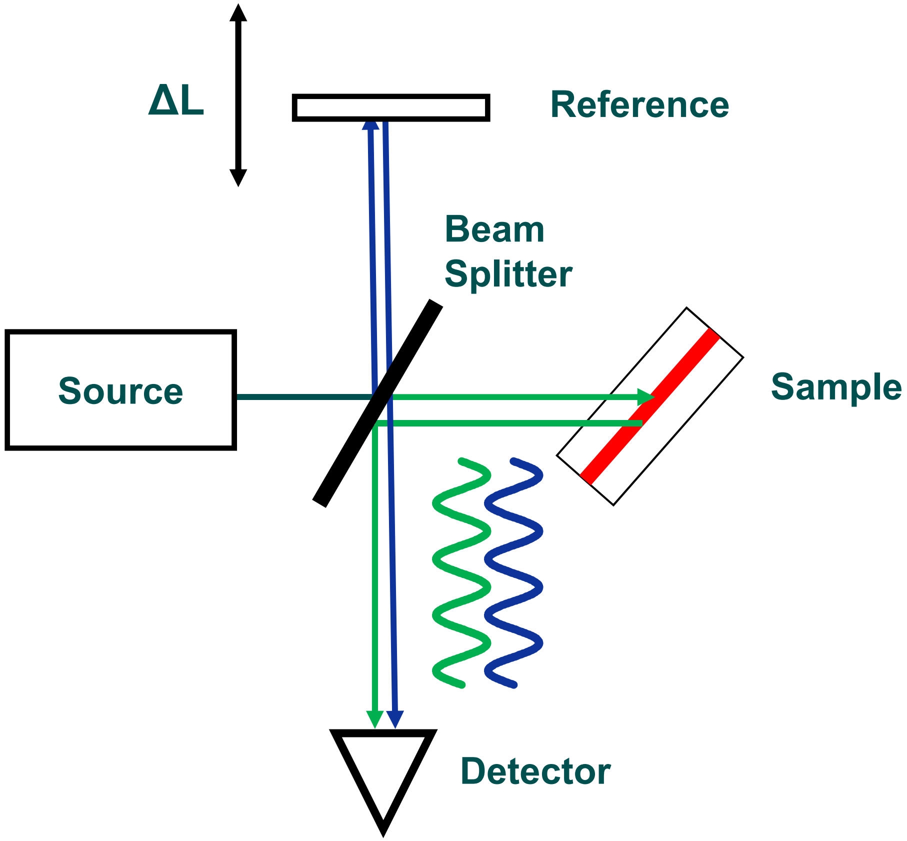
- **Advantages**
  - Doppler flow information in two dimensions
  - There is no direct contact with the skin/wound/burn
  - Can be used in addition to clinical evaluation to decide whether to treat with surgery
- **Limitations**
  - Laser scanned over surface of the skin
    - Requires scanning mechanism (size and speed limitations)

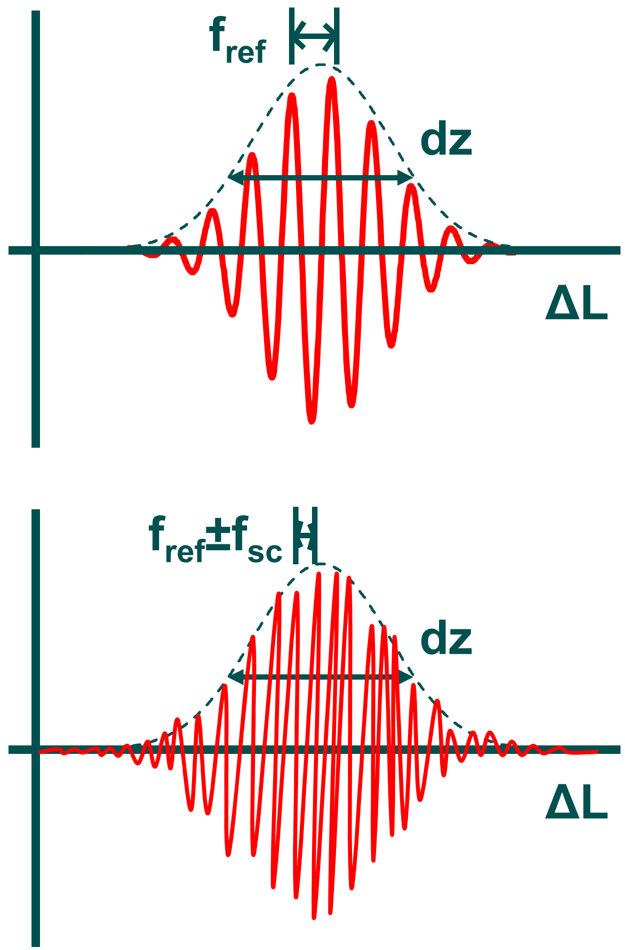
Laser Doppler imaging (LDI)

