Ultrasonic Physics in Musculoskeletal System

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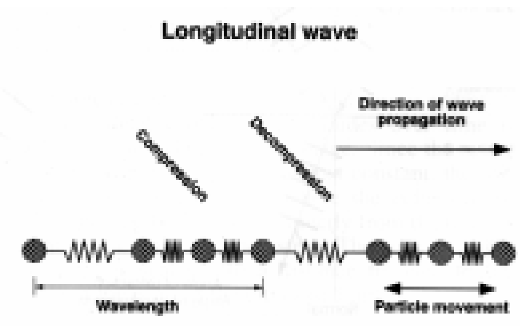
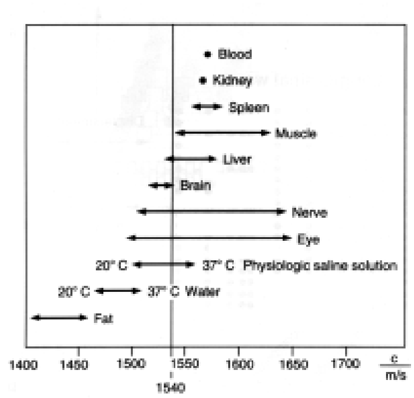
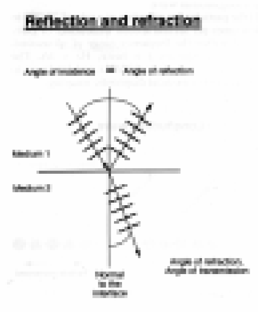
Ultrasonography provides a less expensive and dynamic imaging of various disorders of musculoskeletal system. Disorders of tendons, musculature, bone cortex and soft tissues can often be accurately interpreted using clinical ultrasound. In terms of ultrasonography, the understanding of the physical principles of ultrasound is as important as the knowledge of anatomy.

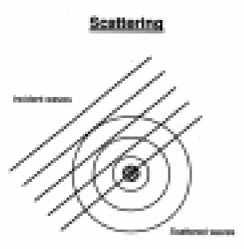
超音波基本物理特性

- 音波可以傳遞機械能，而以應力波在介質引導下行進
- 超音波組織辨識是利用其縱向波特性(波行進方向與震動方向平行)
- 臨床超音波的頻率一般在 2 MHz - 30 MHz 之間，表示每秒震盪數百萬次，但是所使用的振幅很低、能量不大。由於頻率遠高於人耳的聽覺範圍(20Hz-20kHz)，所以稱為超音波。
- 超音波必須依賴介質來傳遞波的能量與動量，若不考慮空氣氣泡或骨頭的影響，在人體軟體組織間傳遞速度大約為 $c = 1540$ m/s ；$c = \lambda f$ 。
- 超音波在人體組織間傳遞，若是遇到組織界面，舒密程度改變，會有部份能量反射(Echo)，反射波的強度與界面組織之聲阻抗差異有關，有時會有折射的現象。 當超音波遇到移動之血球，則因血球的尺度(2-10μm)遠小於超音波的波長(mm)，會產生波的散射的現象(Scattering)。



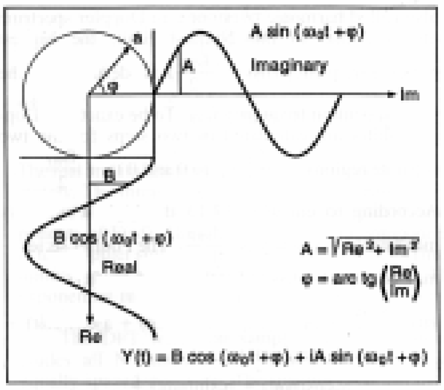


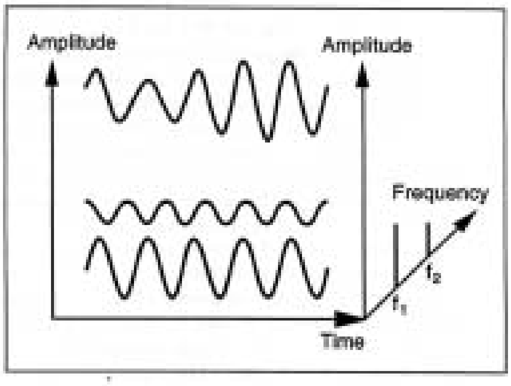




超音波之振幅、頻率、能量與傳播速度

超音波的波動強度、頻率為簡諧運動。 在人體組織假設傳導速度為一定值。
超音波的聲壓強度(Intensity)與聲壓大小(P)的平方成正比，與材質的密度(ρ)及聲速(c)成反比。 $I=P^2/2\rho c$。



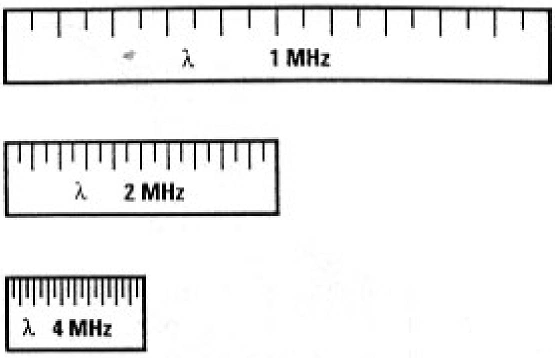


各種材質之聲波傳播速度

Non-biological Materials	Speed of Sound (m/s)	Biological Materials	Speed of Sound (m/s)
Air	330	Lung	600
Water	1480	Fat	1460
Lead	2400	Liver	1555
Aluminum	6400	Blood	1560
		Kidney	1565
		Muscle	1600
		Lens of Eye	1620
		Skull Bone	4080

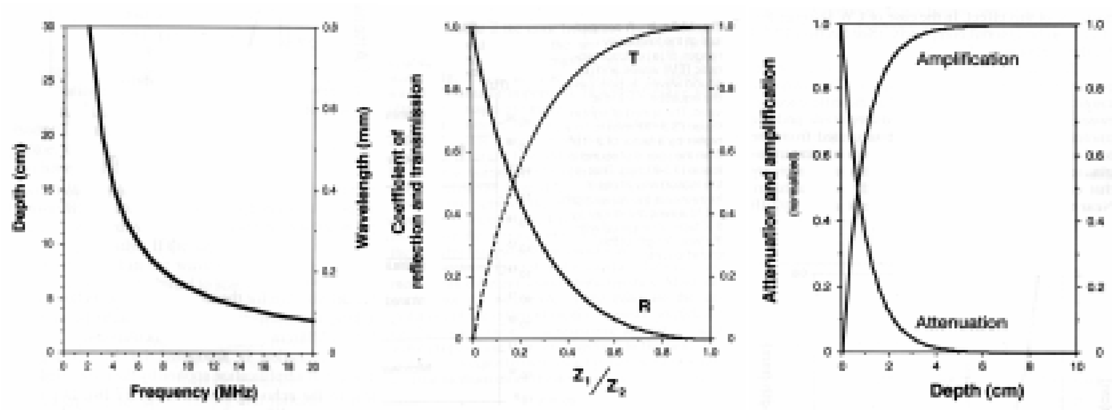
超音波掃描之空間解析度

由於超音波的波長如同量測尺的刻度，愈是高頻的超音波其刻度愈精密，空間解析度愈高。



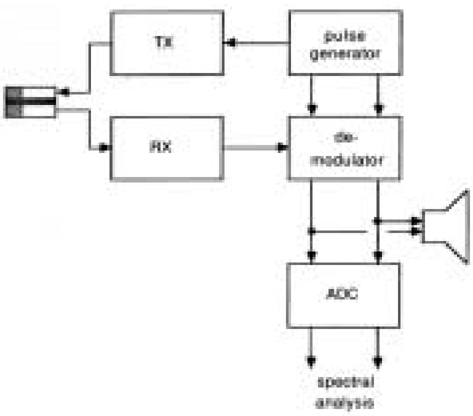
超音波之穿透能力

- 當超音波穿透人體組織時, 部份的能量被組織吸收, 部份的能量穿透組織。 穿透與反射的強度與界面間聲阻抗比值(Z_1/Z_2）有關。 所以超音波強度會隨著深度衰減，衰減的程度與超音波之頻率高低也有關，頻率愈高雖然空間解析度高但是穿透力則較差。
- 一般而言、超音波來回綜合衰減(attenuation)約為 0.5-1.0 dB/MHz cm，所以回聲訊號需用深度補償(DGC)作動態修正。

