Advances in Critical Care
Pediatric Nephrology

Point of Care Ultrasound and Diagnostics

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Editors

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At the outset, our aim for the book is to provide foundational knowledge for physicians, not only to pediatric nephrologists, and clinical scientists who may come across pediatric patients in a critical care setting. There has been incredible growth and advancement in the field of critical care pediatric nephrology over the last few years. With the progression and improvement of renal replacement therapy, ultrasound, and other pharmacological modalities, practices used commonly in adults have been adapted and modified to allow for the increased care and management of pediatric patients, even for the smallest infants. The field of pediatric nephrology has become increasingly specialized and subspecialties such as critical care pediatric nephrology have been developed as a self-containing area of expertise in its own right.

The unique considerations in regard to critical care patients have provided the recent impetus to developing this subspecialty. Experience and knowledge gained from physicians in similar specialties have been crucial in developing treatment plans for this patient population.

In this Edition of “Advances in Critical Care Pediatric Nephrology,” the authors have concentrated on point of care ultrasound as these devices are widely available as guiding management tools. Additionally, they are found freely available in both low-income and high-income centers, allowing for its use in patient populations all around the world. The incredibly beneficial technique of ultrasonography is now being taught to trainees in medical centers around the world and has become akin to that of a stethoscope with the field of pediatric nephrology. Aside from diagnostic tools, we also highlight advancement in the understanding of biomarkers within this patient population, allowing for increased understanding of the unique considerations of patients in a critical care setting. Increased knowledge of clinical biomarkers has allowed pediatric nephrologists to bring the laboratory to the bedside in order to better adjust and deliver appropriate management and treatment of patients.

The editors of this book are experienced “hands-on” pediatric nephrologists from across the world and we have been privileged to have input from a number of expert colleagues for whom we are grateful.
Most importantly, we have learnt so much from individual patients and their car-
ers on a daily basis and would like to dedicate this book to the special patients that
we care for.

Hope you enjoy reading this edition of “Advances in Critical Care Pediatric
Nephrology” textbook as much as we have!

Stay safe and take care.

Gurugram, India  
Akron, OH  
Cape Town, South Africa  
Richmond, VA

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Rupesh Raina  
Mignon McCulloch  
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Part I

Point of Care Ultrasound
Need for Point of Care Ultrasound in Critical Care Pediatric Nephrology

Michael L. Moritz, Rupesh Raina, and Sidharth Kumar Sethi

Ultrasonography has changed the management of critically-ill children by providing immediate diagnostic information previously unavailable through physical examination or other non-invasive bedside testing. Ultrasonography enhances diagnostic precision, monitoring of treatments, and visualization to aid in procedures.

Recent technical advancements have greatly improved image quality while reducing the overall size of the ultrasonography equipment. As a result, Ultrasound performed by the physician at the point of care (POCUS) is becoming increasingly available. Bedside goal-directed echocardiography was the first POCUS application in pediatric practice with guidelines for implementation [1]. As instruments with greater portability have become available, their use has increased in emergency and intensive care areas. Ultrasonography is being increasingly used critically in patients for assessment of volume status, guidance during procedures, evaluation of trauma, and to image the kidney in the setting of acute kidney injury (AKI).

Sometimes, unexpected findings on POCUS will prompt the clinician to take up additional imaging/diagnostic evaluation and may add certain findings that would

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not be otherwise be considered on clinical examination alone. POCUS is not intended to replace formal imaging by ultrasound or echocardiography when indicated.

In order to improve the application of POCUS, guidelines have been brought together by the European Society for Pediatric and Neonatal Intensive Care (ESPNIC) to create evidence-based guidelines for various established and emerging applications of POCUS in pediatric and neonatal intensive care units [2].

1.1 Advantages of POCUS

While conventionally a radiologist would be called to perform an ultrasound, POCUS may be performed by the treating clinician. The greatest advantage of POCUS is its immediate availability at the time of critical illness and the ability to perform serial studies to assess the response of a therapeutic intervention. Additional benefits include portability, low expense, and lack of ionizing radiation.

POCUS is now a complimentary tool for physical examination and an alternative to formal ultrasonography performed by a radiologist.

1.2 Disadvantages of POCUS

The major disadvantage of POCUS is that it is operator dependent. The quality of the images obtained and the accuracy of interpretation are dependent on the skill and experience of the operator. An inexperienced operator may misinterpret a study that could lead to faulty management. It is therefore of great importance that those performing POCUS in the critical care setting be provided with thorough training and that there be properly designed implementation programs. Training programs focused on providing skills to clinicians performing POCUS have been shown to have a positive impact. Guidelines have been developed in this regard by various countries for appropriate training of the individuals who perform POCUS [3, 4].

