Chapter 10 - Colour flow

27 February 2025 14:45

Evolution of Colour Doppler Ultrasound

- **Adoption of Colour Doppler (1982)**:
  - Doppler ultrasound was a **minority imaging technique** until the **introduction of colour Doppler** in 1982.
  - Colour Doppler **colour-codes blood motion** and **superimposes it on the B-mode image**, enabling **rapid visualization of flow patterns** in vessels.
  - High-velocity **jets in arteries and cardiac chambers** could now be easily detected, significantly enhancing diagnostic capability.
- **Benefits of Colour Doppler**:
  - Allowed for **faster spectral Doppler sample volume placement**, reducing **scanning time**.
  - Improved visualization of **intracardiac jets and abnormal flow patterns**.
- **Early Non-Real-Time Flow Imaging Approaches**:
  - Before commercial **colour flow systems**, earlier methods relied on **manual probe scanning** to construct a **2D image** of blood flow.
  - These approaches, using **electronic or mechanical beam sweeping**, had **low frame rates** (only a few frames per second) and were **not real-time**.
  - Reviews on these early techniques can be found in **Evans and McDicken (2000), Wells (1994), and Cobbold (2007)**.
- **Advancements in Beam Forming**:
  - **Classic beam forming** in Chapter 3 describes **single-line imaging**, which limits **frame rates**.
  - The **introduction of zone and full-field beam forming** has improved **frame rates** and enhanced **Doppler sensitivity**.
- **Current Clinical Practice**:
  - Most **clinical applications** of **colour flow ultrasound** still rely on **classic beam forming** techniques.
  - **Alternative Doppler techniques** available commercially (**detailed in Chapter 11**) include:
    - **Doppler tissue imaging**
    - **B-flow**
    - **High frame rate colour flow imaging**
    - **Vector-flow techniques**
- **Focus of This Chapter**:
  - The emphasis is on **colour flow ultrasound imaging**, particularly using **classic beam forming**.

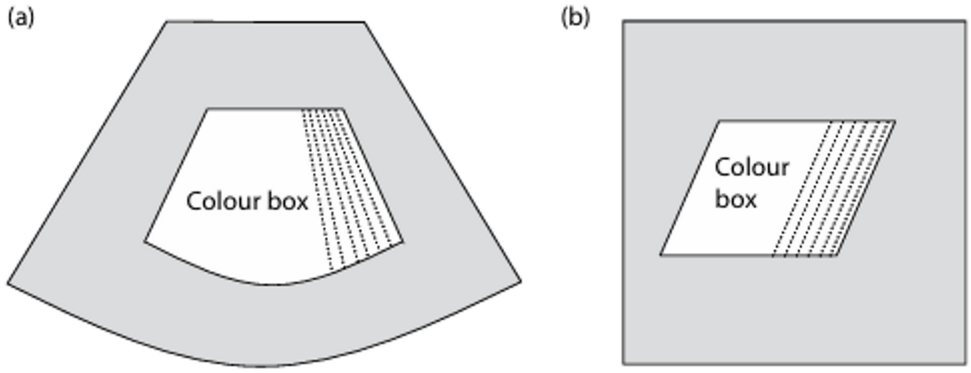
Terminology

- **Evolution of 'Colour Flow' Terminology**:
  - Initially, **colour flow** referred to a **2D ultrasound image of mean Doppler frequency** from blood, displayed using **colour coding**.
  - Over time, other **quantities** (such as **Doppler signal power**) have also been displayed in colour.
- **Definitions Used in This Chapter**:
  - **Colour Flow**:
    - **Generic term** for **imaging of blood flow**.
    - Encompasses **multiple modalities**.
  - **Colour Doppler**:
    - **Displays mean Doppler frequency** from blood in **colour**, superimposed on a **B-mode image**.

- **Power Doppler**:
  - Displays the **power of the Doppler signal** backscattered from blood in **colour**.
- **Directional Power Doppler**:
  - **Displays power of the Doppler signal**, while also using **separate colour coding** to indicate **blood flow direction** (**towards or away from the probe**).

2D Image Production

- **Combination of B-Mode and Pulsed Doppler Techniques**:
  - **Colour flow imaging** integrates elements from **B-mode image formation** and **pulsed Doppler techniques**.
  - The image is built **one line at a time**, using transmitted **ultrasonic pulses** and processing the returned echoes.
  - Unlike B-mode imaging (which processes **echo amplitude**), colour flow imaging **demodulates echoes** to extract **Doppler shift signals**.
- **Multiple Sample Volumes Per Line**:
  - In **pulsed-wave spectral Doppler** (Chapter 9), Doppler data comes from **a single sample volume**.
  - In **colour flow imaging**, each **image line** consists of **multiple adjacent sample volumes**, providing a detailed flow map.
- **Autocorrelation vs. FFT for Doppler Signal Processing**:
  - **Spectral Doppler** uses the **Fast Fourier Transform (FFT)** to extract the **full frequency spectrum** of blood flow.
  - **Colour Doppler** instead uses **autocorrelation** (**introduced in Chapter 7**) to calculate the **mean frequency** detected in each sample volume, which is then **colour-coded**.
- **Pulse Requirements and Frame Rate Trade-Offs**:
  - At least **two pulses per line** are required for **Doppler frequency detection**, but **more pulses** yield a **more accurate frequency estimate**.
  - **Typical colour Doppler systems use ~10 pulses per line** for accuracy.
  - Since B-mode imaging requires only **one pulse per line**, **colour Doppler frame rates are much lower** than B-mode frame rates.
  - Example: If **10 pulses per colour line** and **1 pulse per B-mode line** are used, the **maximum colour frame rate** is **one-tenth** of the B-mode frame rate.
- **Frame Rate Considerations**:
  - A frame rate **above 10 frames per second** is preferred to observe **pulsatile blood flow**.
  - **Lower frame rates** (a few frames per second) occur if the **entire field of view** is used.
- **Optimizing Frame Rate with the 'Colour Box'**:
  - To **increase frame rate**, colour flow is displayed only in a **selected region of interest** called the **colour box** within the B-mode image.
  - **Operator-controlled settings** to optimize frame rate:
    - **Narrowing the colour box** increases frame rate.
    - **Decreasing the box depth** allows **faster updates**.
    - **Reducing line density** (on some systems) can further improve frame rates.
- **Typical Frame Rates in Clinical Applications**:
  - **Peripheral arterial applications**: **10–15 frames per second**.
  - **Venous applications**: **5 frames per second or lower** due to the need for more pulses per line (for measuring **low Doppler shifts**).
  - **Abdominal and obstetric applications**: **Low frame rates** due to **large vessel depths**.