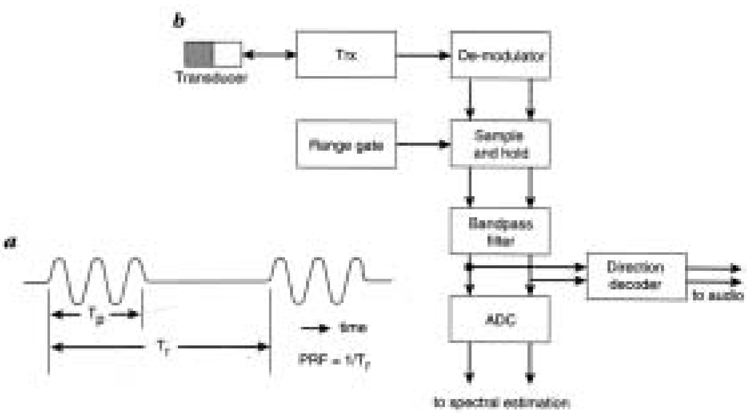


超音波聲源系統基本架構

- 連續波（Continuous Wave）*超音波系統*
- 脈衝波 (Pulse Wave) *超音波系統*



CW US

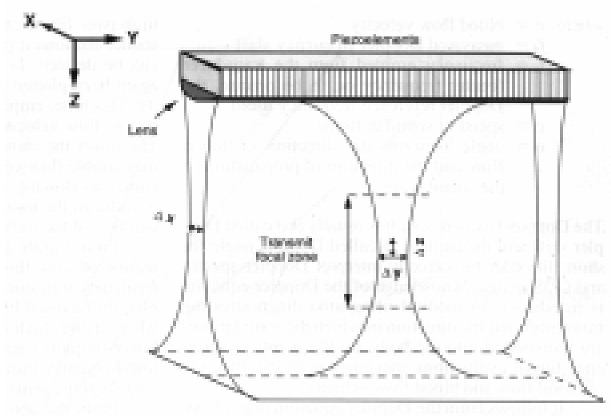


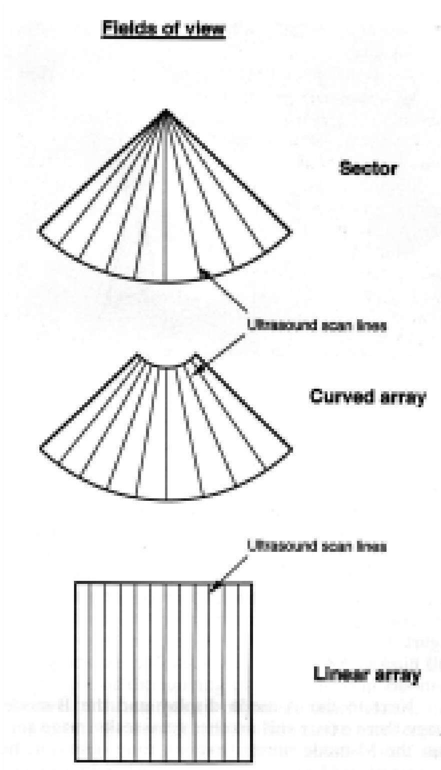
PW US

CW vs. PW Doppler Ultrasound Measurements

Continuous Wave (CW) Doppler	Pulse Wave (PW) Doppler
+ Sensitivity	+ Spatial resolution
+ Inexpensive	+ Visibility and Focusing
+ High S/N ratio	+ Angle correction
+ Low power	- High power
- No spatial information	- Low S/N ratio

<u>超音波掃描聚焦特性</u>





<u>Color Duplex 超音波的影像</u>

(1) 灰階影像 - 掃描區內組織構造(Morphology)；
(2) 彩色影像 - 掃描區內血液或組織移動特性

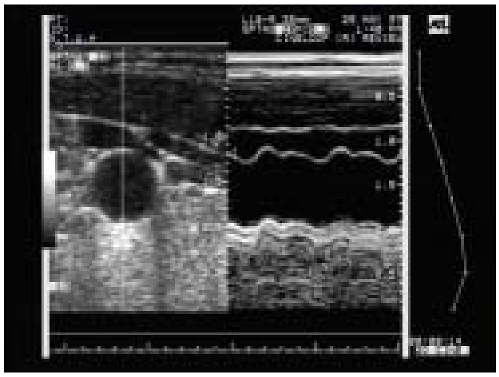
* 兩種影像的基本原理與代表之物理意義不同

* 由於掃描深度及影像處理速度限制，動態影像 在取樣時間解析度 (Frame Rate) 與影像的解析度(Spatial resolution)上很難兼顧

超音波掃描顯示方式

- A 模式顯示反射波的振幅大小; 在聲速固定的假設下 反射點位置可以由回聲訊號延遲時間來代表。
- B 模式是以多條 A模式掃描排列而得。反射波振幅大小以灰階影像亮度表示。由於已知掃描線間隔，可以顯示二維組織幾何影像。灰階對比可以表示組織界面的聲阻抗差異。沿著超音波掃描線，空間的解析度與超音波探頭發射之頻率有關，最大量測深度取決於各脈衝波的時間間隔(Pulse Repetition Frequency)。
- M 模式是連續使用同一條掃描線，觀察回聲（掃描線灰階影像)隨著時間變化的關係。

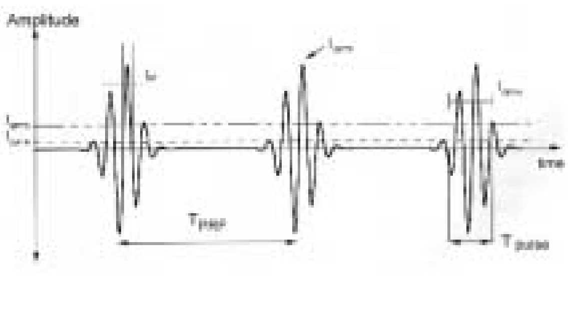
B-mode image of a liver and gall bladder.

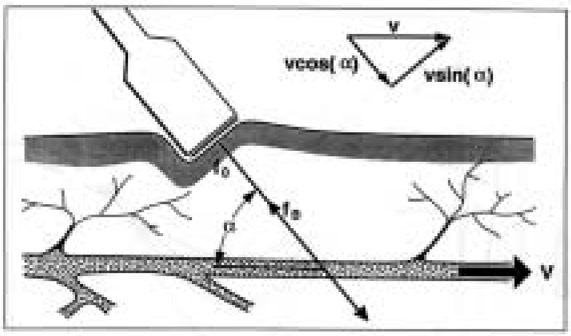


超音波都卜勒（Ultrasound Doppler)

The Doppler effects was first observed and formulated in 1842 by Austrian physicist Johann Christian Doppler (1805-1853). This phenomenon occurs when the source and the receiver are mowing relative to each other. If the sound source is moving toward the receiver, the receiver will obtain a sound wave at a higher frequency than the emitted wave. The frequency-increment is proportional to the magnitude of approaching velocity. Doppler ultrasound provides a non-invasive measurement of blood flow in human body, the first attempt has been done by Satomura (1956) in the investigation of flow in the heart.

