Chapter 6 - B-mode measurements

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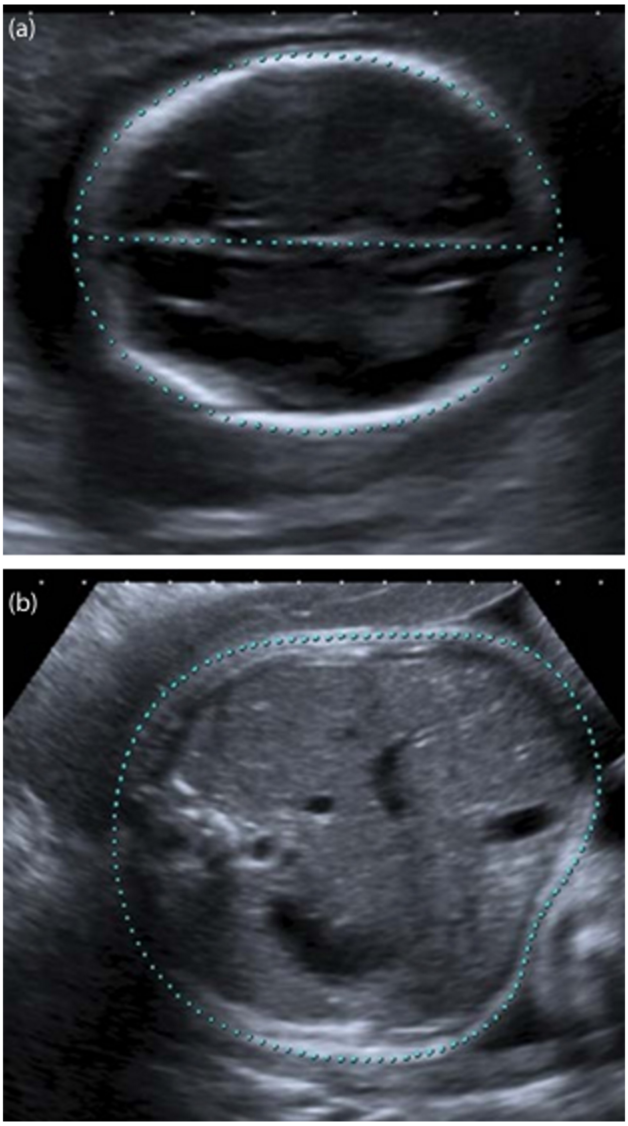
Introduction (Page 129)

- **Ultrasound as a Diagnostic Tool**
  - Ultrasound is one of the most widely used non-invasive imaging techniques in medical diagnosis.
  - Between July 2016 and July 2017, over 9.2 million ultrasound scans were performed on NHS patients in England.
  - This number is nearly twice the number of CT scans and almost three times the number of MRI scans conducted during the same period.
- **Real-time Interactive Imaging**
  - Ultrasound is an interactive imaging technique where the operator holds the probe in contact with the patient.
  - The images of internal anatomy are observed in real time, allowing for immediate interpretation.
- **Cost-effectiveness**
  - Ultrasound is more affordable than other imaging modalities:
    - **Ultrasound**: £40–£49 per scan
    - **CT Scan**: £71–£199 per scan
    - **MRI Scan**: £116–£225 per scan
  - The lower cost and real-time imaging make ultrasound a preferred first-line diagnostic tool in many clinical scenarios.
- **Radiation-Free Imaging**
  - Ultrasound does not use ionizing radiation, making it particularly suitable for obstetric and pediatric applications.
- **Applications in Soft Tissue Imaging**
  - Widely used for imaging soft tissue structures such as:
    - Abdomen
    - Pelvis
    - Heart
    - Neck
  - It is also commonly applied in musculoskeletal imaging, particularly for assessing muscles, tendons, and joints.
- **Use in Blood Flow Analysis**
  - The Doppler effect in ultrasound enables the measurement and visualization of blood velocity.
  - This makes ultrasound an essential tool in studying arterial and venous blood flow.