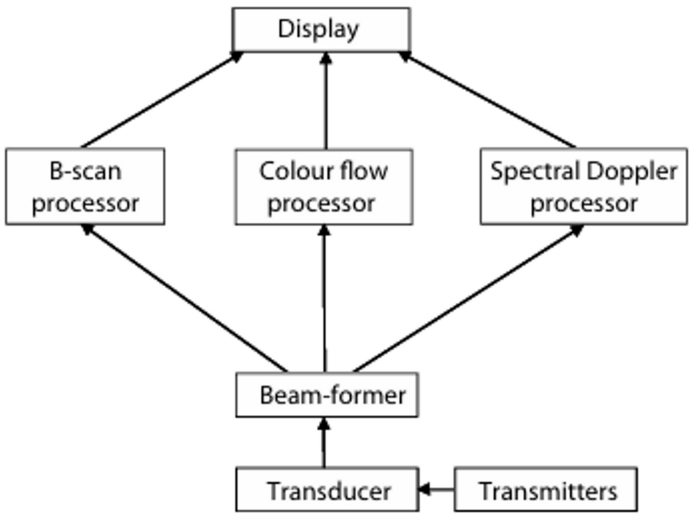
- **Typical colour box shapes and sizes are shown in Figure 10.1**.

Phase- and Time-Domain Techniques

- **Core Principle of Colour Flow Imaging**:
  - All **colour flow techniques** derive the image by analyzing **blood motion**.
  - The detection method depends on whether it evaluates **phase shift** or **time shift** (**as described in Chapter 7**).
- **Two Classes of Motion Detection**:
  Phase-Shift Analysis:
    - Used in **virtually all modern commercial systems**.
    - Implemented using **autocorrelation detection**.
  Time-Shift Analysis:
    - Less commonly used in commercial systems.
    - Computationally **more demanding** and **expensive** to implement.
- **Industry Preference**:
  - Due to efficiency and cost-effectiveness, the **phase-shift approach** is dominant in modern **colour flow ultrasound systems**.
  - The following sections focus on this **phase-shift-based autocorrelation technique**.

Colour Flow System Processing

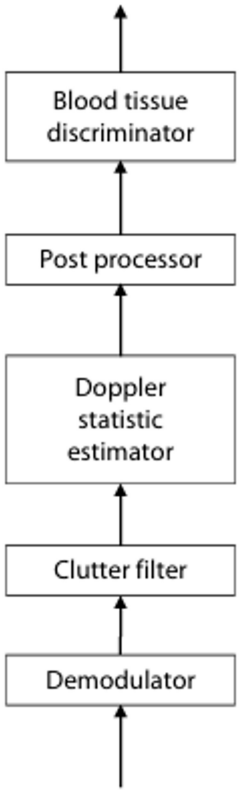
- **Independent Processing of Echoes**:



  - A **colour flow system** separately processes **B-mode** and **colour flow echoes** (**see Figure 10.2**).
  - Additionally, a **spectral Doppler display** can be obtained from a **single sample**

volume, selected by the operator.

- **Pulse Transmission and Line Division**:
  - For each **colour line**, a small number of pulses (**typically 2–20**) are transmitted and received.
  - Each line is **divided into multiple sections**, each representing a **different sample volume**.
- **Simultaneous Processing of Doppler Signals**:
  - In **colour flow imaging**, Doppler signals from **all sample volumes (gates) are processed simultaneously**.
  - This differs from **pulsed-wave spectral Doppler**, where **only one gate** is analyzed at a time.
- **Colour Flow Processor Components**:

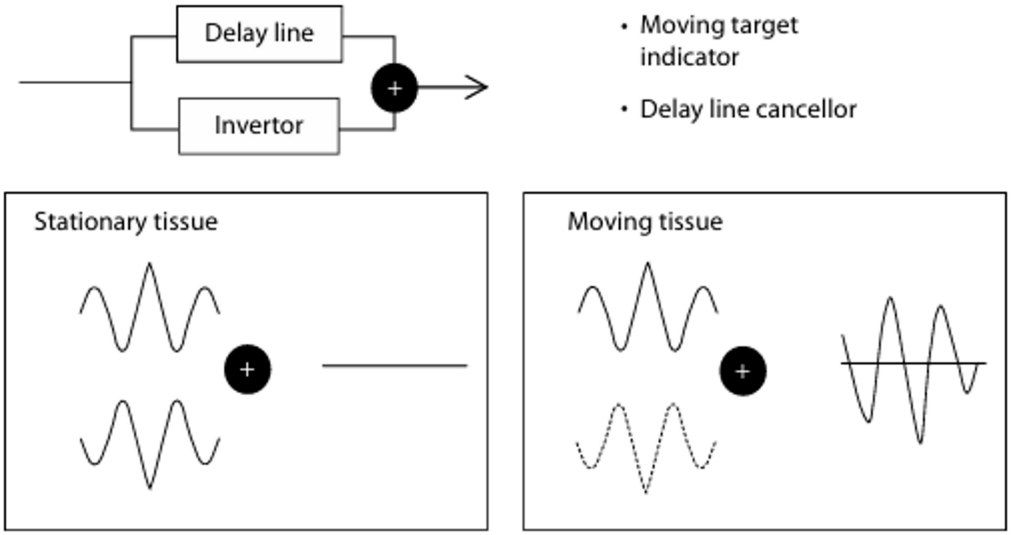


  - **Figure 10.3** illustrates the **key components** of a **colour flow processor**.
  - The **functions of these components** are described in the following sections.

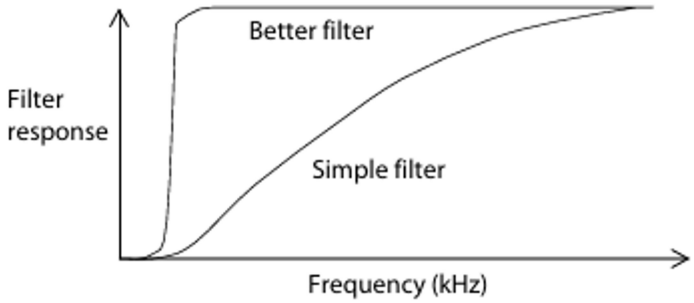
Doppler Transmitter and Processing Components

- **Pulse-Echo Technique in Colour Flow Imaging**:
  - **Colour flow systems** use a **pulse-echo technique** but do not share the same pulses as **B-mode imaging**.
  - Instead, they use **separate lower-frequency pulses** (**see Table 10.1**).
- **Transducer Types**:
  - Any **B-mode transducer** can technically be used for **colour flow imaging**.
  - **Common transducers in commercial scanners**:
    - **Linear-array**
    - **Curvilinear-array**
    - **Phased-array**
  - **Mechanically swept transducers** can be used but introduce challenges:
    - **Vibration artifacts** can interfere with **colour flow detection**, requiring **careful design** to minimize false colour displays.
- **Beam-Former**:
  - Functions similarly to the **B-mode beam-former** (**see Chapter 3**).

    - Controls **beam focusing and sweeping** to generate the **2D colour image**.
- **Demodulator**:
    - Extracts **Doppler shift frequencies** (**see Chapter 7**).
    - The process is **automatic** and does **not require user adjustments**.
- **Clutter Filter**:
    - **Clutter** refers to **signals from stationary or slowly moving tissues**, which can be **40 dB stronger than blood flow signals** (**see Chapter 7**).
    - The **clutter filter** removes these signals, similar to the **wall thump filter in spectral Doppler**.



    - **Early colour flow systems** had **basic clutter filters**, making **low-velocity flow detection difficult** (**see Figure 10.4**).



    - **Modern systems** use **advanced clutter filters**, improving the **detection of low-velocity blood flow** (**see Figure 10.5**).