- 超音波都卜勒將回音都卜勒訊號 (Pulse-Echo cycles) 做頻譜處理，脈波間隔時間 (T_{PRF}) 與深度有關，必須大於超音波往返的時間。
- 超音波都卜勒掃描角度夾角要小於70度，以免流速誤差過高。





$$f_d = \frac{2\ V\cos\alpha}{C}\ f_o$$

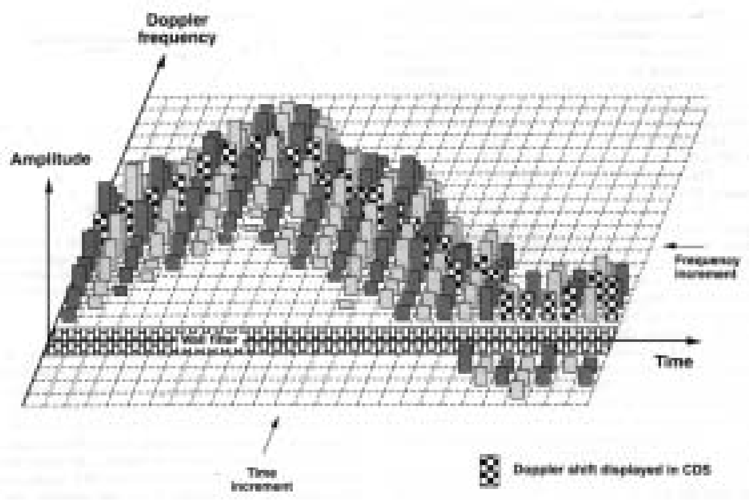
Scattering of Red Blood Cells

超音波都卜勒頻率之解析度

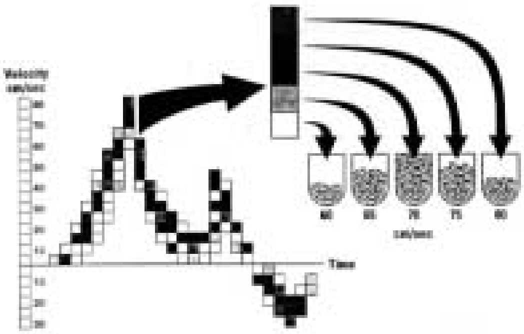
- ❖ 軸向的空間解析度與超音波的脈衝長度與脈波形狀有關
- ❖ 可偵測到的最大(流速) 頻移$f_d < 0.5\ f_{PRF}$。
  例如：觀測血管深度在15 cm時，f_{PRF}約為5.13kHz，因此當頻移(速度)大於2.6kHz 時，就會有些訊號超過部份會被切掉，而頻率高於 $f_{PRF}/2$ 之能量會被疊加到負頻的部份而造成訊號失真 (aliasing)。

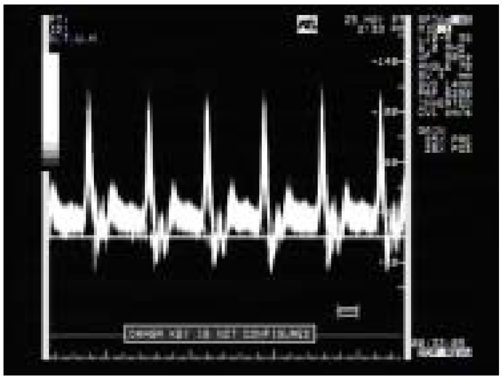
彩色超音波都卜勒(CD)

- ❖ 顯示的速度分為Mean averaged velocity 及Intensity-weighted average velocity 兩種。
- ❖ 由於流速在同一取樣中未必為單一值，在每一個間隔時間，能量最大的都卜勒頻移被轉換成為流速之數值。
- ❖ 一般以紅色表示速度向探頭而來，藍色代表血流遠離探頭。 亮度代表流速數值的高低。 而流速分佈差異(Variation)可用綠色成分混和。

