Doppler ultrasound devices - Safety Aspects (update 2022)

Basic Terminology

Amplitude-coded colour Doppler - special colour Doppler technique which characterises the Doppler signal echo strength, also called Power Doppler.

Colour Doppler Imaging (CDI) - Doppler (average flow) signals are presented in colour sometimes called colour flow mapping (CFM).

Cardiotocography (CTG) - Method for detecting fetal heart beats and registration of uterine contractions by means of ultrasound.

CW-Doppler - continous wave (cw) Doppler devices emit and receive pulses continuously for characterising flow information.

Doppler angle - angle between the central blood vessel axis and the incident Doppler ultrasound beam.

Duplex Scanner -ultrasound device which combines real-time B-Mode imaging with a Doppler ultra-sound mode.

MI - Mechanical Index - a unitless parameter that is calculated online and displayed on the scanner screen to give a rough estimation of the mechanical risk of the emitted beam associated with the actual settings of the device.

Power Doppler mode - synonymous for Amplitude-coded colour Doppler mode.

PW-Doppler - pulsed wave Doppler (PWD) devices emit and receive pulses not continuously but pulsed for characterizing flow information. Pulsed emission is needed for Colour, Power and Spectral Doppler systems.

Spectral Doppler - a real-time method of spectral-analysis of the Doppler signal, displaying the time-varying velocity distribution of the detected pulsed Doppler (flow) signals.

TI -Thermal Index - a unitless parameter that is calculated online to give a rough estimate of the thermal risk of the emitted beam associated with the actual settings of the device.

Tissue Doppler Imaging (TDI) - movements of organs, structures are detected and displayed rather than blood flow.

Triplex Scanner - ultrasound device which combines real-time B-Mode imaging with both a Doppler and colour Doppler ultrasound mode.

Introduction

The safety aspects of colour flow and Spectral Doppler ultrasound devices are well discussed. This tutorial is intended to provide a better understanding of the greater potential risk presented by these imaging modes than by other imaging modes (B-Mode, 3/4D). Basic terminology and the technique are presented to explain those parameters which contribute to this and to give some safety related recommendations for the clinical use of these systems.

Basic Science

Measurement Principle

Doppler systems are used mainly to measure the velocity of blood or the movement of tissue (TDI). The measure-ment technique is based on the compare-son of two frequencies, that of the incident ultrasonic wave (f_{emit}), and of the wave backscattered by moving scatterers (f_{refl}, e.g. red blood cells, tissue inhomo-geneities) within the body [1].

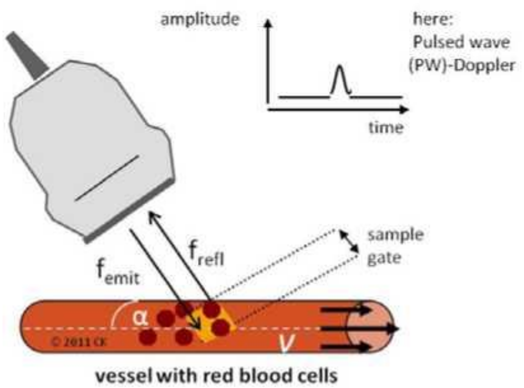


Fig.: ***Doppler signal generated by moving blood***

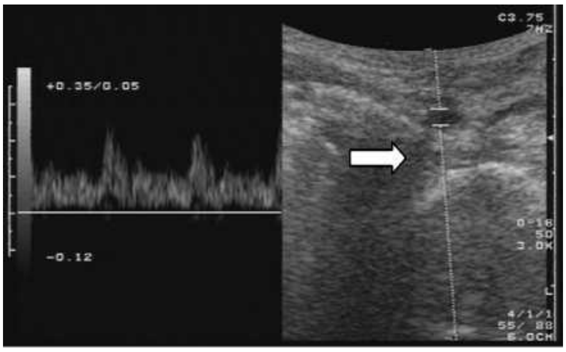
These frequencies are different if the distance between the emitting transducer and the backscattering (reflecting) object varies with time.

The resultant frequency shift f_D - known as the *Doppler frequency shift* - is proportion-nal to the velocity v of the scatterer relative to the emitting and to the reflected frequency ($f_D = f_{refl} - f_{emit}$). If the absolute velocity v of the moving object is required, it is necessary to correct the velocity v by a

factor cos a: where c is the mean speed of sound in the exposed tissue and a is the angle between the beam axis and the direction of movement (so called Doppler angle). This angle should be arranged to be as small as possible by the user to minimise the error introduced by the cosine term.
The time-varying Doppler frequency shift or absolute velocity information of the moving objects are post-processed and result in Spectral, Colour or other Doppler information; Normally Duplex or Triplex imaging is used. In these, one or two different Doppler modes are combined simultaneously with B-Mode imaging to overlay the vascular morphology and anatomy on one image.