Mean-Frequency Estimator

- **Real-Time Constraints on Doppler Frequency Estimation**:
    - **Colour flow imaging** requires **faster Doppler frequency estimation** than spectral Doppler.
    - Processing time is **0.2–2 ms for colour flow** vs. **5–40 ms for spectral Doppler**.
    - **Fewer pulses per line** are used:
        - **Colour flow**: **2–20 pulses**
        - **Spectral Doppler**: **80–100 pulses**
    - The number of pulses per line is called the **ensemble length**.
- **Breakthrough in Real-Time Colour Flow Imaging**:
    - In 1982, **Namekawa et al.** and **Kasai et al. (1985)** discovered that **autocorrelation** could efficiently estimate **mean frequency**, eliminating the need for **FFT-based processing**.

- **Autocorrelation** enabled the **commercial adoption of real-time colour flow ultrasound**.

- **Key Quantities Estimated by Autocorrelation**:
  Power – Proportional to the **square of the Doppler signal amplitude**.
  Mean Doppler Frequency – The **average Doppler frequency** in each sample volume.
  Variance – Related to **Doppler signal variability**, defined as the **square of the standard deviation** of Doppler signal amplitude over the ensemble length.
- **Advancements in Colour Flow Estimation**:
  - Since **autocorrelation**, various alternative techniques have been developed for estimating **mean frequency** and **maximum Doppler frequency**.
  - Most modern colour flow scanners use **2D autocorrelation** or its variants, as described by **Loupas et al. (1995a, b)**.
  - Reviews of alternative estimation techniques can be found in **Evans and McDicken (2000)** and **Evans (2010)**.

Post-Processor

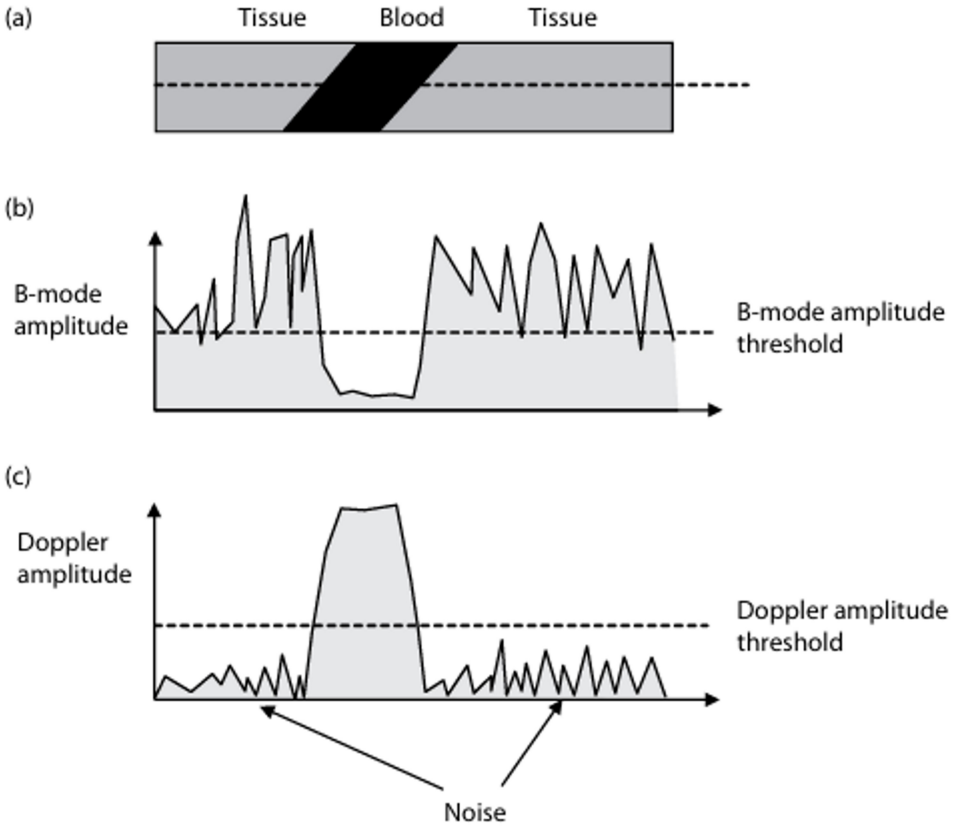
- **Colour Speckle in Doppler Imaging**:
  - Even when **blood or tissue velocity remains constant**, **mean Doppler frequency estimates fluctuate randomly**.
  - This variation appears on the **colour flow image** as a **speckle pattern**, known as **"colour speckle"**.
- **Cause of Colour Speckle**:
  - Speckle arises from variations in **echo amplitude** received at the transducer.
  - These variations are due to **random changes in red blood cell positions** within the **sample volume** from pulse to pulse.
  - The same phenomenon causes **speckle in B-mode images** and **spectral Doppler waveforms**.
- **Noise Reduction through Frame Averaging**:
  - **Speckle can obscure subtle changes in colour display**.
  - The **degree of noise** can be reduced using **frame averaging**, similar to **B-mode imaging**.
  - This averaging introduces a **persistence effect**, where older data influences the current display, making flow patterns appear smoother.