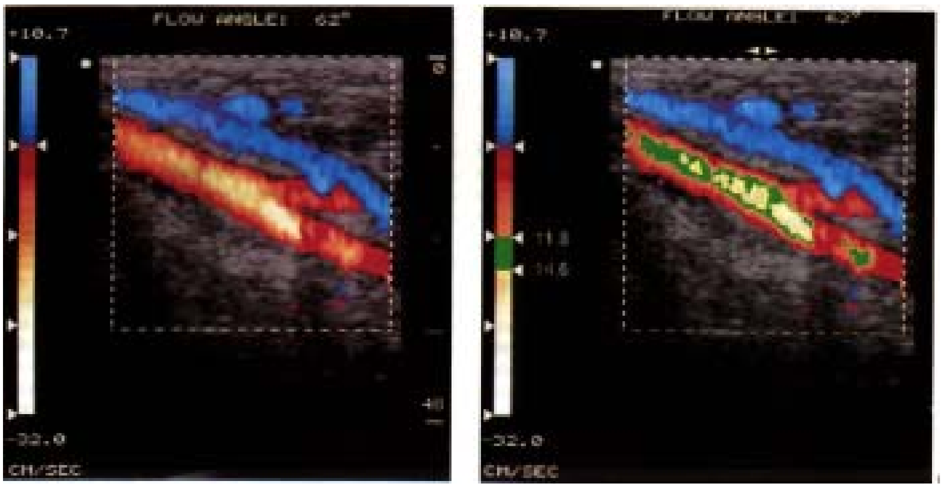


Three-Dimensional display of Doppler Spectra

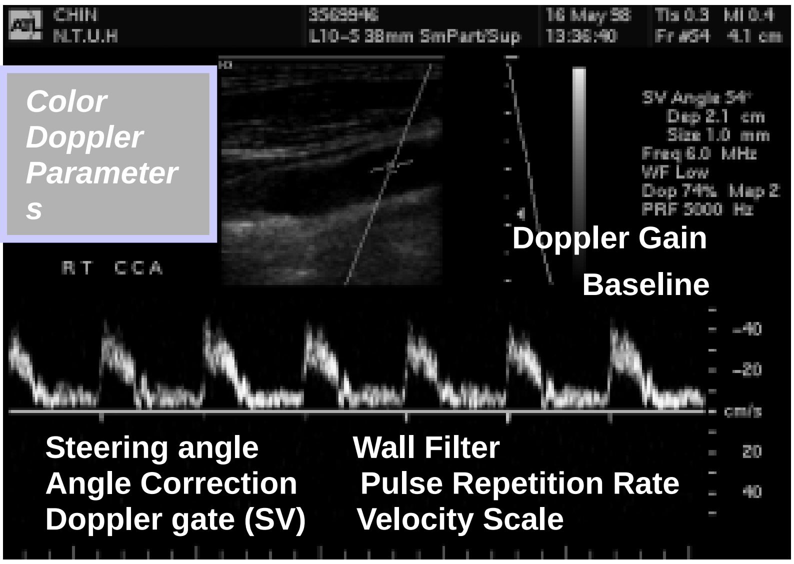




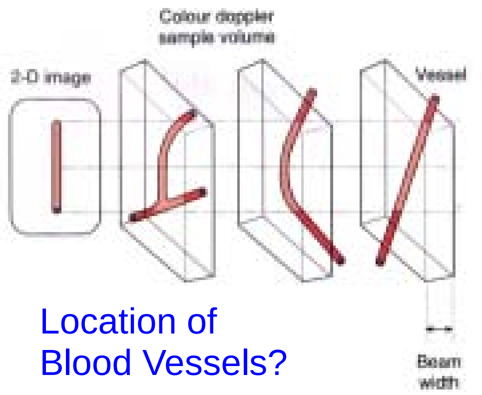
RBC volume → Brightness

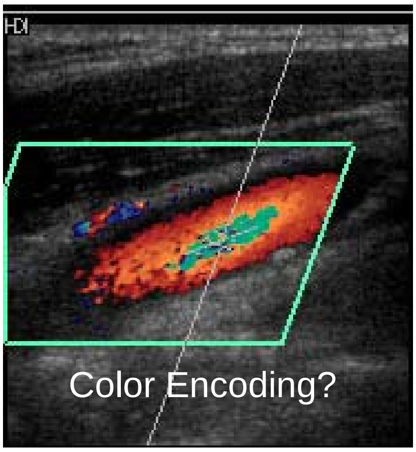


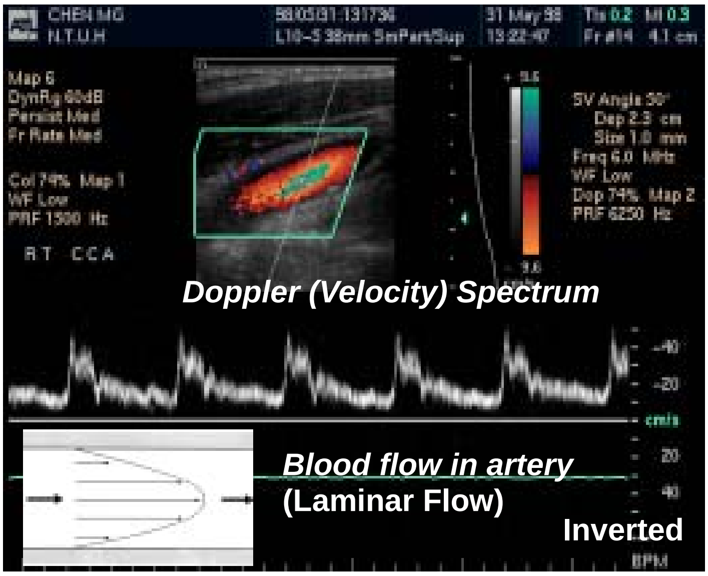
Color Doppler Color Coding

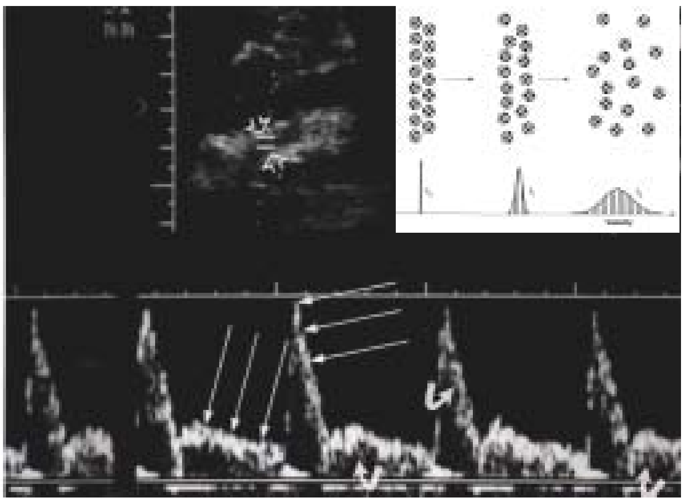


<u>Color Doppler for finding Blood Vessel</u>



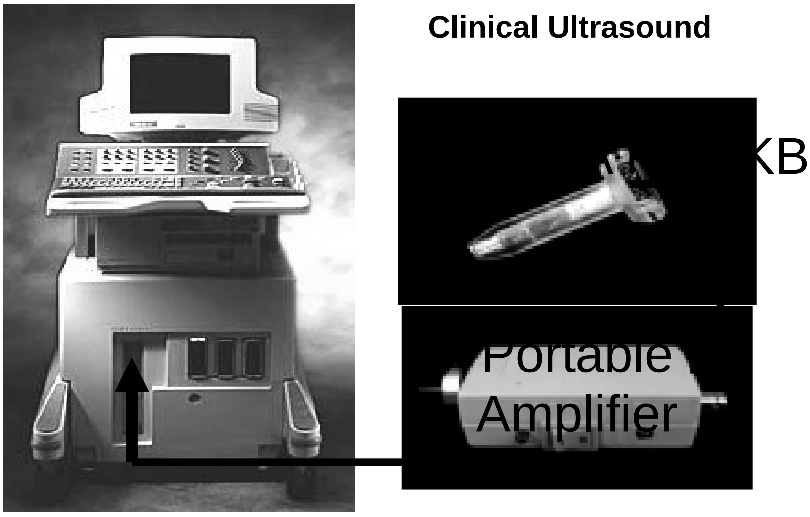




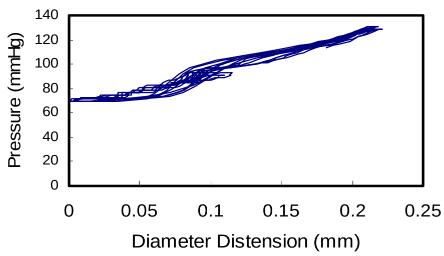


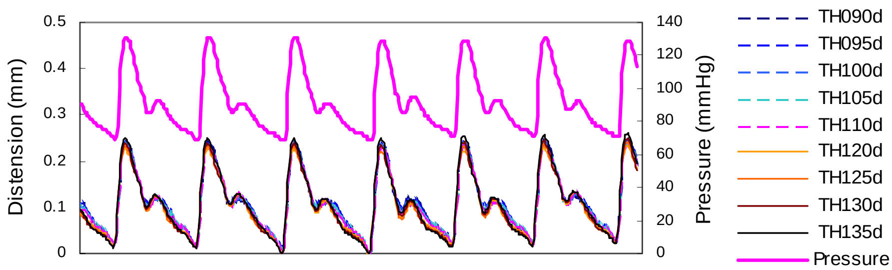
Clinical Applications of M-Mode Ultrasound

Clinical Ultrasound



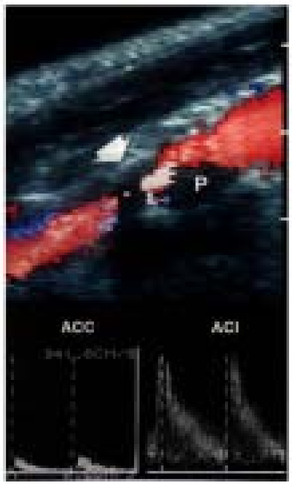
Non-invasive Assessment of Arterial Elasticity