Spectral Doppler

A real-time method of analysing the frequency (or velocity) content of the Doppler signal within a single sample gate (arrow) is used for Spectral Doppler techniques. Often this Doppler is called PW-Doppler only.



Spectral Doppler signal (left) from a sample gate (arrow) within a carotid artery

The varying frequency spectrum of the detected Doppler (flow) signals is displayed as a function of time. Once the Doppler angle has been placed correctly, quantitative measurements of the flow velocity can be made and indices related to the flow characteristics can be derived.

Colour Doppler Imaging (CDI)

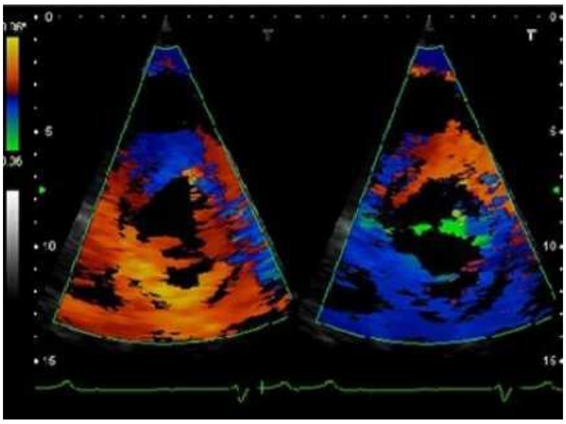
Colour Doppler imaging can provide information about blood flow (Colour flow mapping) and tissue movement (Tissue Doppler Imaging).
CDI is an elegant technology that superimposes a two-dimensional colour flow distribution on the standard B-mode image and permits simultaneous evaluation of vascular morphology and haemodynamics in a semi-quantitative fashion [1-3].

Colour Doppler Image of a normal liver. Red and blue denote opposite directions of flow

An alternative processing to Colour flow mapping uses, instead of frequency shift, the power in the Doppler signal to form the image [Power Doppler, 4], but this is beyond the scope of this short tutorial.
The CDI and TDI techniques are derivations of the Spectral Doppler technique, but involve more complex signal processing. In contrast to the single gate used in spectral Doppler, in CDI and TDI techniques, each line of the ultrasound beam within a pre-selected region-of interest is sampled repeatedly and the information obtained is processed digitally using autocorrelation techniques. While in Colour Doppler Imaging the fast but weak echoes derived from blood are represented on an appropriate colour scale of its direction, speed and flow character, in Tissue Doppler the slow but strong echoes detected from organs or tissue are transformed into a colour scale using a colour scan converter and a filtering process to obtain information about direction, speed and flow character (turbulence).

Tissue Doppler Imaging (TDI)

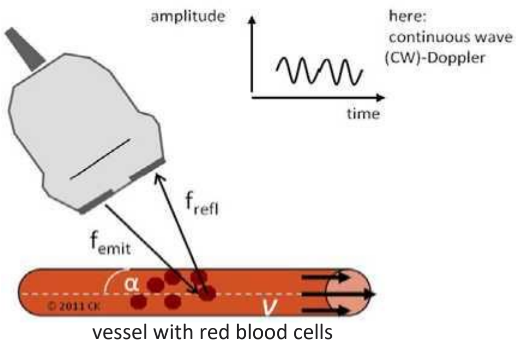
The Tissue Doppler imaging method provides quantitative analysis of regional tissue movement especially myocardial function through the analysis of myocardial velocities, displacement imaging, strain rate imaging and strain imaging [5].



Tissue Doppler Imaging characterizing the heart muscle movements

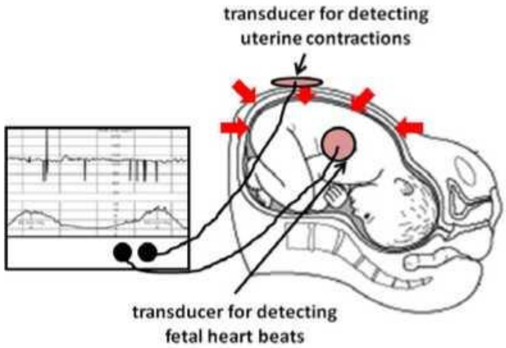
Continuous wave (CW)-Doppler

These Doppler devices continuously emit and receive ultrasound waves (CW). At least two piezo-elements are used, one for transmitting and one for receiving purposes. According to the Doppler equation the blood flow can be detected and evaluated in the same way as with PW-Doppler devices but no information about the depth from which the Doppler echoes come is available because the lack of gating means there is missing timing information. However, with this CW method, the highest velocities can be detected with no change in settings at the device. This is an advantage compared to the pulsed wave Doppler method.