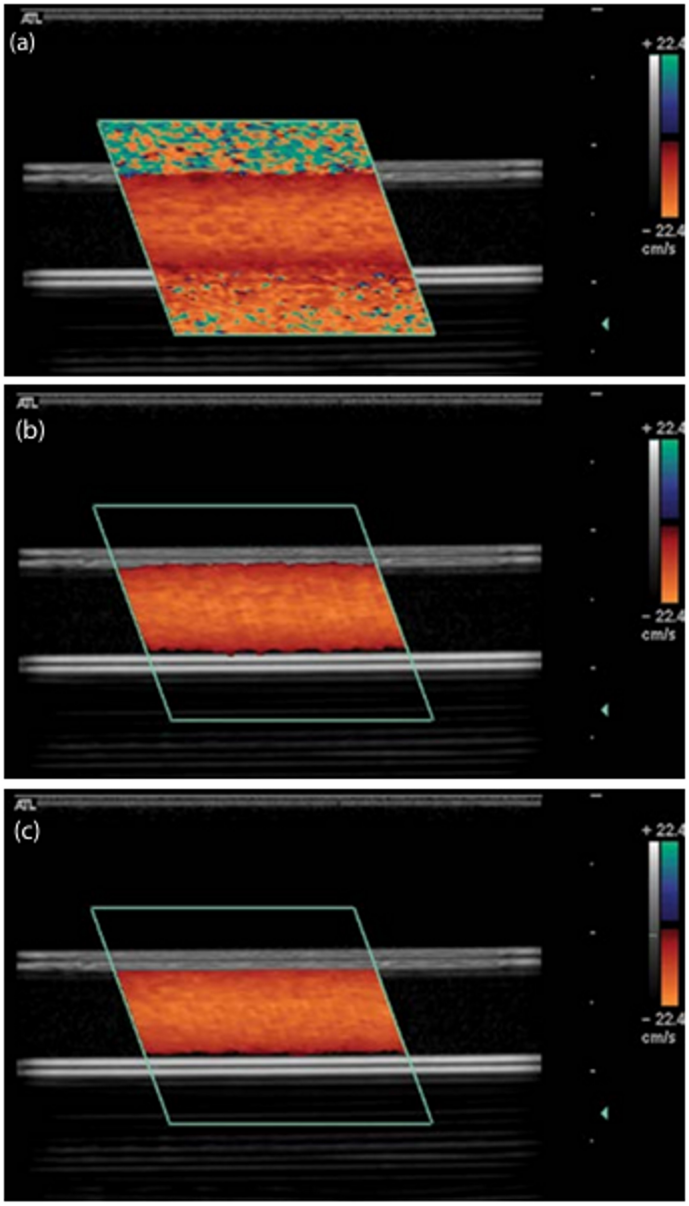
Blood-Tissue Discriminator

- **Purpose of Blood-Tissue Discrimination**:
  - Each pixel in the image contains data for both **B-mode brightness (echo amplitude)** and **mean Doppler frequency (colour flow signal)**.
  - However, **only one of these can be displayed** in the final composite image.
  - The **blood-tissue discriminator** ensures that **colour is displayed only in true blood flow regions** and not in **moving tissue**.
- **Methods for Blood-Tissue Discrimination**:
  B-Mode Amplitude Threshold:
    - If the **B-mode signal amplitude** is **high**, the region likely represents **tissue** rather than blood.
    - A **threshold based on B-mode amplitude** is set to **suppress colour display** in areas where **B-mode brightness exceeds the threshold**.
    - This method is controlled by the **'colour write priority'** setting (**see Figures 10.6 and 10.7**).

  Doppler Signal Amplitude Threshold:
    - **Slowly moving tissue** produces **low Doppler frequency shifts** but with **high amplitude** signals.
    - The **clutter filter** removes these **low-frequency tissue signals**, allowing **blood signals (which have higher amplitude post-filtering)** to be correctly displayed.

- A **Doppler amplitude threshold** is applied to distinguish **blood from tissue signals**.





- This method is controlled by the **'colour gain'** setting (**see Figures 10.6 and 10.7**).

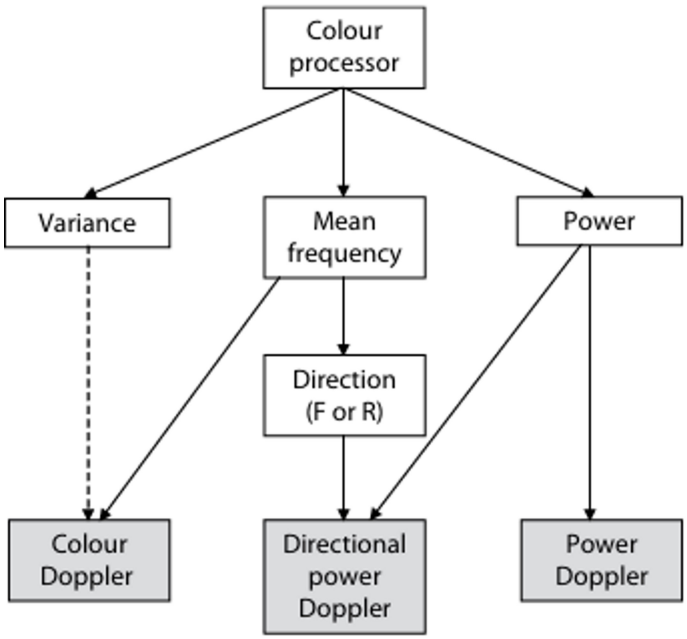
Flash Filter:

- **Sudden motion** of the **tissue or transducer** generates Doppler shifts that appear as **false colour regions** called **flash artefacts**.
- These artefacts occur due to:
  - **Transducer motion**
  - **Breathing movements**
  - **Cardiac motion**
  - **Bowel motion**
- **Basic amplitude thresholding** is often insufficient to remove flash artefacts.
- **Manufacturers have developed advanced filtering techniques** that detect and suppress **rapid changes in Doppler signal levels**, minimizing flash artefacts.

Colour Modes in Doppler Imaging

- **Autocorrelator Outputs and Colour Coding**:
  - The **autocorrelator** generates three outputs:
    Mean Doppler frequency
    Variance (related to signal variability)

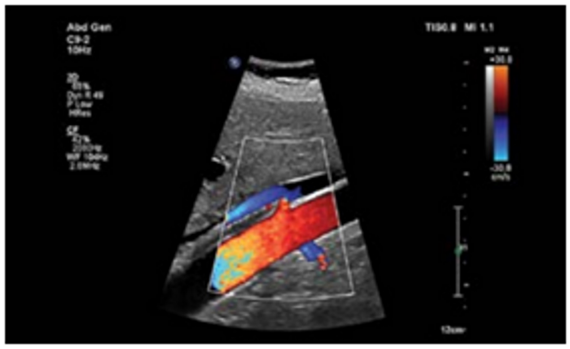
Power (proportional to the square of Doppler signal amplitude)
    - These outputs can be **colour-coded and displayed individually or in combination**.
- **Selection of Colour Modes**:
    - There are **multiple possible colour display modes**, but only a **few practical options** are commonly used.



    - The most relevant **colour modes** are discussed in the following sections (**see Figure 10.8**).

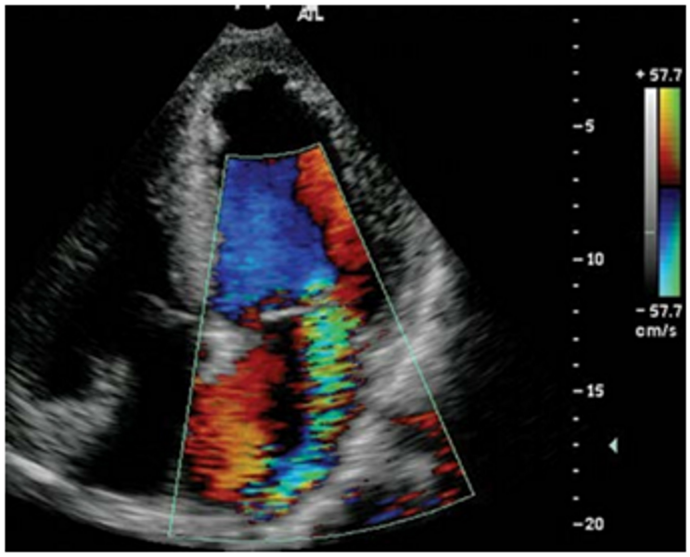
Colour Doppler

- **Primary Mode in Early Commercial Systems**:
    - **Colour Doppler** was the **first widely used mode** in commercial colour flow systems.
    - It **colour codes the mean Doppler frequency** for each pixel.
- **Standard Colour Coding for Blood Flow Direction**:
    - **Any colour scale** could theoretically be used, but most manufacturers use a **standard red-blue scale**:
        - **Red** → Blood flowing in **one direction**.
        - **Blue** → Blood flowing in the **opposite direction**.



    - **Figure 10.9** illustrates this standard red-blue Doppler scale.
- **Variance Display for Turbulence Detection**:
    - **Variance** (signal variability) can be displayed **alone** or as a **composite with the mean frequency**.

- When displayed with **mean frequency**, variance appears as **green**, overlaid on the **red or blue background**.
- This mode was **common in early colour flow systems**, as variance was believed to indicate **turbulence from narrowed arteries or cardiac valves**.