- **Assessment of burn wound depth and healing potential**
  - Fundamental in planning burn wound management
    - Deep dermal burn wounds are usually treated with surgery, which usually involves removing the damaged skin followed by skin grafting
  - Difficulties in burn wound assessment
    - Difficult to distinguish superficial dermal wounds from deep dermal burns
    - Difficult to assess burn wound depth on
      - a child
      - someone with dark skin (including those with suntan, birthmarks or tattoos)
      - when the injury is complicated by edema, tissue hypoxia or burn wound conversion
  - Clinical evaluation
    - Visual and tactile assessment is the most widely used method of assessing burns
    - Accuracy is dependent on the experience of the clinician
  - Enables decisions about surgery to be made earlier, and for some, for surgery to be avoided



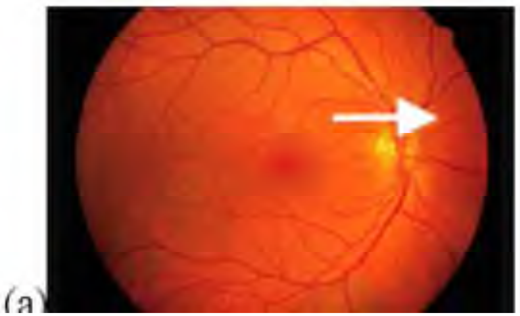
Doppler OCT

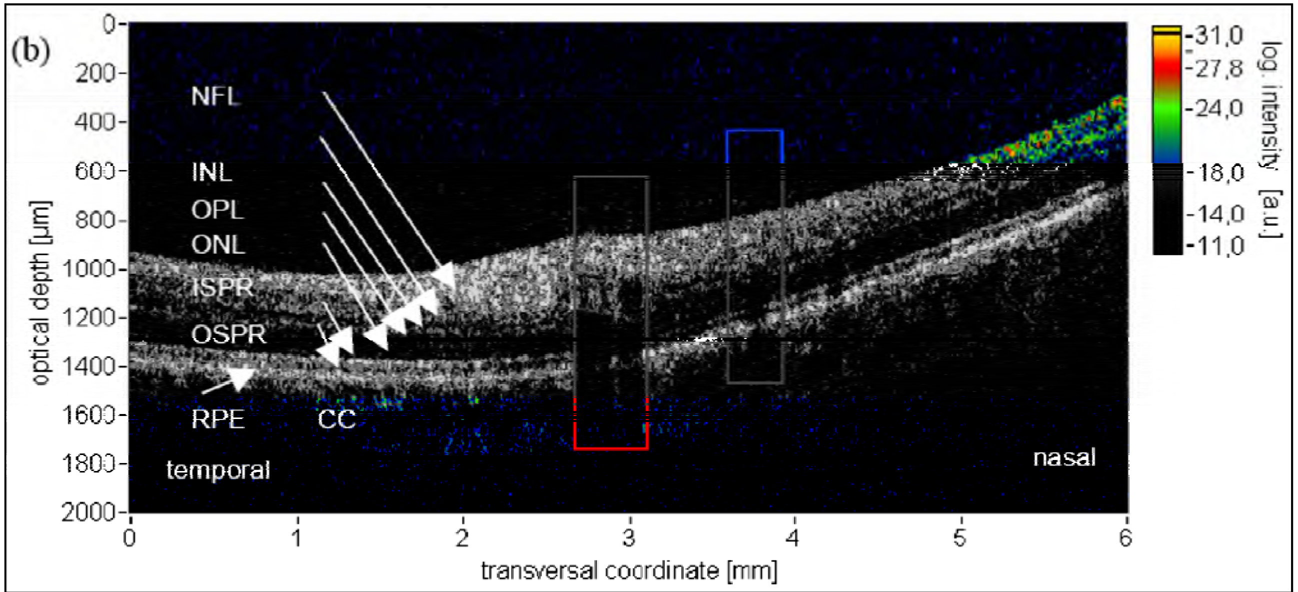


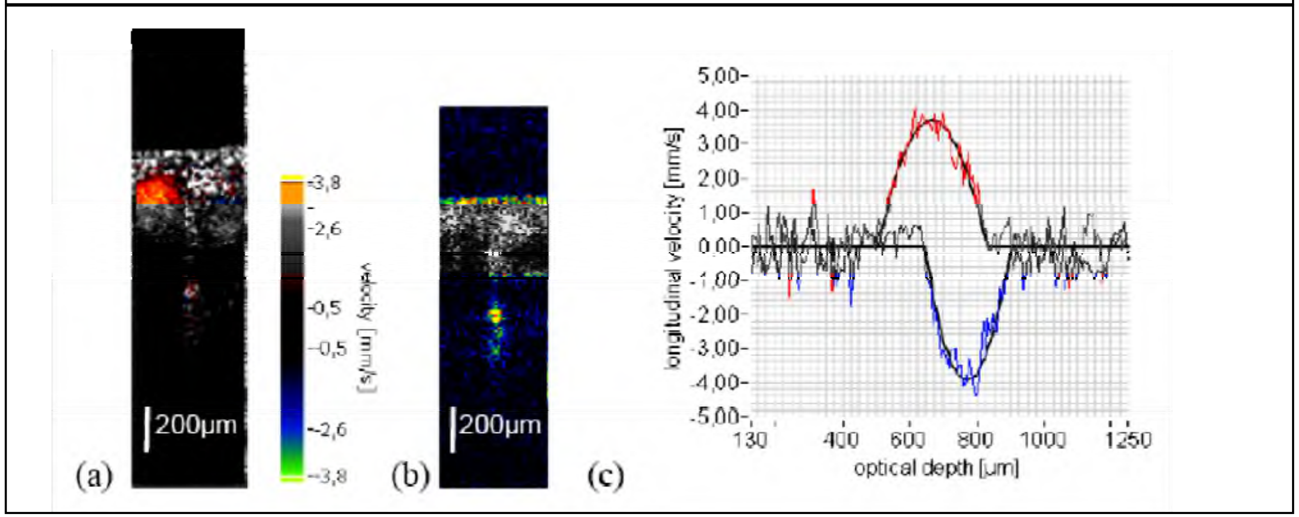