Measurement Systems (Page 130)

- **Evolution of Measurement Systems**
  - Early ultrasound measurement systems were limited to simple axial measurements.
  - Before digital scan converters, measurements were made using A-mode displays.
  - Measurements relied on aligning the ultrasound beam with the target and placing markers on signals in the display.
  - Distance was determined by calculating the time interval between signals and converting it using the assumed speed of sound.
- **Limitations of Early Methods**
  - Horizontal plane measurements required manual techniques such as rulers and planimeters.
  - Some non-linear measurements were traced with string for distance estimation.

    - These early methods required extreme precision and dedication, and despite their limitations, many early measurement data remain valid today.
- **Calliper Systems**
    - Modern ultrasound scanners use electronic callipers for measurement, ranging from simple linear distances to complex volume calculations.
    - Measurements are based on images stored in scan converter memory, relying on accurate data placement in memory.
    - Distance along the beam axis is calculated using an assumed ultrasound velocity of **1540 m/s**.
    - Various algorithms account for probe geometry to accurately determine echo locations in the image.
- **Electronic Callipers and Pixel-Based Measurement**
    - Measurements within the image memory are based on pixel distances between calliper points.
    - The distance in pixels is converted into real-world units (millimetres or centimetres) based on pixel size.
    - Pixel size calculation depends on the probe geometry and selected scan settings.
- **Track-Ball Control for Callipers**
    - Most calliper controls use a track-ball system for easy placement.
    - Some systems allow software adjustments for sensitivity to enhance accuracy.
    - While linear measurements remain precise, non-linear measurements may introduce significant errors due to track-ball control variability.
- **Linear Distance Measurement**
    - The first and most commonly used ultrasound measurement is **linear distance**—a straight-line measurement between two points.
- **Non-Linear Distance, Circumference, and Area Measurements**
    - Non-linear distances, such as irregular circumferences, are traced manually using a track-ball system.
    - The system records the path and calculates total length by summing the distances between small segments of the tracing.
    - Circumference measurements are critical in obstetrics (e.g., fetal **abdominal circumference (AC)**).

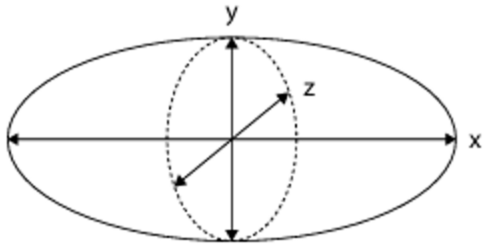


- **Ellipse Fitting for Circumference and Area**
  - Many ultrasound systems offer **ellipse fitting**, useful for measuring structures that are approximately elliptical (see **Figure 6.1a**).
  - The user places callipers at the longest and shortest axes of the ellipse and adjusts its size.
  - The system calculates circumference using an **exact or approximate formula** (e.g., **Ramanujan's approximation** from 1914).
- **Alternative Circumference Measurement Methods**
  - The **cross-diameter method**, used in fetal growth studies, measures **two orthogonal diameters (d1 and d2)** and applies an equation: Circumference≈π×(d1+d22)×1.57\text{Circumference} \approx \pi \times \left(\frac{d1 + d2}{2} \right) \times 1.57Circumference≈π×(2d1+d2)×1.57
  - Some systems provide a **point-to-point method** (**Figure 6.1b**), where users plot a series of points along the structure's outline.
  - The system connects points with lines or curves to estimate circumference, providing a balance between **ellipse fitting (fast but less precise for irregular shapes)** and **tracing (more accurate but time-consuming)**.

Measurement Systems (Continuation - Page 131)

- **Cross-Sectional Area Calculation**
  - The perimeter of a structure is determined using a measurement method, and the **cross-sectional area** is then calculated.
  - This is done by counting the number of pixels enclosed within the perimeter and multiplying by the area of each pixel.

- While not widely used, some studies suggest it is more accurate and reproducible than circumference-based methods.