- **Figure 10.10** shows a **cardiac jet** where **green variance coloration** appears within the jet.

- **Limited Use Outside of Cardiac Applications**:
  - The **variance mode** is primarily used in **cardiac imaging** and is **less common in other applications**.

Power Doppler

- **Early Implementation and Optimization**:
  - **Power Doppler** was initially included in early **colour flow systems**, but it **offered little improvement** over standard **colour Doppler** due to **shared instrument settings**.
  - **Rubin et al. (1994)** introduced **optimized processing**, leading to **greater sensitivity** and making power Doppler a more popular technique.
- **Optimization Steps for Power Doppler**:

  Noise Handling:
  - In **colour Doppler**, high colour gain results in a **multicoloured mosaic** of noise, making vessel visualization difficult.
  - In **power Doppler**, noise appears as a **low-level uniform hue**, allowing the **vessel of interest to remain visible**.
  - Optimization involved **lowering the threshold** to better differentiate **blood signal** from **background noise**.

  Increased Frame Averaging (Persistence):
  - Unlike **colour Doppler**, power Doppler does not require **high temporal resolution** for tracking **blood flow over time**.
  - **More extensive frame averaging** (higher persistence) reduces **colour noise**, enhancing detection of **small vessels with low-signal levels**.
- **Visualization and Display**:
  - Early implementations **filled the entire colour box with power Doppler data**, making **small vessels visible** (**see Figure 10.11**).
  - **Downside**: The **underlying tissue anatomy was obscured**.
  - **Modern Approach**: Most manufacturers now **superimpose power Doppler on the B-mode image** to maintain anatomical context (**see Figure 10.12**).
- **Common Colour Scale for Power Doppler**:
  - A **'heated body scale'** is commonly used:

        - **Black → Red → Orange → Yellow**, as **Doppler power increases**.

Directional Power Doppler

- **Combination of Power and Directional Information**:
    - **Directional power Doppler** enhances **standard power Doppler** by incorporating **directional information** from **mean-frequency data**.
    - This allows **colour coding of power Doppler signals** based on the **flow direction** (**see Figure 10.13**).
- **Intended Advantages**:
    - Provides the **increased sensitivity** of **power Doppler**.
    - Maintains the **directional information** of **colour Doppler**.
- **Functionality**:
    - The **mean Doppler frequency** determines the **direction of blood flow**.
    - This directional data is then **applied to the power Doppler signal**, resulting in **directionally colour-coded blood flow images**.

Instrument Settings and Controls in Colour Flow Imaging

- **Preprogrammed Default Values**:
    - Most modern colour flow systems have **default settings preprogrammed** for specific clinical applications.
    - These defaults can be easily **recalled from an application list**, and the operator only needs to adjust a few controls for **individual patient needs**.
- **Control Categories**:
  The available controls are grouped into three categories:
    Controls Affecting Colour Image Acquisition
    Controls Affecting Doppler Signal Extraction and Frequency Estimation
    Controls Affecting the Display of Colour Flow Signals
- **Clinical Practice**:
    - The final section describes how these controls are **used in clinical practice**, helping optimize imaging for each patient.

Controls Affecting the Acquisition of Colour Flow Images

- **Power or Acoustic Output**:
    - The **amplitude of the ultrasound pulses** used for **colour flow image generation** can be adjusted.
    - **Increasing power** improves **sensitivity**, but to maintain **safe patient exposure**, it's best to adjust **other controls** like **colour gain** to achieve the desired **image quality**.
- **Pulse Repetition Frequency (PRF)**:
    - **PRF** refers to the total number of **pulses transmitted per second** by the transducer.
    - The PRF is primarily limited by the **depth of the field of view**, with **higher PRF** possible for **smaller depths** due to shorter **transmit-receive times**.
    - **PRF selection** depends on the **expected velocities** in the region of interest. For instance, **PRF adjustments** may be needed:
        - To prevent **aliasing**.
        - To detect **low flow**.
    - In modern systems, **PRF is automatically determined** based on other controls such as **colour box size** and **velocity scale**, instead of a dedicated **PRF control**.
- **Pulse Distribution Between Image Types**:
    - The total number of transmitted pulses is shared among:
        - **B-mode image**
        - **Colour flow image**
        - **Spectral Doppler**
    - To maximize **PRF for colour imaging**, the **spectral display should be switched**

off, and the **colour box** should be minimized in **depth and width**, resulting in a **higher frame rate** for the colour image.

Controls Affecting the Acquisition of Colour Flow Images (Continued)

- **Steering Angle**:
  - **Applicable to linear-array systems**, where the **colour beam** can be steered at different angles relative to the **B-mode scan lines**.
  - Most systems offer **three angles** (e.g., **−20°, 0°, +20°**), though some provide more choices.
  - **Beam steering** is important in **colour flow imaging** because many **peripheral vessels run parallel to the skin**. A **perpendicular beam** would result in a **zero Doppler signal**.
  - By combining **beam steering** and **probe angulation**, it's typically possible to achieve an **angle between 40°–70°** for optimal imaging. This allows for both **adequate colour flow imaging** and good **B-mode visualization of vessel walls**.
  - **Power Doppler** is less dependent on the **beam-vessel angle**, and generally doesn't require steering away from the **0° direction**.
- **Focal Depth**:
  - Colour flow systems typically use **one transmit focal depth** for image acquisition.
  - In some systems, the focal depth is **automatically set** to the **center of the displayed field**; in others, it needs to be **manually adjusted** to match the **depth of interest**.
- **Box Size**:
  - The **depth and width of the colour box** are user-defined.
  - The **depth** influences the **PRF**:
    - **Shallower depths** allow for **higher PRF** and **higher frame rates**.
  - **Narrowing the width of the colour box** also increases the **frame rate** by reducing the number of **Doppler lines** needed.
- **Line Density**:
  - **Line density** refers to the number of **Doppler lines per centimeter** across the image.
  - **Reduced line density** increases **frame rate** but at the cost of **lower lateral spatial resolution** in the colour image.
- **Gate Length**:
  - **Gate length** controls the number of **cycles in the transmitted pulse**, which in turn affects the **sample volume size**.
  - **Longer gate length** improves **sensitivity** but **reduces axial resolution** (the ability to distinguish small structures along the axis of the beam).
- **Depth of Field**:
  - **Reducing the image depth** allows for a **higher PRF** to be used.
  - This leads to **higher frame rates** for improved real-time imaging, especially useful for visualizing fast-flowing blood.

Controls Affecting the Extraction and Estimation of Doppler Frequencies

- **Filter Cut-Off**:
  - The **filter cut-off frequency** is typically set as a fraction of the total **frequency scale**, rather than an absolute value (e.g., 200 Hz).
  - As the **frequency scale increases**, the **clutter filter level** also increases.
  - To detect **low blood velocities**, the **frequency scale** must be set to **low values**.
  - There are usually **three or four clutter filter options**, and selecting a filter level that is **too low** may allow **clutter from slowly moving tissue** to interfere with the signal.