$$f_d = \frac{2v_{ref}}{\lambda_0} \pm \frac{2v_{sc}}{\lambda_0}$$

Doppler OCT



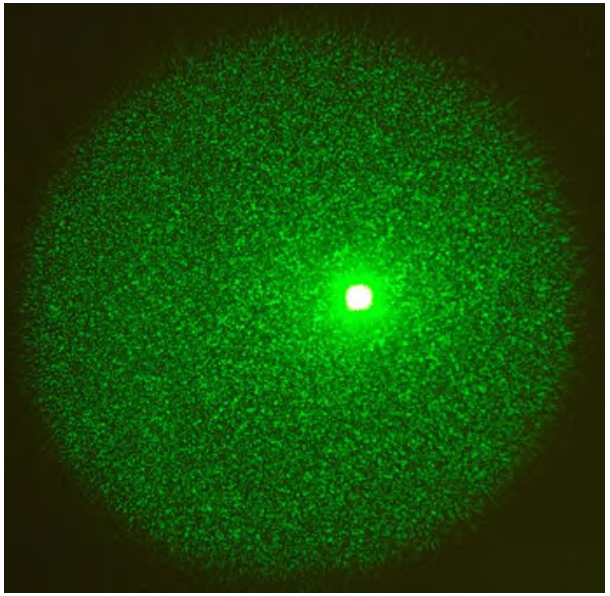




Retinal blood vessel flow Letigeb et al, Opt. Express 11, 3116-3121 (2003)

Laser Speckle

- **Speckle was discovered as an unexpected phenomenon when the first lasers were in operation (~ 1960)**
- **Optical interference effect**
  - Objects are illuminated with coherent (laser) or partially coherent light
  - Constructive and destructive interference from multiple sub-resolution objects
  - Grainy in appearance, with light and dark "speckles"
- **Laser speckle offers the possibility of developing a full-field technique for velocity map imaging**
  - Produces an instantaneous map of velocities in real time
  - No need for scanning
  - Blood flow measurement in assessing conditions such as
    - Inflamation, healing process, burn assessment, intra-operative measurement, dermatology (psoriasis, skin flap failure, skin irritation), physiology