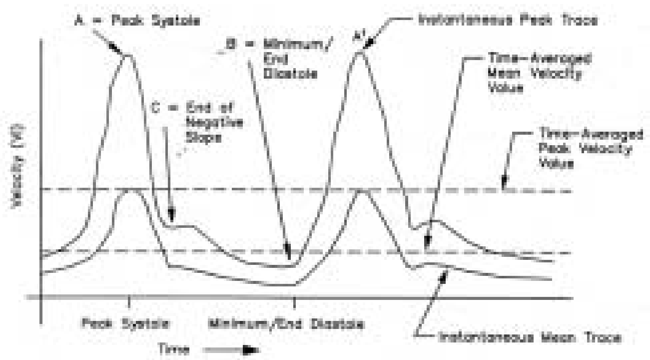


Clinical Applications of Color Doppler Ultrasound

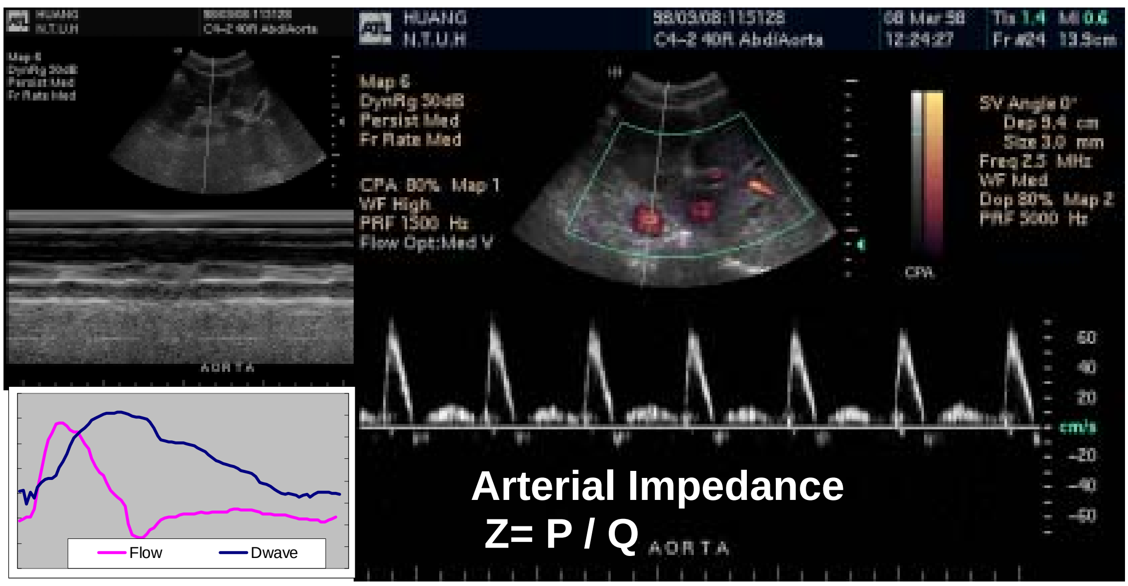
- ***Arterial Stenosis* (turbulent jet)**
- ***Arterial Resistance***
- ***Tumor Vascularity (feeding artery Doppler spectrum)***
- **Vascularity of Renal/Liver Transplants (predicting rejection)**
- **Tumor Vascularity (angiogenesis, malignancy and metastases)**



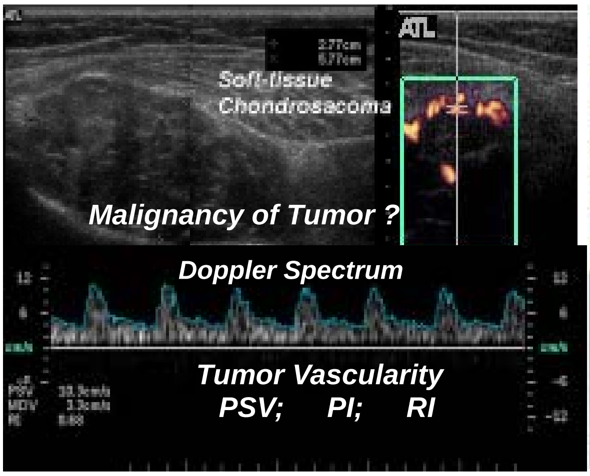
Stroke
(ICA stenosis)

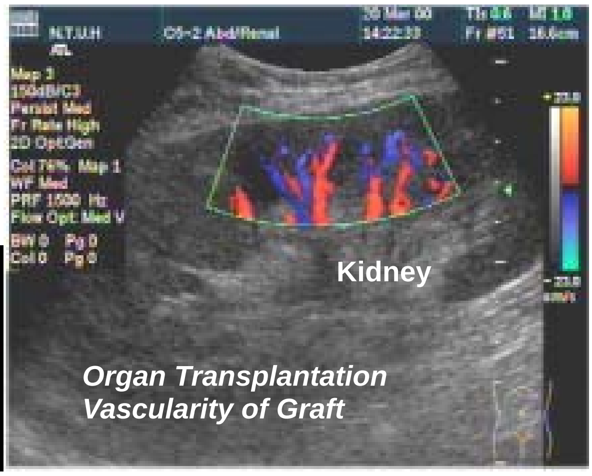


Exploring Doppler Spectrum



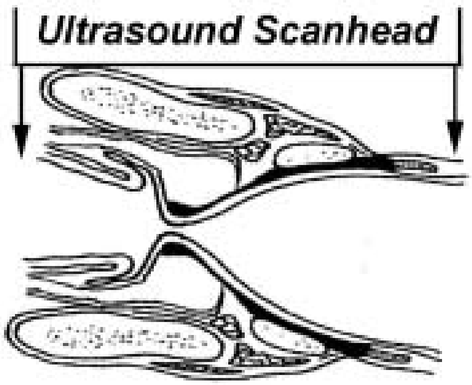
Non-invasive Assessment of Arterial Impedance (Vascular After-Load)

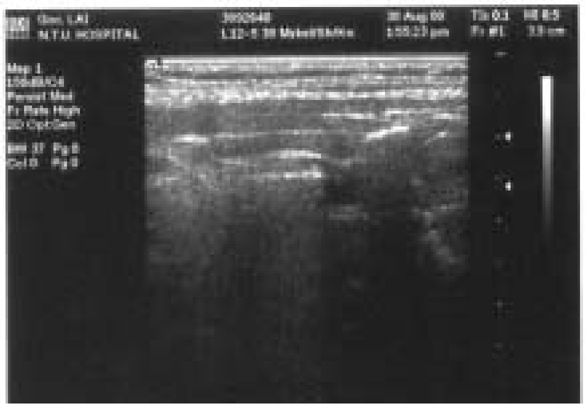


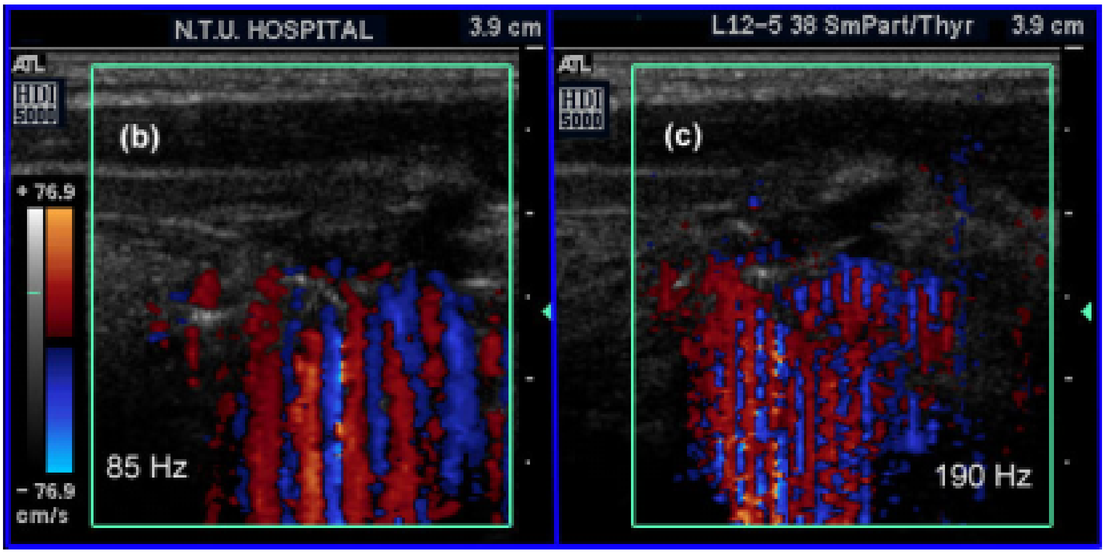


Noninvasive Assessment of Vocal Folds Biomechanics

(Vibratory Motion Color Artifact)