It is important to remember that, POCUS is intended to be an extension of the physical examination and a tool to enhance the safety of procedures and aid in diagnosis and not to replace formal ultrasonography performed by ultrasonographers and interpreted by radiologists.

1.3 Main Applications in Critical Care Pediatric Nephrology

While POCUS has a variety of applications, those of particular interest to the nephrologists are especially related to a critically sick child in pediatric intensive care. In an intensive care setting, a bedside kidney ultrasound can help in excluding obstructive uropathy, for guiding insertion of vascular access, verifying its proper placement, and to assess volume status.
- **Focused Renal Ultrasound in the Setting of Acute Kidney Injury (AKI)**
  POCUS can aid in the evaluation of AKI. POCUS can aid in the assessment of urinary tract obstruction by assessing bladder volume and presence and severity of hydronephrosis or hydroureter. It can also aid in the assessment of intrinsic kidney injury, by evaluating corticomedullary differentiation, renal echogenicity, renal size, and renal symmetry. It can also assist in a percutaneous renal biopsy of a native kidney or renal transplant allograft when indicated.

- **Vascular Access Placement**
  Ultrasound-guided placement of catheters has been a widely studied indication for POCUS in adults. Numerous studies have demonstrated the superiority of ultrasound-guided CVC placement over landmark techniques [5]. The Agency for Healthcare Research and Quality were the first to recommend in 2001 the use of dynamic real-time ultrasound guidance (looking at the needle when the vessel is punctured as opposed to static quick look before cannulation be used) for placement of central venous catheters in order to improve patient safety. Soon after this, the National Institute for Clinical Excellence in the United Kingdom recommended in 2002 the use of two-dimensional sonographic guidance for the insertion of Internal Jugular Lines in both adults as well as children. The American College of Emergency Physicians stated Level 1 evidence exists in favor of the use of ultrasound for placement of CVC [5]. While data on pediatric patients that investigated the use of static or dynamic ultrasound guidance of CVC placement is limited, all favor the use of POCUS guidance for CVC placement.
  The chapters in the current textbook will provide details on various imaging techniques (long axis and short axis), the pros and cons of the techniques available (the landmark technique, static and dynamic techniques, and use of pulse doppler while puncturing the vessel assisted by real-time ultrasound) and related recommendations.

- **POCUS for Cardiac Evaluation, Lung Fluid, and Volume Status Assessment**
  By combining various ultrasound protocols and views, an assessment of intrabdominal free fluid, the examination of aorta, and deep veins of lower extremities and thorax may be done. This can assist in the diagnosis of hemopneumothorax, pleural effusions, and pulmonary edema [6]. This can help assess if additional fluid boluses will be helpful or harmful.
  While POCUS can be useful to assess volume status, it does have limitations. While IVC measurement may be help in the assessment of shock, reliability can be affected by spontaneous respirations, mechanical ventilation, and tidal volume. To deal with such caveats, many clinicians would combine additional cardiac views to make vital decisions regarding fluid boluses, vasopressor, and inotrope management. Estimation of right atrial pressures (RAPs) through the measurement of IVC through formal echocardiographic evaluation can be done both in spontaneously breathing and mechanically ventilated patients.
  In addition, lung ultrasound is commonly used to assess for the presence of pneumothorax and pleural effusion. It also helps in assessment of pulmonary consolidations, acute respiratory distress syndrome and acute pulmonary edema [6].
Various protocols have been developed to deal with different conditions when bedside ultrasound is used, so that the assessment may be performed in a systematic manner. Some of these are abbreviated as RUSH (Rapid Ultrasound for Shock and Hypotension) for shock, BLUE (Bedside Lung Ultrasound in Emergency) for respiratory distress, FEEL (Focused Echo Evaluation in Life support) for cardiorespiratory arrest, and FAST (Focused assessment sonography for trauma) [7].

This book has detailed chapters on lung fluid assessment and the cardiac evaluation bedside by the treating nephrologist in the acute intensive care setting. The experience of the operator in clinical assessment is as important as the skills in the use of ultrasound guidance. Training and documentation of training are equally essential and are being dealt with in the last chapter in the section. The technology has brought with it a potential to revolutionize pediatric critical care medicine. However, it is necessary that clear guidelines that address the requisite training to be competent in its use are developed and careful studies are performed.