- **Ensemble Length**:
  - **Ensemble length** refers to the **number of pulses** used to generate each **colour line**.
  - **Longer ensemble lengths** lead to **lower variability** in estimated **mean frequency**, improving the accuracy of **low velocity estimations**.
  - In **cardiology**, higher **blood velocities** are of primary interest, so **shorter ensemble lengths** are typically used.
  - In **radiology**, **low venous blood velocities** are often the focus, so **longer ensemble lengths** are used.
  - The **velocity scale** is often linked to the **ensemble length**:
    - **Lower velocity scales** require longer ensemble lengths for improved **low velocity visualization**.
    - **Longer ensemble lengths** result in **longer measurement times**, which reduces the **frame rate** when **low PRF** is used.

Controls Affecting the Extraction and Estimation of Doppler Frequencies (Continued)

- **Baseline**:
  - To address **aliasing**, the **baseline can be shifted** to allow for higher **positive velocities** to be displayed.
  - This technique is similar to the one used in **spectral Doppler** to resolve aliasing issues.
- **Persistence or Frame Averaging**:
  - **Persistence** refers to the **averaging of Doppler shift estimates** across **current and previous frames**.
  - **Stronger frame averaging** reduces **colour noise**, enhancing the **visualization of stable flow patterns**.
  - However, if **frame averaging** is kept fixed throughout the **cardiac cycle**, **rapidly changing flow patterns** will not be properly visualized.
  - Some systems automatically adjust the **persistence level** based on **velocity**:
    - **High velocity**: **Low persistence** for better visualization of **high-velocity pulsatile flow** (e.g., in arteries).
    - **Low velocity**: **High persistence** to visualize the **less pulsatile flow** (e.g., in veins).

Controls Affecting the Display of the Colour Flow Signals

- **Colour Gain**:
  - **Colour is displayed** when the **Doppler signal amplitude** exceeds a threshold.
  - The **colour gain control** adjusts this threshold:
    - **Too low gain** results in **no colour display**.
    - **Too high gain** can cause **noise** to appear as a **mosaic pattern** throughout the image.
  - The **colour gain** is adjusted for each patient, similarly to **spectral Doppler gain**.
  - **Figure 10.14** shows examples of **too high**, **correct**, and **too low gain** settings for flow in the **common carotid artery**.
- **Colour Write Priority**:
  - **Colour write priority** ensures that **pixels with high B-mode echo values** (likely from tissue) are **not displayed in colour**.
  - This control allows the operator to adjust the **B-mode echo amplitude threshold**:
    - **Above the threshold**: No colour is displayed.
    - **Below the threshold**: Colour data are displayed.
- **Power Threshold**:
  - This control applies a threshold to the **calculated power value**.
  - **No colour is displayed** if the **power is below the threshold**.
- **Flash Filter**:

- The **flash filter** removes **colour flashes** caused by **transducer or tissue motion**.
- **Flash artefacts** can result from rapid motion such as:
  - **Transducer motion** relative to the patient.
  - **Breathing**, **cardiac motion**, or **bowel movements**.
- The **flash filter** is often **user-controlled**, allowing the operator to **turn it on or off**.

Use of Controls

- **Starting the Examination**:
  - The operator **selects the probe and application** from the **pre-set menu**, which provides **default values** based on typical patient characteristics for the selected application.
  - The examination typically starts with **B-mode imaging** to familiarize the operator with the anatomy, then progresses to **colour flow imaging**.
- **Adjusting the Colour Box**:
  - The operator **adjusts the size of the colour box** to cover the region of interest.
  - With a **linear-array transducer**, the **colour box can be steered** to optimize the **colour Doppler angle of insonation**.
- **Selecting Doppler Mode**:
  - The operator chooses the appropriate **mode** (either **Doppler or power Doppler**).
  - **Scale and baseline** are adjusted to ensure the **blood velocity range** is displayed correctly.
- **Colour Gain Adjustment**:
  - The **colour gain** is set to fill as much of the vessel as possible with colour while avoiding excess **noise in the tissue**.
- **Optimizing Doppler Angle**:
  - For **colour Doppler**, **probe angulation and steering angle** are adjusted to ensure the Doppler angle is **away from 90°**, preventing **colour drop-out** due to the **clutter filter** acting on low Doppler shifts near 90°.
- **Additional Adjustments**:
  - While the above adjustments are often sufficient, the operator can fine-tune other controls as needed to optimize the image for the specific examination.

Penetration

- **Penetration Depth**:
  - **Penetration depth** refers to the **maximum depth** at which **Doppler signals** can be reliably detected, distinguishing them from **noise**.
- **Improved Penetration**:
  - **Increased output power** can improve penetration, but **high-output power** is **hazardous** to the patient (as described in **Chapter 16**).
  - At **greater depths**, the returning **ultrasonic signal** is of **small amplitude** due to **attenuation** within the tissue.
- **Signal Detection from Noise**:
  - The **Doppler system** needs to **distinguish the true Doppler signal** from the surrounding **noise**.
  - **Low-noise components** in well-designed systems help with this task.
- **Averaging for Improved Signal Detection**:
  - **Signal processing** techniques like **averaging** improve signal detection by **increasing the signal size** while **reducing random noise**.
  - For Doppler systems, averaging is often achieved using:
    Larger ensemble lengths
    Frame averaging
  - However, these techniques reduce **frame rate**, which is a trade-off for better signal clarity.

Display of Low Velocities and Flow in Small Vessels

- **Visualization of Low Velocities**:
  - The key components for visualizing **low velocities** are the **clutter filter** and the **PRF** (Pulse Repetition Frequency).
  - To optimize the settings for **low velocity detection**, adjustments are made by:
    - Increasing the **ensemble length**
    - Using **persistence**
    - Reducing the **PRF** and **clutter filter** levels
  - These settings are typically **automatically adjusted** by selecting the appropriate **clinical protocol** and **velocity scale**, although some systems may allow direct operator control via a hidden menu.
- **Display of Flow in Small Vessels**:
  - The first requirement for **displaying flow in small vessels** is ensuring that both **B-mode** and **colour flow images** have **adequate spatial resolution**.
  - **Power Doppler** demonstrates superior capabilities over **colour Doppler** in visualizing **small vessels**.
  - **Figure 10.15** compares the **colour Doppler** and **power Doppler** images in a test setup with a **1 mm diameter vessel** embedded in tissue-mimicking material.
    - The ideal result is a **continuous line of colour** indicating blood flow.
- **Effects of Persistence on Small Vessel Flow**:
  - **Figure 10.15a and b**: When **persistence is set to zero**, the **colour Doppler image** shows **drop-out** in several locations, caused by **variability in the calculated mean frequency**.
    - **Low mean frequency values** may trigger the **blood-tissue discriminator**, resulting in **no colour display** in certain regions.
  - **Figure 10.15c and d**: Increasing **persistence** reduces the variability in both **mean frequency** and **Doppler power**, leading to **fewer drop-outs** and more continuous flow visualization.
- **Power Doppler Advantages**:
  - Power Doppler has **improved detection of small vessels** in clinical practice due to:
    - **Higher frame averaging**
    - The **inherently less confusing nature** of the image (no aliasing effect and limited angle dependence) (**see Figure 10.16**).
  - **Penetration depth** for **colour Doppler** and **power Doppler** is **similar** when using the same machine settings. However, **power Doppler** offers **better visualization** in small vessel flow.