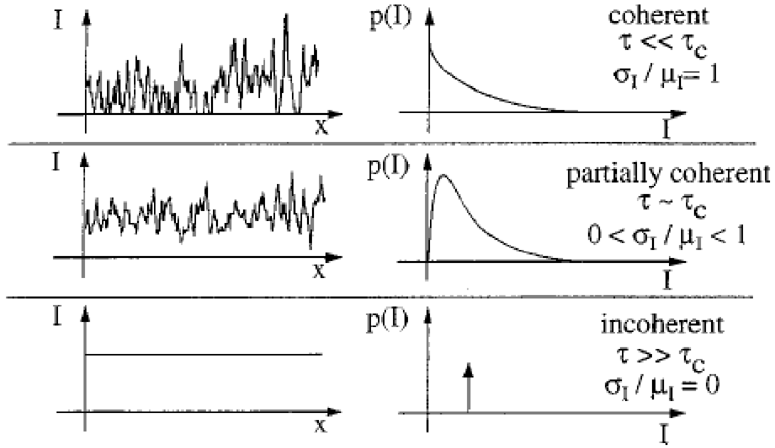


Laser Speckle

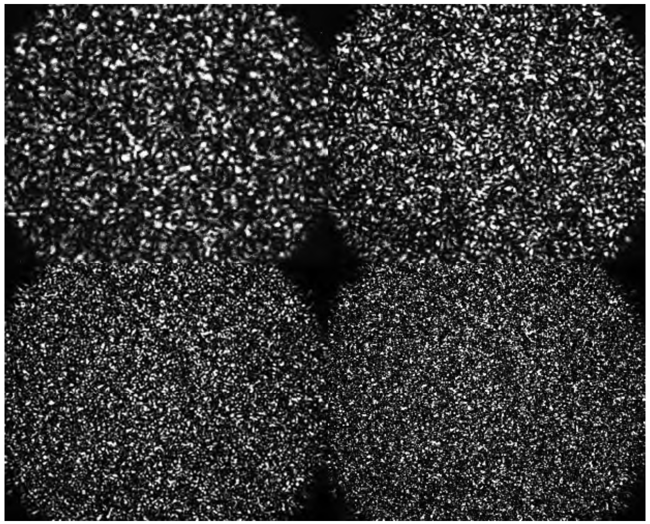
- **Properties of speckle**
  - A random phenomenon which can only be described statistically
  - The size of the individual speckles has in general nothing to do with the structure of the surface
    - Determined entirely by the aperture of the optical system used to observe the speckle pattern (eye, camera aperture, etc.)
  - Speckle contrast

$$C_{speckle} = \frac{\sigma}{< I >} \leq 1$$

    - σ: standard deviation
    - <I> mean intensity
  - Ideal case = 1
  - Completely blurred = 0



Thompson, APPLIED OPTICS, 36 (16) 3726, 1997

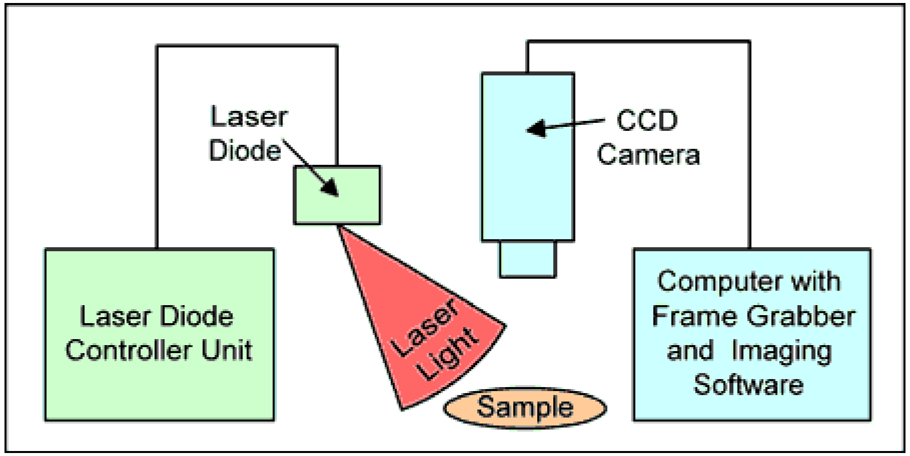


Laser Speckle

- **Time-varying speckle**
  - Speckle pattern changes with motion
  - Small movements of a solid object → speckles move with the object (i.e., they remain correlated)
  - Larger motions → speckles “decorrelate” and the speckle pattern changes completely.
  - Decorrelation also occurs when the light is scattered from a large number of individual moving scatterers, such as particles in a fluid.