Volume = k . x . y . z
(k often chosen as 0.52)

- **Volume Estimation**
  - Volume is typically estimated from **three orthogonal linear measurements** taken from two ultrasound images acquired at **90° angles** (e.g., sagittal and transverse).
  - The volume is calculated using the formula: V=k·x·y·zV = k \cdot x \cdot y \cdot zV=k·x·y·zwhere **k** is a shape-dependent constant, often assumed as **0.52** for spherical structures (see **Figure 6.2**).
  - More accurate values for **k** can be determined through comparisons with known reference volumes (e.g., bladder volume compared with urine collected after emptying).
- **Alternative Volume Methods**
  - Some ultrasound systems offer **automatic volume calculations** based on cross-sectional area tracings.
  - In certain applications, 3D ultrasound techniques provide **direct volume measurements**, removing the need for manual geometric assumptions.

Measurement Systems (Continuation - Page 132)

- **Volume Estimation**
  - The most common method for volume estimation in **2D ultrasound** is based on **three orthogonal measurements** taken from two perpendicular images (e.g., sagittal and transverse).
  - The volume formula is: V=k·x·y·zV = k \cdot x \cdot y \cdot zV=k·x·y·zwhere **k** is a shape factor (often assumed as **0.52** for spherical shapes).
  - If a sphere is not a good approximation, **k** can be refined using empirical measurements compared to known reference volumes (e.g., bladder volume measured against urine output after emptying).
  - Other structures measured using this method include **gestation sacs** and **cardiac ventricles**.
- **Single-Image Volume Estimation**
  - Some ultrasound systems allow **volume estimation from a single plane**, such as bladder volume measurement using only height and breadth.
  - This method assumes **symmetry in the third dimension**, which may introduce inaccuracies.
  - Due to this limitation, it should be used with caution.
- **3D Ultrasound for Volume Measurement**
  - **Three-dimensional (3D) ultrasound** now enables direct volume measurements, improving accuracy compared to 2D-based calculations.
  - Applications include:
    - **Fetal birth-weight prediction**
    - **Cardiac left ventricular volume assessment**
    - **Measurement of neonatal cerebral ventricles**

- **Automatic Measurement Systems**
  - Advanced **image-processing algorithms** allow for automation of certain ultrasound measurements.
  - Automated methods are used in **cardiology** and **obstetrics**, where precision and reproducibility are critical.
  - Simple automatic measurements, such as **distance between adjacent surfaces**, have been available for some time.
  - Machine learning developments show promise in improving **plane selection and measurement accuracy**.

Measurement Errors (Page 133)

- **Sources of Measurement Errors**
  - Measurement errors arise from multiple sources, including **random errors** and **systematic errors**.
  - Errors affect accuracy and reproducibility, both of which are crucial in clinical measurements.
- **Random Errors**
  - These errors occur due to natural variations in measurement conditions.
  - Random errors often result from observer-dependent factors, such as **manual calliper placement**.
  - Repeated measurements can help reduce random error by averaging values.
- **Systematic Errors**
  - Unlike random errors, systematic errors remain consistent across multiple measurements.
  - These errors may result from **instrument calibration issues** or **incorrect ultrasound velocity assumptions**.
  - Systematic errors are not revealed through repeated measurements but can be identified by comparison with reference standards.
- **Example of Systematic Errors**
  - A test object with a known circumference of **314 mm** was measured multiple times.
  - The results showed a **consistent systematic error of 6 mm** across different observers and devices.
  - This highlights the need for careful scanner calibration and standardized measurement protocols.
- **Compounding Errors in Calculations**
  - Measurement errors propagate when multiple measurements are used in calculations.
  - Example:
    - If an **abdominal circumference (AC)** and **head circumference (HC)** each have a **3% error**, then the **AC/HC ratio** may have an error of **6%**.
  - This effect is significant in complex volume estimations and ratio-based clinical parameters.

Sources of Errors in Ultrasound Systems (Page 134)

- **Human Error**
  - Common causes include **inadequate training, inexperience, lack of standardized protocols, or failure to follow procedures**.
  - Errors arise from improper image selection or **incorrect calliper placement**.
  - Measuring **oblique** instead of longitudinal/transverse sections can lead to **overestimation**.
  - Human error is particularly significant in fetal measurements, with studies highlighting its **frequency and magnitude**.
  - Failure to **repeat or average** measurements further contributes to inaccuracy.
  - **Over-sensitive track-balls** or poorly designed measurement systems can deter operators from making multiple readings.