Display of Complex Flow Patterns

- **Ideal Colour and Power Doppler Displays**:
  - **Colour Doppler** ideally relates **colour** to **blood velocity** in the scan plane.
  - **Power Doppler** ideally shows **colour based on the presence or absence of moving blood**.
  - However, two factors limit these ideal displays:
    Angle dependence
    Aliasing
- **Angle Dependence in Doppler Imaging**:
  - The **Doppler shift** arises primarily from blood moving in the direction of the ultrasound beam, resulting in a **cosine dependence** on the angle between the beam and the blood flow direction.
  - **Colour Doppler** is **angle-dependent**, which can be demonstrated using a **flow phantom** (**Figure 10.17a**).
    - Flow towards the transducer is shown in **red**, and flow away is shown in **blue** (**Figure 10.17b**).
    - **Angle variation** can make it appear that the flow direction is changing midway, but careful analysis of the **angle of insonation** confirms that the

flow is in one direction.
        - **Centre flow** is not detected due to **poor Doppler angles**, which result in **small Doppler shifts** removed by the **clutter filter**.
    - **Power Doppler** maintains **uniform colour** across a wide range of angles, but signal loss may occur as the angle approaches **90°** (**Figure 10.17c**).
    - **Directional power Doppler** has similar angle dependence, but **flow direction** is coded in **different colours** for flow towards or away from the transducer.
    - **Tortuous vessels** can be confusing in **colour Doppler** due to angle dependence (**Figure 10.19**), whereas **power Doppler** provides a **uniform hue** and is easier to interpret.
- **Aliasing**:
    - **Aliasing** occurs when **Doppler shift frequencies** exceed the **Nyquist limit** (PRF/2). This causes two issues:
        Inaccurate Doppler frequency calculation
        Incorrect flow direction prediction
    - **Power Doppler** is not affected by **aliasing** as it does not calculate **Doppler frequencies**, thus providing a more consistent image.
    - **Directional power Doppler** can still suffer from **aliasing** as **directional information** is calculated.
    - **Figure 10.20** illustrates how **Doppler shift increases** with blood velocity up to a **critical velocity**, beyond which **aliasing** occurs. The **Doppler power** remains constant, despite aliasing.
- **Combined Effects of Angle Dependence and Aliasing**:
    - **Angle dependence** and **aliasing** can both occur in the same image, as shown in a **flow model of a diseased artery** (**Figure 10.21a**).
    - At **low flow rate** (**Figure 10.21b**), **colour Doppler** shows an **orange region** for increased **mean Doppler frequency** in the stenosis, and **jet formation** with **recirculation** post-stenosis.
    - **Higher flow rate** (**Figure 10.21c**) results in **aliasing**, where the **orange region** is now **green**.
    - **Power Doppler images** remain **uniformly coloured** regardless of flow rate.
    - **At low flow rate**, there is a **gap in the recirculation region** due to low velocity, which **fills** at higher flow rates.
    - **Practical implication**: Caution must be taken when **poor filling in power Doppler images** is used to infer **thrombus**.

Display of Rapidly Changing Flow Patterns

- **Colour Doppler and Flow Changes**:
    - The ability of the **colour Doppler image** to accurately follow **rapidly changing flow patterns** depends on the **frame rate** and **persistence** settings.
    - **Maximizing frame rate** is achieved by:
        - Using a **small ensemble length**.
        - **Restricting the colour box size**.
        - In some systems, **simultaneous acquisition of multiple beams** can further improve frame rate.
    - For **lower velocities**, a **larger ensemble length** is needed, which **reduces the frame rate**.
- **Persistence for Noise Reduction**:
    - A **degree of persistence** is **acceptable and desirable**, as it helps reduce **noise** and improves the **visualization of small vessels**.
    - **Persistence** allows the system to **average over multiple frames**, which makes flow patterns smoother and easier to interpret.
- **Observing Changes in Flow**:
    - **Colour flow imaging** can capture **changes in blood flow** during the **cardiac cycle**, but for **dynamic flow observation**, **spectral Doppler** is typically more effective.

- **Power Doppler and Flow Dynamics**:
  - **Power Doppler** does not provide information on the **dynamic nature of blood flow** (e.g., changes in velocity over time).
  - **Persistence in power Doppler** is typically set **high** to **maximize noise reduction**, as the focus is on **overall blood presence** rather than dynamic changes in flow.

Artefacts in Colour Flow Imaging

- **Introduction to Colour Flow Artefacts**:
  - Many artefacts that affect **B-mode images** are also applicable to **colour flow images** due to the **similar physics** of ultrasound pulse propagation in both modes.
  - Some artefacts were discussed earlier in this chapter, but this section aims to **list all major artefacts** in one location.
  - Useful papers on colour flow artefacts include works by **Hoskins and McDicken (1997)**, **Nilsson (2001)**, **Kamaya et al. (2003)**, **Arning and Eckert (2004)**, **Campbell et al. (2004)**, and **Rubens et al. (2006)**.
- **Shadowing**:
  - **Shadowing** occurs when there is a **reduction in Doppler signal amplitude** due to **ultrasonic pulse attenuation**.
  - This results in **colour signal loss** when there is an **intervening high-attenuation region**, such as **calcified areas** or **bowel gas**.
  - This is similar to the **shadowing effect** observed in **B-mode imaging**.
- **Ghost Mirror Images**:
  - **Ghost mirror images** can be created when the ultrasound beam undergoes **partial reflection** from a **highly reflective surface**.
  - These mirror images appear as duplicate images on the display and can be misleading if not identified.

Artefacts in Colour Flow Imaging (Continued)

- **Angle Dependence**:
  - The displayed colour in **colour flow imaging** is dependent on the **angle** between the ultrasound beam and the direction of blood motion:
    - **Colour Doppler**: The displayed colour depends on the **cosine of the angle** between the beam and the direction of motion.
    - **Power Doppler**: **Minimal angle dependence** except near **90°**, where Doppler frequencies drop below the **clutter filter threshold** if the velocity is too low.
    - **Directional Power Doppler**: Similar to **Power Doppler**, but it differentiates flows **towards and away from the transducer**, displaying them in **different colours**.
- **Aliasing**:
  - **Aliasing** occurs when the Doppler shift exceeds the **Nyquist limit** (PRF/2), and higher velocities are displayed with **opposite colour direction**:
    - **Colour Doppler and Directional Power Doppler**: Both suffer from **aliasing**.
    - **Power Doppler**: **Does not suffer from aliasing**, as it does not estimate Doppler frequency.
- **Drop-Out**:
  - **Drop-out** refers to the **loss of colour** when the calculated **mean frequency** or **power** falls below the threshold set in the **blood-tissue discriminator**.
  - This is more likely when there is **high variability** in the frequency or power, especially at **low velocities** or in **small vessels**.
  - The system will **not display colour** if the calculated values fall below the threshold, most noticeably in small vessels or regions with low velocities.