Laser Speckle Imaging (LSI)

- **Acquire successive images of sample speckle**
  - Each image will display a slightly different speckle pattern, caused by the change of position of moving scatterers in the area of interest.
  - If the time lapse between images is known
    - Examine the intensity variation of individual speckles at the same position in each image
    - Calculate the velocity of the scatterers responsible for the variation.



Laser Speckle Imaging System

Laser Speckle Imaging (LSI)

- **Velocity (in arbitrary unit)**
  - Computed from the inverse of the correlation time
- **Relative velocities**
  - Relative spatial and temporal velocities can be easily obtained from the ratios of the correlation times
- **Absolute velocity**
  - Theoretically, it is possible
  - Relate the correlation time to the absolute velocities of the red blood cell
  - However, it is difficult to do in practice
    - The number of moving particles that the light interact with and their orientation are unknown.
- **The relative blood flow is computed by taking the ratio of the correlation time image at any point and a baseline image**

$$\frac{\sigma_s}{<\mathrm{I}>} = \left\{ \frac{\tau_c}{2\mathrm{T}} \left(1 - \mathrm{e}^{\frac{-2\mathrm{T}}{\tau_\mathrm{c}}} \right) \right\}^{\frac{1}{2}}$$

$$v \propto \frac{1}{\tau_c}$$

T: exposure time of the CCD

τ_c: correlation time

σ_s: standard deviation of the speckle pattern intensity

<I> : mean intensity of the speckle pattern

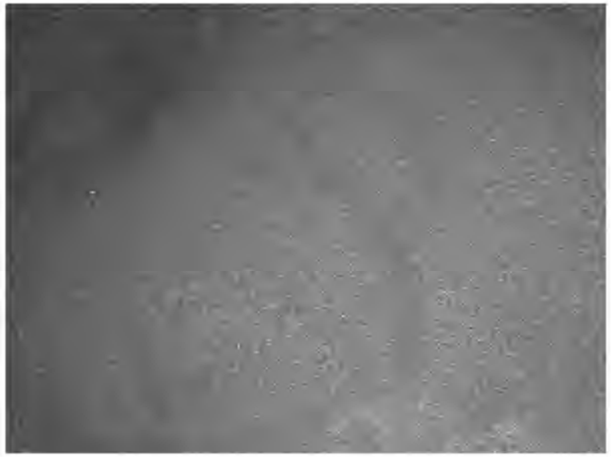
v: relative velocity

Laser Speckle Imaging (LSI)

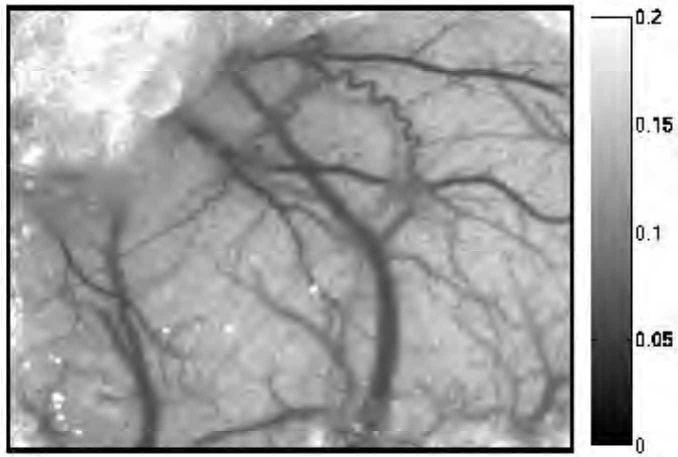
- **Important considerations**
  - Laser wavelength
    - Suitable to achieve some tissue penetration for blood flow mapping.
  - Pixel Size
    - To ensure proper sampling of the speckle pattern, the size of a single speckle should be approximately equal to the size of a single pixel in the image
  - ROI for statistical estimates
    - The size of the region over which the speckle contrast is computed must be large enough to contain a sufficient number of pixels to ensure accurate determination of standard deviation & mean intensity
    - But not so large that significant spatial resolution is lost
    - In practice: 5x5 or 7x7