    - **Standardized training, audit systems, and evidence-based protocols** can help minimize human errors.
- **Image Pixel Size and Calliper Precision**
    - Ultrasound images are composed of **pixels**, and the smallest measurable distance is **one pixel**.
    - If an image has **512 pixels** and a depth setting of **20 cm**, then each pixel represents **0.39 mm**.
    - **Calliper increments** may be larger than pixel size (e.g., **1 mm**), further affecting precision.
    - To improve accuracy, magnifying the **real-time image** with depth scaling or zoom controls reduces pixel-based uncertainty.
- **Image Resolution**
    - **Finite spatial resolution** can cause **blurring of edges**, leading to **misplacement of callipers**.
    - Lateral beam width errors can be minimized by setting **focal zones** at the region of interest.
    - Differences in scanner **performance** can affect **measurement comparability**, particularly in fetal femur length studies.
    - **Higher ultrasound frequencies** generally enhance resolution, improving accuracy.
- **Velocity/Distance Calibration**
    - Measurement accuracy depends on proper **placement of echoes** in the scan converter memory.
    - Errors occur if the **velocity assumption** for echo calculation is incorrect.
    - Algorithms used to determine **scan line positions** influence distance calibration, affecting accuracy.

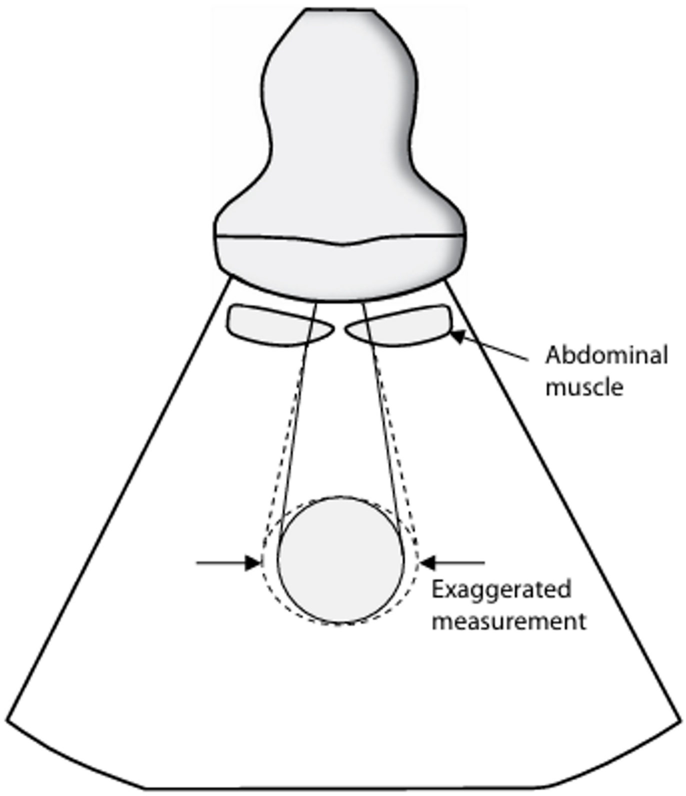
Interpretation of Measurements (Page 135)

- **Impact of Measurement Uncertainty**
    - Clinicians must be aware of the **degree of uncertainty** in ultrasound measurements.
    - Understanding **normal biological variation** is essential for accurate diagnosis.
    - Large uncertainties require cautious interpretation, while small uncertainties allow for **greater confidence** in clinical decisions.
- **Using Normal Reference Data**
    - Normal reference data are essential for evaluating ultrasound measurements.
    - **Scanner calibration** and **measurement techniques** should align with the reference data used.
    - Differences in measurement techniques may lead to **misinterpretation** when comparing results across different datasets.
- **Example: Fetal Abdominal Circumference (AC) Measurements**
    - Studies have shown **3.5% differences** between manual and calculated AC measurements.
    - The **cross-diameter method** often underestimates AC compared to direct perimeter tracing.
    - Operator variation can contribute to **measurement discrepancies**.
- **Quality Control in Measurement Packages**
    - Modern ultrasound scanners include **automated measurement packages** for fetal growth assessment, bladder volume, and other clinical parameters.
    - The **choice of charts and calculation algorithms** should be carefully evaluated before clinical use.
    - Misalignment between **measurement methods and reference data** can lead to errors in **diagnostic decision-making**.