CardioTocography (CTG)

Another application which uses the CW-Doppler method is cardiotocography (CTG) or fetal heart beat monitoring. One or two transducers are placed on the mother's abdomen to detect and record the fetal heart beat and additionally the uterine contractions over time. The devices emit continuous ultrasound of 1-2 MHz with very low intensity output. CTGs are used for early diagnostic and controlling purposes at the end of a pregnancy or during delivery to prevent potential fetal complications, e.g. to identify babies who may be short of oxygen and for further additional assessment of fetal well-being.



CTG method
(red arrows showing uterine contractions)

Limitations of Doppler techniques

Colour Doppler technology makes it easier to find abdominal or pelvic vessels and to recognise areas of abnormal flow, especially in cardiology. The total ultra-sonic exposure time may be reduced making the required information more readily available. Colour Doppler may even make possible certain diagnoses that would not be feasible with standard spectral pulsed Doppler (PW) techniques. Although blood flow features are vividly displayed with colour Doppler, accurate localisation of these features and the correct interpretation of flow abnormali-ties requires considerable sonographic skill as well as a solid understanding of vascular anatomy and Doppler principles.

Besides operator skill, however, CDI or TDI have several technical limitations as listed in the table below:

Feature | Doppler technique	CDI TDI	PW	CW	CTG
Flow/movement information is - qualitative	+			
- quantitative		+	+	+
Doppler angle correction		+	(+)	
Display of - average velocities - temporal velocity	+	+	+	+
changes - flow/movement	+	+	+	+
direction	+	+	+	+
Flow/movement invisible at 90° incident beam	+	+	+	+
Aliasing-Artefact possible	+	+		

Because of the large amount of signal processing required to generate the colour image, the pulse repetition frequency and the frame rate may be lower than with B-mode on its own. These reductions may impair the image quality or lead to aliasing artefacts. The automatic programme for colour Doppler systems make use of Doppler signals from the vessel lumen to calculate the time average velocity and to estimate the vessel diameter. Incomplete filling of the vessel lumen with colour pixels may lead to significant under-estimation of vessel diameter [6].

Safety Implications

Exposure parameters

There are two main characteristics that distinguish colour Doppler imaging and Tissue Doppler from spectral (pulsed) Doppler mode. These colour techniques cannot operate independently of B-mode imaging, and the emitted acoustic energy is not concentrated in a small target volume, but is swept over a wide area, thus reducing time averaged intensities.
Modern ultrasound devices emit intensities (e.g. spatial peak temporal average intensity I_{SPTA}) in Colour Doppler mode with a mean slightly higher than those of conventional B-mode, but ~ 50% lower than those emitted in spectral pulsed Doppler mode [7]. In general the latest generation of Doppler devices emit, on average, lower intensities in Doppler mode compared to those reported in a survey done in 1998 (with the exception of B-mode for which the latest survey showed an increase [7]). The highest intensities generally occur with the narrowest colour scanned field widths.
Their pressure amplitudes however, are on average increased slightly with mean values for all three modes reaching 3.9-4.2 MPa. For B-mode and colour Doppler mode, this is an increase of the order of 50%, while for Spectral pulsed Doppler mode the increase is approximately 75% in the last 10 years [7]. This fact must be taken into account when assessing cavitation phenomena [8].
Colour Doppler examinations are very often followed by spectral pulsed Doppler measurements. Even if these measurem-ents are carried out using frozen B-mode and colour images, the increase in acoustic energy entering the body cannot be ignored. CW- Doppler and CTG devices on the other hand have in general much lower output emissions than the pulsed Doppler methods and are not of concern for safety reasons if used prudently.

Thermal TI and Mechanical MI Index

The on-screen display of two indices is mandatory for modern systems: these are the thermal TI and mechanical MI index. Both indices the thermal index (TI) and the mechanical index (MI) are based on theoretical tissue models and inform the user about the potential risks - (thermal or nonthermal in nature) - associated with the actual device settings and should be observed regularly [9].

Conclusions and recommendations

- The intensity (ISPTA) levels used in colour flow and Tissue Doppler imaging present no significant hazard from the thermal standpoint [10].

- Care should be taken when these higher pressure amplitudes are used in conjunct-tion with contrast agents that may increase the likelihood of cavitational effects
(i.e. with gas-filled microbubble contrast agents).

- Care should be taken when colour flow mapping is combined with pulsed Doppler examination.

- The EFSUMB guidelines for use of Doppler ultrasound should be followed where possible [11]

- Keep a watch on the displayed MI/TI indices. Start with low indices and adjust the settings as needed using the ALARA-principle [12].

- Doppler ultrasound examinations should not be used routinely in the first trimester of pregnancy [12].

References

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