Laser Speckle Imaging (LSI)

- **Raw Vs. Speckle Contrast Image**
  - 785 nm laser diode expanded to illuminate a 6x4mm area of rat cortex (skull removed, dura intact)
  - The area was imaged onto an 8-bit CCD camera
  - Speckle contrast range: 0 ~ 1
    - 1: no blurring of the speckle pattern
    - 0: the scatters are moving fast enough to average out all of the speckles
  - Darker color → higher blood flow



raw speckle image



speckle contrast image

D. Boas, Harvard Medical School

Laser Speckle Imaging (LSI)

Figure 13. Laser speckle contrast image of part of a forearm, showing increased perfusion around a superficial burn (scalded by steam).

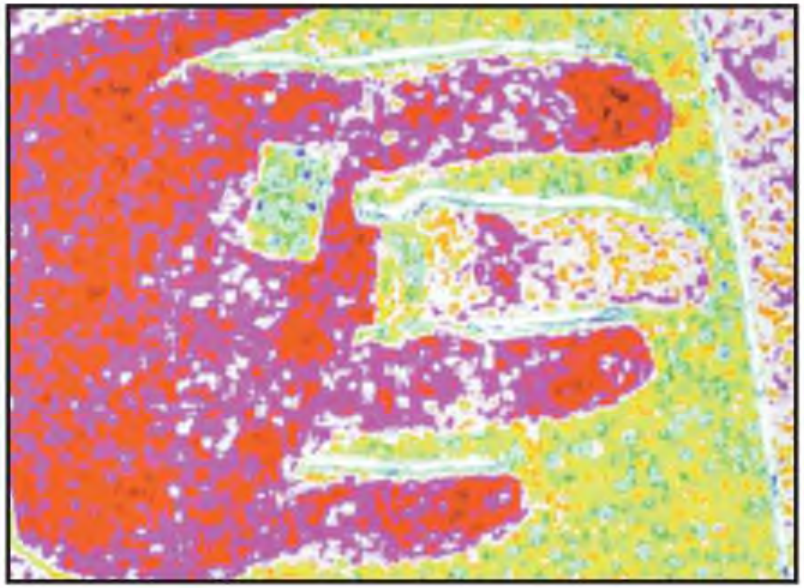
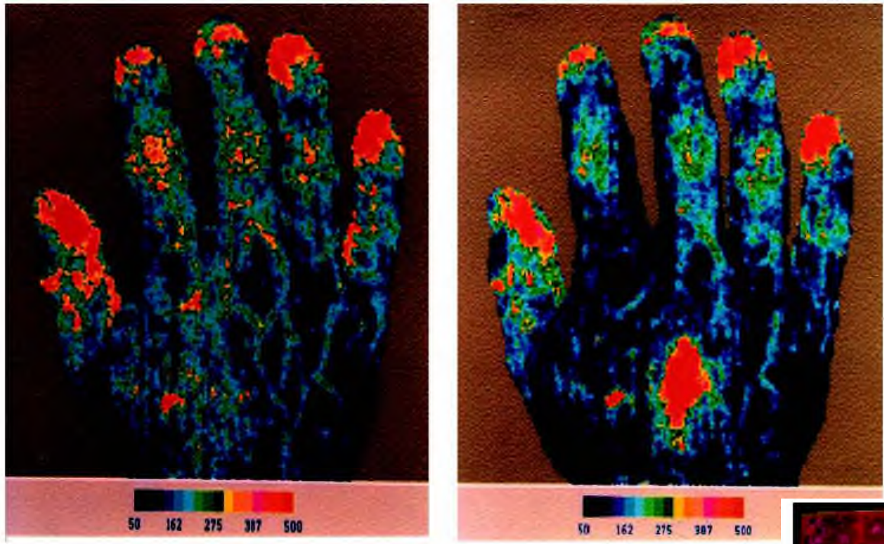