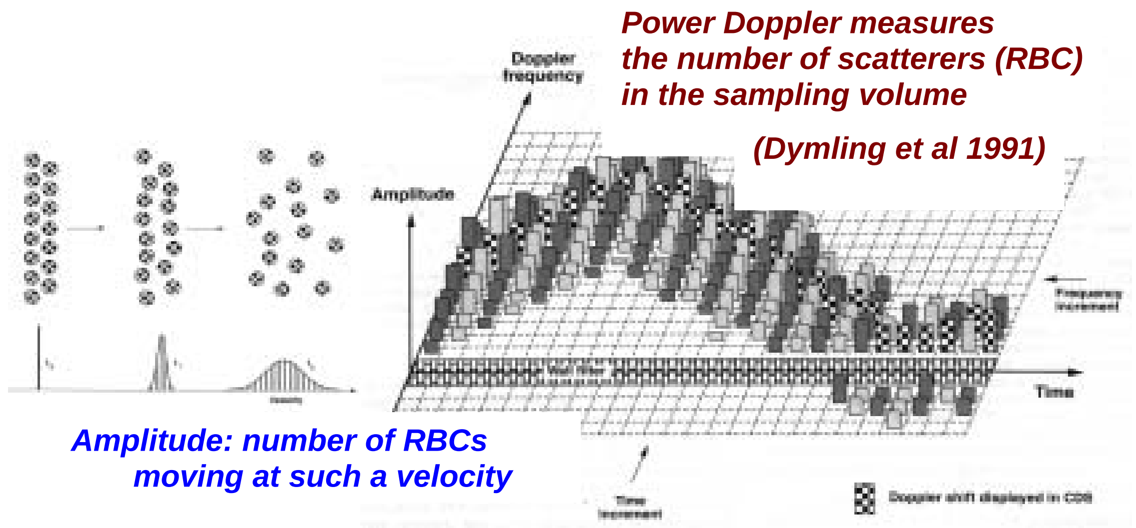






Power Doppler Ultrasound

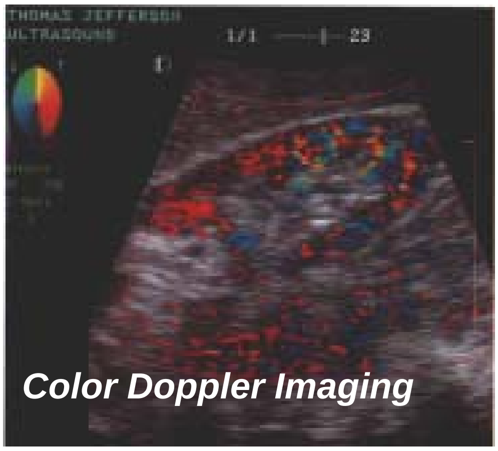
Power Doppler is a new method of ultrasound flow imaging that based on the integrated power of the Doppler spectrum rather than the mean Doppler spectrum. Power Doppler imaging is more sensitive in terms of blood flow detection than conventional color Doppler, thus it has the potential of displaying tissue perfusion. Since the **strength of power Doppler is proportional to the number of scatterers (RBCs)** flowing through the region-of-interest (ROI). Its relation to the flow volume is quite complex. Nevertheless, it is inherently unaffected by aliasing (i.e., low PRF) and relatively insensitive to the insonating angle or scanning depth.

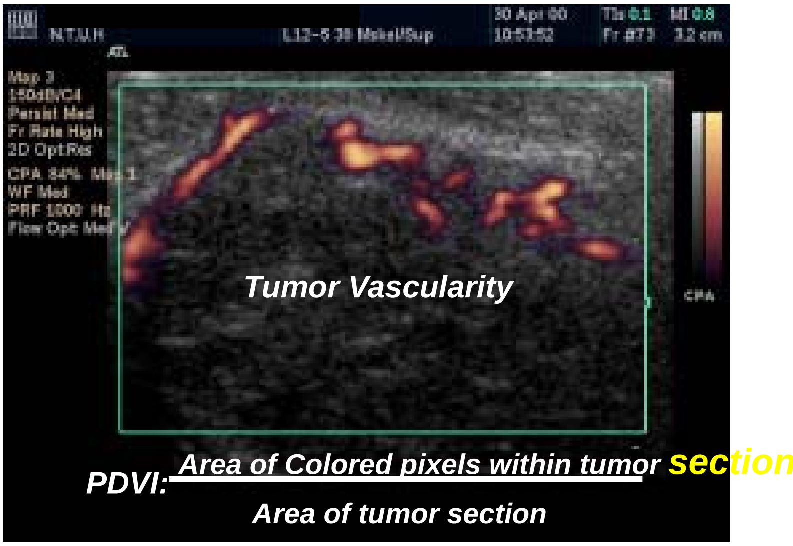


Clinical Applications of Power Doppler Ultrasound

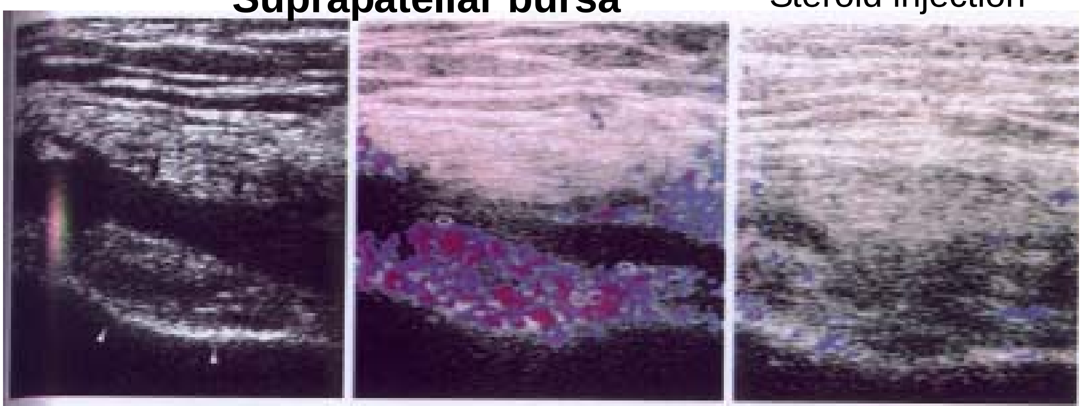
Since the **power Doppler (PD)** can **quantify** the fractional of moving blood volume through the ROI, attempts have been made to investigate the **soft tissue perfusion** in various hypervascular microvessel beds. The power Doppler imaging are often normalized and optimized to enhance the signals of moving scatters at low velocities (0.8 – 6 cm/sec), its magnitude does not proportional linearly to blood velocity. However, due to high sensitivity of tissue perfusion, the potential applications of PD are:

- ✧ *vascularity in normal and transplanted renal tissues for rejection prediction,*
- ✧ *tumor vascularity for malignancy and metastases*
- ✧ *placental vascularity for possible previa accreta,*