Interpretation of Measurements (Continuation - Page 136)

- **Ultrasound Propagation and Measurement Accuracy**

- Ultrasound scanners assume an average **velocity of 1540 m/s** for soft tissue.
- Actual tissue velocities vary by approximately **±5%**, leading to minor distortions.
- Measurement errors can arise when crossing **tissue boundaries** with different sound speeds.
- Advanced **beam-forming techniques** attempt to correct for speed variations, improving image accuracy.
- However, these corrections are used **only for focusing**, not for **distance calibration**, meaning that **systematic errors may persist**.



- **Refraction and Measurement Errors**
  - **Refraction** occurs when the ultrasound beam **changes direction** as it passes through tissues with different sound speeds.
  - This can distort measurements, especially near the **maternal midline in obstetric imaging**, where structures may appear **elongated or displaced** (**Figure 6.4**).
- **Errors in Circumference and Area Measurements**
  - Circumference and area calculations are prone to **systematic and random errors**.
  - Manual tracing methods depend on **operator skill** and may lead to **overestimation or underestimation**.
  - The **distance between tracing points** affects accuracy:
    - **Too far apart** → shortened measurement.
    - **Too close together** → increased error due to excessive inclusion of small deviations.
  - **Errors of up to 15%** have been documented in test-object studies.

Interpretation of Measurements (Continuation - Page 137)

- **Errors in Volume Estimation**
  - Volume calculations depend on multiple measurements, leading to **compound errors**.
  - If volume is derived from three diameters, each with a **5% error**, the total volume error may reach **15%**.
  - Human error plays a role, especially in finding **maximum diameters** of irregular structures or measuring multiple cross-sections.

    - **Assumptions about shape** introduce the largest errors, particularly when using a single scan plane.
    - To reduce error, researchers have proposed **different shape constants**, as seen in bladder volume estimation studies.
- **Summary of Measurement Errors**
    - Controlled test object studies provide **error estimates** for different measurements (**Table 6.2**).
    - Clinical errors depend on **image quality, anatomical shape, and measurement assumptions**.
    - With careful imaging and measurement selection, errors can be minimized.
    - However, in some clinical settings, errors may be **two to three times larger** than controlled values.
    - **Calculated parameters like volume may have errors up to 100%**

Summary (Page 138)

- **Role of Measurements in Clinical Ultrasound**
    - Measurements are widely used across various ultrasound specialities.
    - Calliper systems provide flexibility in measuring distances, areas, and volumes.
- **Error Considerations**
    - Errors arise from **instrumentation, ultrasound propagation, and operator handling**.
    - Good practice in **equipment selection, training, and measurement technique** minimizes errors.
- **Equipment Selection**
    - Systematic and random errors should be evaluated before purchase.
    - Measurement accuracy and image quality should be assessed during **acceptance testing**.
    - Pre-programmed **charts and measurement algorithms** should align with local clinical standards.
- **Measurement Techniques**
    - Users must adhere to standardized local procedures for consistent measurements.
    - Best practices include:
        - Choosing the **appropriate probe type and frequency**.
        - Using **image magnification** for better resolution.
        - Setting **focal zones** at the region of interest.
        - Avoiding **image distortion from refraction**.
        - Carefully **placing callipers** to ensure precision.
- **Reducing Random Errors**
    - **Repeating measurements** helps identify inconsistencies and improve reliability.
    - Averaging multiple readings reduces **random fluctuations**.
- **Clinical Interpretation**
    - Clinicians must account for **measurement uncertainty and biological variability**.
    - Results should be interpreted with **confidence if errors are small**, or with caution if variability is high.