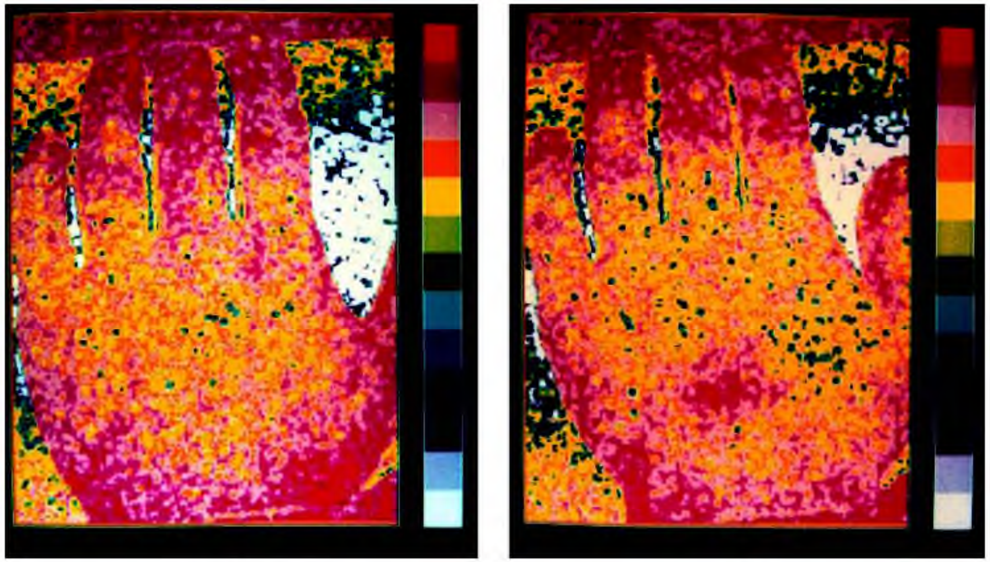
Image of a hand, showing the reduction in perfusion caused by a rubber band around the base of a finger. (The rectangle is a control patch to ensure there was no gross movement of the hand.)

Laser Speckle Imaging (LSI)



(a) (b)

Figure 11. Laser Doppler images, showing perfusion (a) before and (b) after gently scratching a small area on the back of a hand.



(a) (b)

Figure 12. Laser speckle contrast images, showing perfusion (a) before and (b) after gently scratching a small area on the back of a hand.

Laser Speckle Imaging (LSI)

- **Comparison Four Blood Perfusion Imager**

	Laser Doppler imagers		Laser speckle contrast imagers	
	Moor Instruments (moorLDI)	Lisca AB (PIM II)	Kingston (LASCA)	Harvard
Wavelength	633, 685, 780 and 830 nm	670 nm	633 nm	780 nm
Depth probed	0.1–2 mm	0.1–1 mm	0.1–1 mm	0.1–1 mm
Laser power	2 mW	1 mW	30 mW[a]	30 mW[a]
Maximum scan area	500 × 500 mm	300 × 300 mm	150 × 150 mm[a]	20 × 20 mm[a]
Pixels displayed	256 × 256	256 × 256	640 × 480	640 × 480
True resolution	256 × 256[b]	64 × 64[c]	128 × 96[d]	128 × 96[d]
Time for image capture or scan	5 min[e]	4 ½ min[f]	1/50 s	1/60 s
Time for capture plus processing	**5 min[e]**	**4 ½ min[f]**	**1 s**	**1 s**

[a] **As the whole area is illuminated in the laser speckle technique, the laser power required will always be higher than that of the scanning laser Doppler imagers. However, the power required can be reduced by having a more sensitive CCD camera or by imaging a smaller area. Likewise, the area that can be imaged depends on the laser power and the** camera sensitivity. The areas quoted here are those actually used by the groups concerned.

[b] The moorLDI processes each pixel in the array, at the expense of a relatively slow scan rate.

[c] The Lisca PIM II processes an array of 64 × 64 pixels and interpolates this to obtain the 256 × 256 display.

[d] The quoted resolution for the laser speckle contrast imagers assumes that a 5 × 5 pixel block has been selected for computing the local contrast. If a 7 × 7 block is used, in order to improve the statistics, the true resolution is reduced to 90 × 70 pixels.

[e] By reducing the number of scanned points to 64 × 64, the scan time can be reduced to 40 seconds.

[f] This can be reduced to just over 1 ½ minutes at the expense of image quality.