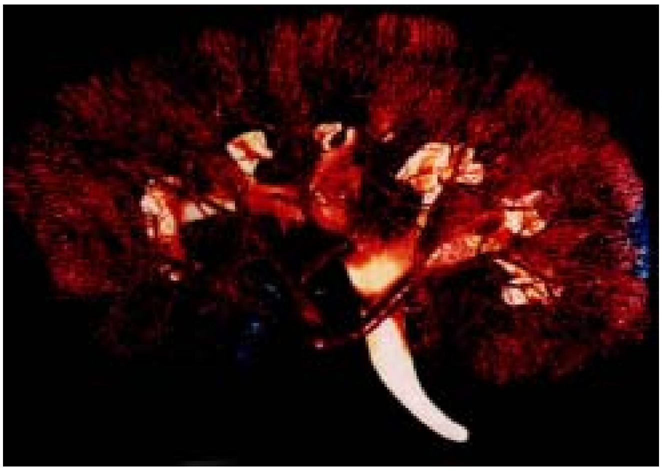


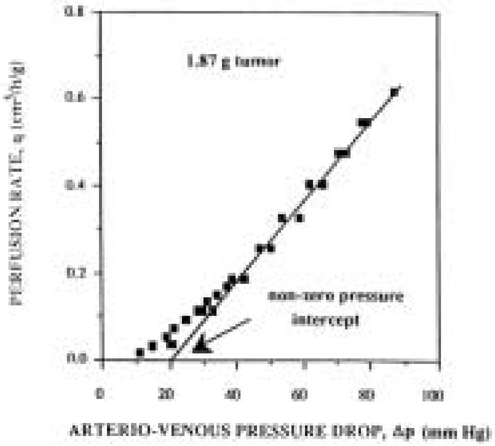
Suprapatellar bursa Steroid injection



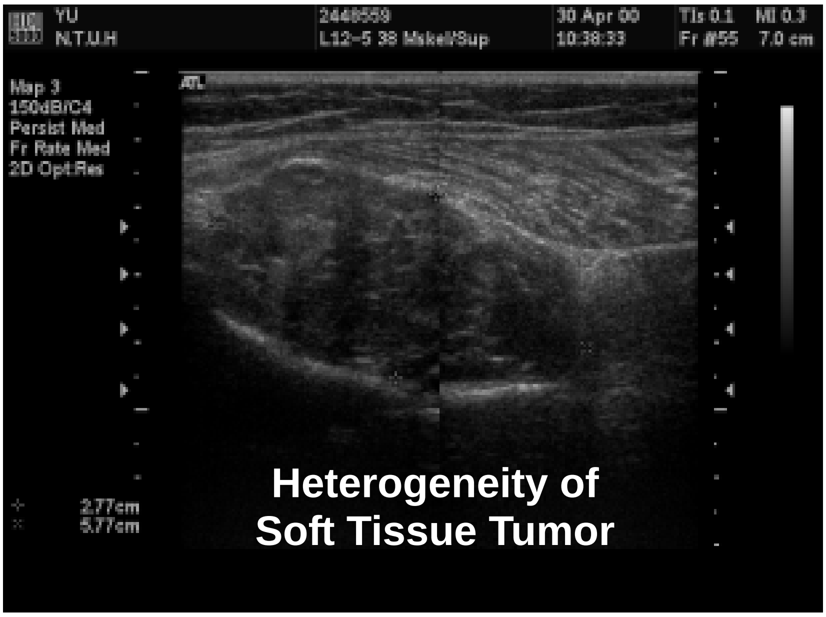
b. c.

…gure 1. Images were obtained in a 62-year-old woman with calcium pyrophosphate deposition disease and bilateral knee pain. (a) Trans…erse gray-scale US scan of the suprapatellar bursa shows a moderate knee effusion (arrows). Arrowheads indicate the cortex of the femur. (b) Corresponding transverse PDS image reveals marked hyperemia within the synovium and adjacent tissues (arrows). (c) Transverse PDS image obtained 8 days after aspiration and intraarticular steroid injection reveals substantial diminution in synovial perfusion, which corre…ated with improvement in symptoms.





1.87 g tumor
non-zero pressure intercept
PERFUSION RATE, q (cm³/h/g)
0.0
0.2
0.4
0.6
0.8
0
20
40
60
80
100
ARTERIO-VENOUS PRESSURE DROP, Δp (mm Hg)



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L12-5 38 Mskel/Sup
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TIs 0.1
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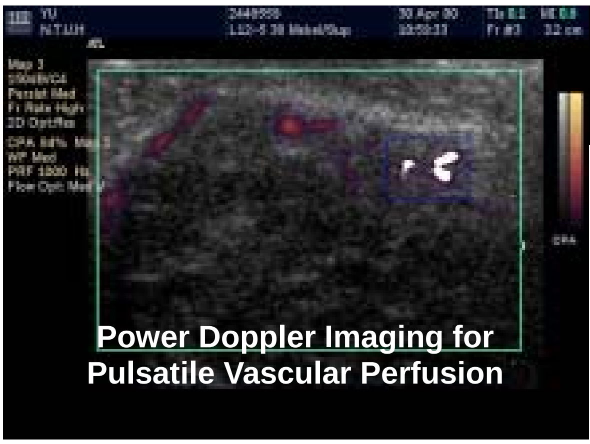
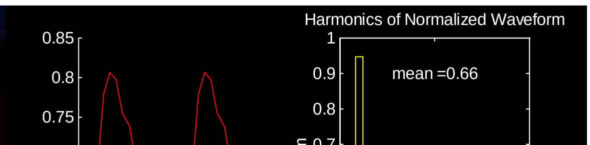
MI 0.3
7.0 cm
Map 3
150dB/C4
Persist Med
Fr Rate Med
2D Opt:Res
ATL
2.77cm
5.77cm
Heterogeneity of
Soft Tissue Tumor



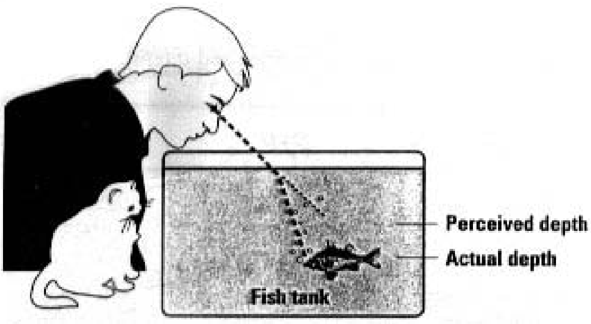
Power Doppler Imaging for
Pulsatile Vascular Perfusion



Harmonics of Normalized Waveform
mean =0.66
0.85
0.8
0.75
1
0.9
0.8

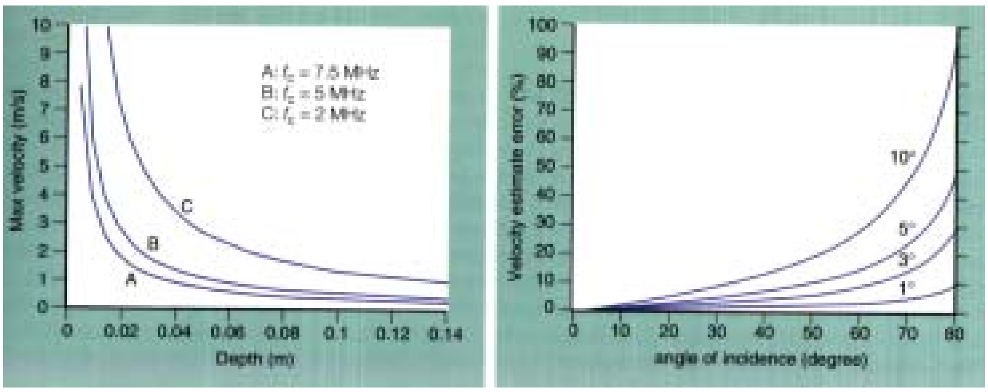
常見之超音波影像失真或假像（Image Artifacts）

- 由於超音波假設波速為一定值 C=1540m/s 而與實際介質之波速不同，所以實際形體位置與影像有些許差異。
- 當超音波遇到介質強烈之折射，會在特定位置產生折射的幻影
- 當超音波遇到金屬或玻璃的物體會有在後面出現彗星尾巴般的影像
- 超音波都卜勒由於PRF太低或是Intensity 太高會有Aliasing 失真或Mirror 般的假像