Noise in Colour Flow Imaging

There are several types of **noise** that can appear in **colour flow images**:

- **Electronic Noise**:
  - This noise is produced within the **colour flow system electronics**.
  - If **colour gain** is set too high, the noise appears as **colour in tissue regions** with no actual flow.
- **Clutter Breakthrough 1**:
  - **Moving tissues** (such as **cardiac motion**, **vessel wall motion**, or **bowel movement**) produce Doppler shifts that may be **above the clutter filter level**, creating **colour patterns** that are not associated with **blood flow**.
- **Clutter Breakthrough 2 (Twinkling Artefact)**:
  - **Random colour signals**, often with a **long tail**, may be observed at regions with **heavily calcified areas** (e.g., **kidney stones**).
  - This artefact, called **twinkling**, is believed to be caused by **phase jitter** in the Doppler system, especially when the **echo amplitude** is high due to **calcifications**.
  - The artefact can be reduced by adjusting the **colour-write priority**.
- **Audio Sound**:
  - **Audio sound** produced within the body can be detected by the colour flow system.
  - This sound is indistinguishable from Doppler shifts caused by **blood and tissue**, resulting in **colour noise in tissue regions**.
  - This typically occurs when scanning the **neck** while the patient **speaks**, or in cases of **bruits** from **turbulent flow** in **diseased arteries**.
- **Flash Artefacts**:
  - **Flash artefacts** are **false areas of colour** caused by **movement of the transducer** relative to the tissue.
  - Some systems can reduce these artefacts using a **'flash filter'**.
- **Speckle**:
  - **Colour speckle** refers to the **variation** in the **autocorrelator's estimate** of **mean frequency** and **power**, which creates **noise** superimposed on the underlying colour and power Doppler images.
  - The **speckle pattern** can be reduced by using **persistence**.

Colour Display at Vessel-Tissue Boundaries

- **Ideal Display**:
  - Ideally, the **power Doppler image** would show **uniform colour** up to the **edge of the vessel**, reflecting the continuous flow within the vessel.
  - For **colour Doppler**, blood velocities at the **edge of the vessel** are **low**, so the displayed colour should reflect this reduced flow.
- **Factors Leading to Incorrect Colour Display**:

  Partial Volume Effect:
  - At the **edge of vessels**, the **colour sample volume** is located **partially within the vessel** and **partially in the tissue**.
  - This causes a **reduction in Doppler signal amplitude**, which leads to **colour distortion** in the **power Doppler image**.
  - In **colour Doppler**, the **mean frequency** in the vessel portion of the sample volume is displayed, so the **displayed colour** is unaffected (**Figure 10.22**).

  Image Smoothing:
  - If **image smoothing** occurs (via **averaging adjacent pixels** or **interpolation**), it can introduce **false colours** at the **vessel boundaries** for both **colour Doppler** and **power Doppler** images.
  - This smoothing effect may lead to **incorrect colour representation** at the edges of the vessel.

  Clutter Filter:
  - The **clutter filter** is designed to remove unwanted signals from **stationary or slow-moving tissue**, which often has **higher signal strength** than the

blood flow.
    - As the **velocities at the edge of vessels are low**, the Doppler frequency shifts are also low, making it harder to distinguish the **blood signal** from the **tissue signal**.
    - The **clutter filter** may block the **low-frequency signals** at the vessel edge, resulting in **no colour display**.

  Blood-Tissue Discrimination:
    - The **blood-tissue discriminator** also helps **prevent colour display** at the edges of vessels where the Doppler shift is weak.
    - Due to the **high tissue signal strength** at the vessel boundary and **low Doppler frequency shifts** from the blood, the discriminator may filter out the blood signal, preventing the display of **colour** in these regions.

Measurements in Colour Flow Imaging

- **Overview of Measurements**:
  - Most **quantitative measurements** are made using **spectral Doppler**, but **colour flow images** can occasionally be used for certain measurements.
  - In **research studies**, **offline computer analysis** of colour flow images is widely used for quantitative analysis, although these techniques have not yet become common in **clinical practice**.
- **Single-Site Velocity Measurement**:
  - Some **colour flow systems** allow the **mean frequency** to be displayed at a **specific location** chosen by the operator.
  - This value can then be converted to **velocity** using **angle-correction techniques**, similar to those used in **spectral Doppler**.
  - This measurement is occasionally useful in **clinical research studies**, such as in **estimating arterial stenosis** by using **peak velocity** from the colour Doppler image rather than from the spectral Doppler waveform.
- **Quantitative Analysis of Flow Patterns**:
  - **Blood flow patterns** are known to change significantly in **disease** (**Chapter 8**), but there has been little effort to use **colour Doppler images** for **quantifying flow patterns in disease**.
  - Current methods of **quantification** have not been proven to be **clinically useful**.
- **Volume Flow Measurement**:
  - **Volumetric flow** requires estimating both the **vessel cross-sectional area** and the **mean velocity**.
  - **Colour flow imaging** can provide the **velocity profile** if the vessel is imaged in the **longitudinal plane**. The **diameter** can be obtained from the **B-mode image**.
  - **Cross-sectional area** is calculated assuming the vessel is **circular** in shape, with the diameter used to estimate the area.
  - The **mean velocity** is assumed to be **symmetric** across the vessel (i.e., all points at the same radius have the same velocity).
  - **Volume flow** is calculated by multiplying the **measured area** and **mean velocity**.
  - This technique makes several assumptions, such as **symmetric flow** and **circular vessels**, limiting its use to **normal or relatively undiseased vessels**.
  - In clinical practice, there is **limited demand** for **volumetric flow measurement**, and this method is not widely used.

Time-Domain Doppler Technique

- **Overview**:
  - The **time-domain approach** is described in **Chapter 7**, where the **change in target depth** between consecutive echoes is estimated.
  - **Target velocity** is calculated by dividing the **change in depth** by the **pulse repetition interval**.
  - Initially described by **Bonnefous and Pesque (1986)**, this technique is used in **commercial colour flow systems** and for **tissue Doppler** in some systems.

- **Cross-Correlation Method**:
  - The **time delay** is calculated by comparing the **echo patterns** of **consecutive transmission pulses** using a technique called **cross-correlation**.
  - The process involves **sliding one line of echoes past another** in a series of time shifts, comparing each step to find the **time shift that gives the closest correlation**. This shift provides a measure of how the target has moved between pulses.
  - The method assumes the **echo pattern shifts as a whole**, without significant changes in shape. However, as a region of tissue or blood moves, the **echo pattern changes** due to changes in the **relative position of scatterers** and the **location of red cells** in relation to the transducer.
  - This change in echo shape is referred to as **'decorrelation'**. When the echo pattern changes too much, the system cannot measure the time difference between the current and previous echoes.
- **Key Features and Performance**:
  - **Aliasing**:
    - Unlike the phase-domain method, the **time-domain technique does not suffer from aliasing**. The **upper limit of velocity detection** is determined by the **decorrelation** effect.
  - **Accuracy**:
    - The **time-domain method** calculates **velocity more accurately** than the **autocorrelator** for the same ensemble length.
    - For the same accuracy, the **time-domain approach** requires a **smaller ensemble size**, offering potential improvements in **frame rate** or **line density**.
    - However, **modern systems** use **2D autocorrelation**, and its accuracy is comparable to the time-domain method, so this advantage is **no longer present**.
- **Directionality**:
  - The **time-domain technique** calculates **velocity along the beam**, meaning it measures only the **component of velocity in the direction of the beam**.
  - This makes the method **dependent on the angle** between the beam and the direction of motion.