Laser Speckle Imaging (LSI)

- **Endoscopic Laser Imaging of Tissue Perfusion: New Instrumentation and Technique**

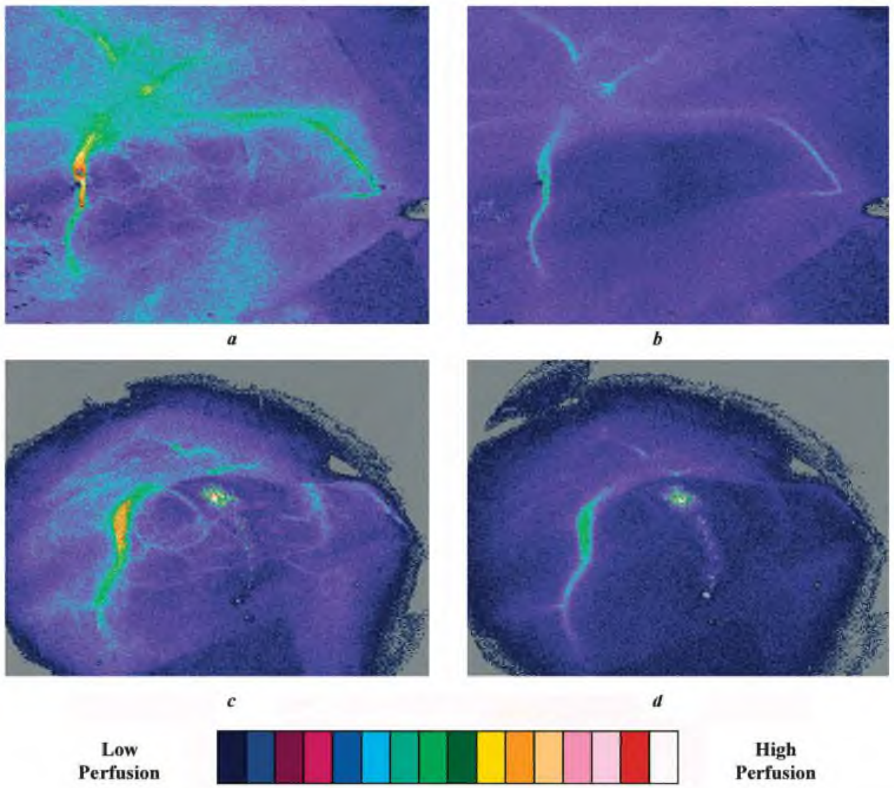
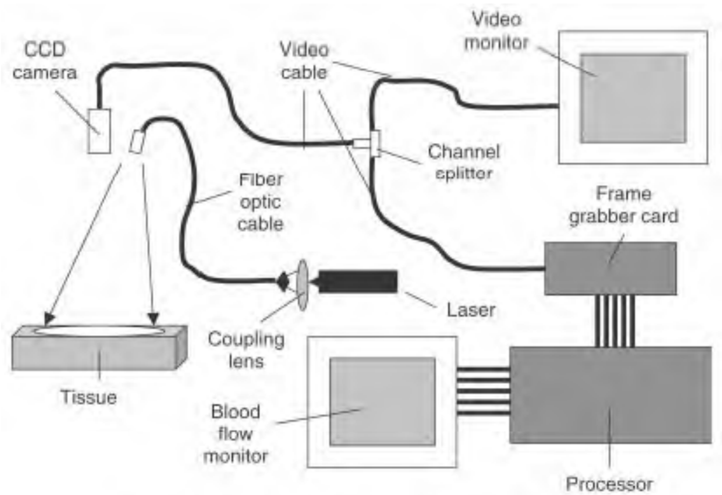


Fig. 3. LSI perfusion images of rabbit knee joint capsule. **a**, **b**: Images obtained with remote instrument; (**c**, **d**) images obtained with endoscopic instrument; each pair of images shows blood flow to the joint capsule before and after femoral artery occlusion.

In-Vivo Measurements

Figure 3 compares perfusion maps of rabbit MCL generated using the remote LSI and the endoscopic LSI. The images are color coded, with low flow areas represented by blue, moderate flow areas represented by green and yellow, and high flow areas represented by pink, red and white. Figure 3a,b show the decreased blood flow to the joint capsule produced by femoral artery occlusion measured using the remote LSI system. Figure 3c,d show similar images generated with the endoscopic LSI system. The field of view is similar to the remote instrument and the same blood vessels can be seen in each image. The dark blue object in the bottom left corner of each image is a corner from the square target used for motion detection.



Block diagram of remote LSI instrumentation.