References

Modes and Equipment

Vivek Sharma, Sidharth Kumar Sethi, and Rupesh Raina

2.1 Introduction

Ultrasonography or diagnostic Sonography can be used for diagnostic and therapeutic procedures in real time. Ultrasounds are sound waves of frequency above 20,000 Hz and are used to create images of internal organs non-invasively. It has become the first-line investigation for medical use because of easy availability, affordability, lack of ionising radiation, portability and a broad range of indications as it tremendously expedites diagnosis [1]. In present times increasing number of clinicians are trying to incorporate ultrasound in there examinations both in OPD and as bedside investigation for POCUS (Point Of Care UltraSound), as the first-line imaging modality to diagnose a wide spectrum of abnormalities like pleural effusion, ascites, pericardial effusion, hypovolemia, hydronephrosis, etc [2].

Therapeutic procedures like biopsies and draining of collections and fluid and other interventions are much easily done using ultrasound guidance. The latest machines have high resolution with improved image quality and are equipped with special features like elastography to assess the stiffness of tissues, contrast ultrasound which is not nephrotoxic unlike CT or MR contrast, to name a few. Addition of AI (Artificial Intelligence) in most machines has increased their durability along with reducing scan time and improved resolution of images. Special transducers or probes with smaller footprint and higher frequency are available for paediatric population. Some scanners are handheld which are suitable for preliminary
examination at remote places. All these qualities of ultrasound have made it especially suitable for use in paediatric imaging [3].

Its drawbacks include limitation of the field of view, the need for patient cooperation and difficulty to view structures behind bones or gas shadows. Essential special skill development and training are required for the doctors and sonographers conducting such studies.

2.2 Physics of Ultrasound

Ultrasound waves are high-frequency sound waves that can traverse interfaces of tissues with different properties [4]. The frequency of sound that humans can hear is from 20 to 20,000 Hz. Medical ultrasounds are in the range of 1–20 megahertz (MHz). The principle of USG is based on the detection of ultrasound waves which when passing through different density of tissues (acoustical impedance) and reflected back to the transducer (echoes) are processed to produce images. They follow the equation $v = f \lambda$, where $v$ is the velocity of sound in meters per second, $f$ is the frequency in Hz and lambda is wavelength (distance between two compressions) (Fig. 2.1). Wavelength is inversely proportional to frequency. This means that smaller wavelengths have higher frequencies and do not penetrate deeper tissues so are invaluable in imaging superficial structures as in ultrasound imaging of children who do not have thick tissues. Similarly if more penetration is required lower frequency transducers are used as they have deeper penetration. The density of the medium or its elasticity determines its velocity. The velocity at which sound travels through tissues depends on its acoustic impedance. Propagation velocity is the velocity at which the sound waves travel through the tissues. The higher the stiffness or density, more the propagating velocity as the sound is transmitted by pressure waves through a medium (Fig. 2.2). For ultrasound imaging, the velocity is assumed to be constant at 1540 m/s. The time it takes for the echo to travel back to the probe is measured to calculate the depth of the tissue interface causing the echo. The propagation velocity of ultrasound waves through tissues can be both transverse and longitudinal. The frequency of these waves is the number of vibrations that particles in a medium make per second. The medium required by the waves to travel should be either solid, liquid or gas, unlike electromagnetic waves that can pass through vacuum. When an ultrasound wave encounters a material with a different density (acoustical impedance), some part of the sound wave is reflected back to the probe and is detected as an echo. The greater the difference between acoustic impedance,
the larger is the echo. If the ultrasound wave hits gases or solids, the density difference is so great that most of the acoustic energy is reflected and it becomes impossible to look deeper. These high-frequency ultrasound waves are produced by piezoelectric crystals present in transducers that are connected to a computer. The transducers perform dual action of producing the high-frequency ultrasound waves as well as picking up the reflected waves to be sent to the computer for processing into images that appear on the screen [5–7].

2.3 Ultrasound Jelly or Gel

This thick substance is made of water and propylene glycol and is an inert synthetic compound which when applied over the skin does not drip or run and sticks to that place. Ultrasound waves cannot pass directly from the air to the tissues to be imaged and reflect strongly whenever there is an interface between air and biological tissues. To facilitate this penetration and to make sure that no air bubbles form, jelly is used on the patient’s skin in the region of probe contact for decent image acquisition [8].