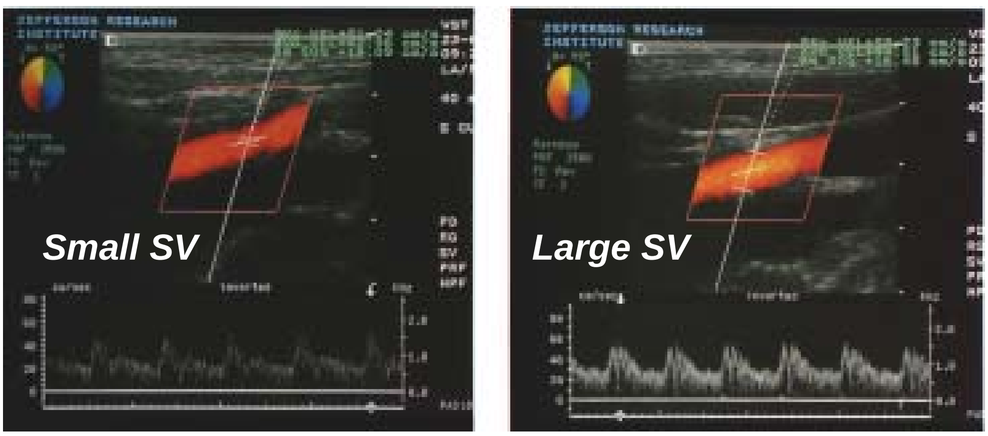


Ambiguity of Color Doppler Ultrasound

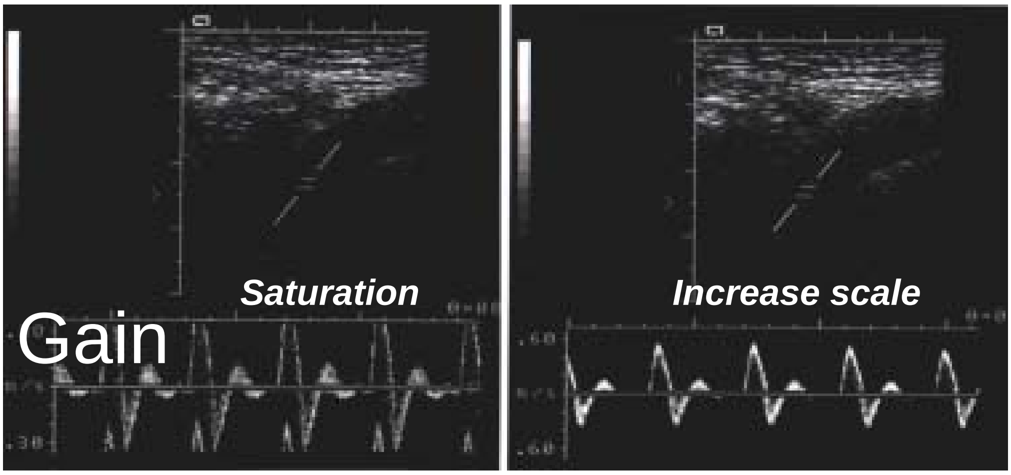
✧ *Dependence of depth and angle of incidence*



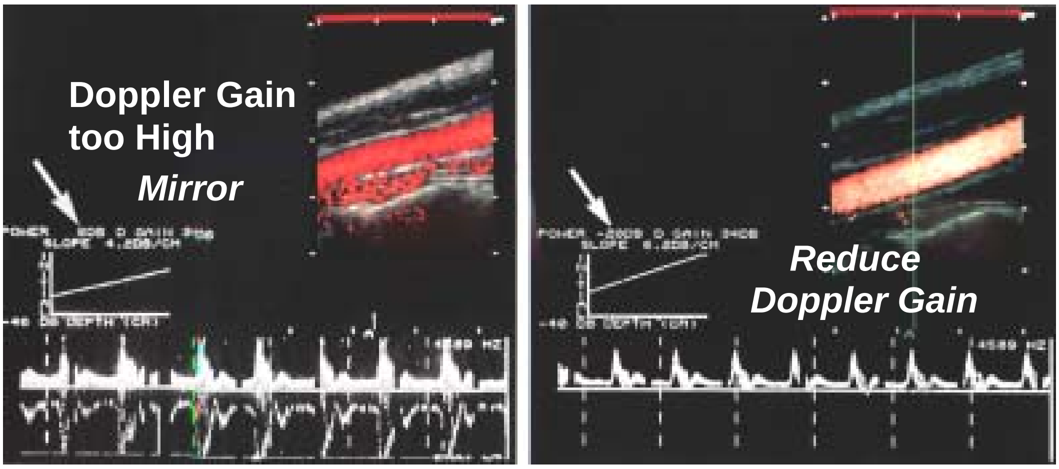
✧ *Effect of Doppler Sampling Volume (gate)*



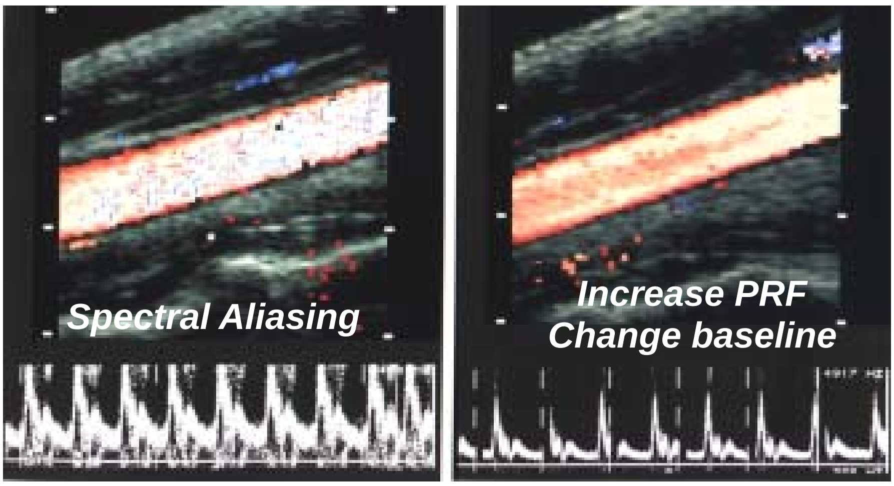
✧ *Effect of Scale*



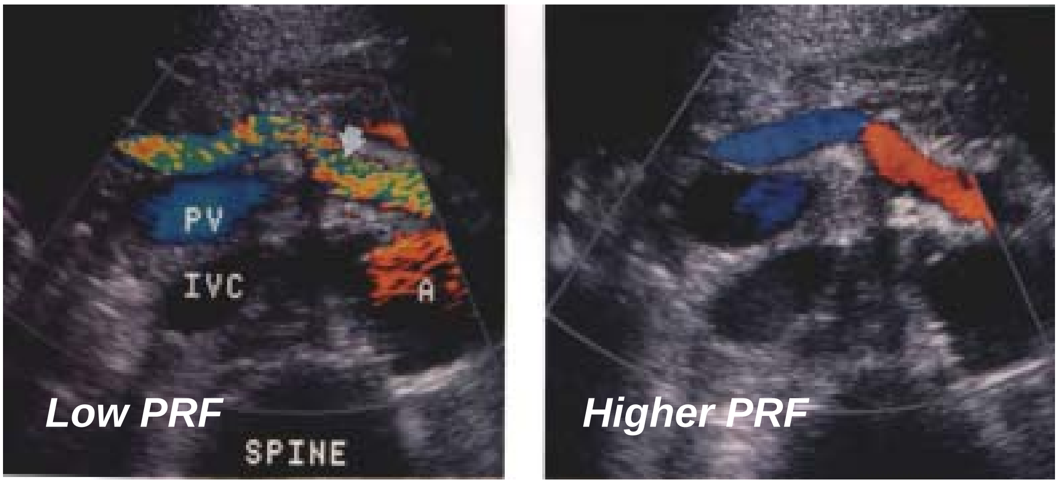
✧ *Effect of Doppler Gain*



✧ *Effect of Pulse Repetition Frequency (PRF)*



Use of Color Doppler artifact in abdominal scanning



Low PRF results in higher sensitivity of flow detection (venous flow)

Concluding Remarks

- ✧ The quality of diagnostic ultrasound relies on a proper selection of US scanhead 、pulse frequency、2D gain、Doppler gain、scale and insonating angle
- ✧ Doppler Ultrasound provide a way of measuring blood flow non-invasively in vessels of order of a few hundred microns
- ✧ High frequency fluctuating movements cause CDI artifacts which can be used to quantify the dynamic behavior of soft tissues
- ✧ Color Doppler and Power Doppler look into different physics of flow in human body
- ✧ Power Doppler Imaging for microvessel perfusion (higher sensitivity and resolution)