2.4 Interactions of Ultrasound with Tissues

What happens to the sound waves on entering the body? Once the ultrasound waves enter the body they meet biological tissues like fat, muscles or nerves which have different properties called acoustic impedance and different things can happen to them, as only some of the waves return to the probe to help image formation. Some of the sound waves that enter the body undergo attenuation which means that they are lost completely, this can be through absorption, when the energy of ultrasound waves is converted to heat. Some waves penetrate the tissues and bend slightly away because of different acoustic impedance, which is called refraction. This kind of interaction can cause artifacts that need to be recognised. There is no contribution of the first two types of waves to image production. The third process is extremely important and is known as reflection. It is these reflected waves that travel back to
the transducer and are processed for image production. Irregular structures scatter sound waves in all directions and a small portion is reflected. These waves also reach the transducer and this is called scattered reflection.

2.5 Equipment–Machine and Transducers

Transducers or probes are handheld devices which are connected to the ultrasound machine. The transducer converts electric signals into sound energy; which can be transmitted into tissues and convert sound energy reflected back from the tissues into electric signals (Fig. 2.3). Image production and quality are done by the machine which is basically a computer with various controls and display [6]. The controls are quite standardised with minor variations from machine to machine. The correct selection of transducer type is the key to the appropriate performance of ultrasound. Transducers are described by the size and shape of their face called footprint. One has to select the correct transducer which is fit for a given exam. Sometimes a combination of transducers have to be used for emergency and critical point of care ultrasound. Most ultrasounds are done by using a transducer on the surface of the body, but special transducers are available for specialised purposes to improve diagnostic accuracy including endo-vaginal, endo-rectal and trans-oesophageal transducers. For general ultrasounds, Curvilinear, Linear and Convex Array transducers are suitable and commonly available [3, 9].

Curvilinear transducers (Fig. 2.4a) have a frequency of 2.5–7.5 MHz. The arrangement of piezoelectric crystals is curvilinear, hence the name. The beam shape is convex and creates a sector-shaped image. It is good for in-depth examinations like that of the abdomen. There is a subtype called micro convex or convex array transducer (Fig. 2.4c), which has a smaller footprint as it generates images

![Cross-section of a transducer](image-url)
from electronically steered beam generating a pie-shaped image that comes from a point. It is good for getting between ribs as in cardiac ultrasound, paediatric abdominal ultrasound and brain examinations. Its frequency ranges from 3 MHz to 11 MHz.

Linear transducer (Fig. 2.4b), as the name suggests has linear arrangement of piezoelectric crystals. The shape of beam is rectangular. Owing to the higher frequency, near-field resolution is good. It has a wide footprint and a frequency of 2.5–12 MHz. Various applications are vascular examinations, neonatal ultrasounds, intra-operative ultrasounds and many more [5].

2.6 Image Orientation and Transducer/Probe Position

The transducer or probe has a marking on the side, which can be a ridge or a coloured dot to indicate the correct direction for image orientation (Fig. 2.5a). This transducer indicator corresponds to an indicator on the screen (Fig. 2.5b) which could be a letter or a proprietary symbol. The screen indicator is normally on the top left of the screen or on the right-hand side of the patient and indicates that image or orientation of the image has not been flipped. The operator has to make sure that the screen indicator is there and nothing has been adjusted. During the examination the transducer marker should be pointed towards the patient’s head when obtaining longitudinal images and towards the patient’s right for transverse images (Fig. 2.6a, b). On the screen the structure which is towards the left of the screen is superior and that towards the right of the screen is inferior. For example, if there is a lesion at any pole of the kidney how shall you make out whether it is at the superior pole or at the inferior pole, especially if the image of the liver or spleen is not included? Just point the marker on the transducer towards the head of the patient, if the lesion is seen towards the left of the screen, i.e. towards the right of the patient, then the lesion can be determined to be at the superior pole of the kidney. The other point for
The orientation is—what is anterior? The structure at the top of the screen indicates that it is closer to the transducer and so it is oriented anterior. Thus the structure at the bottom of the screen is posterior [5].

2.7 Modes

Principle modes of ultrasound used in diagnostic imaging [8]

1. A mode or amplitude mode was the first technique invented for ultrasound use. A mode consists of $x$- and $y$-axis, where $x$ represents depth and $y$ represents amplitude. Single dimensional vertical peaks of different heights are generated when ultrasound waves encounter boundaries of tissues. It does not give the spatial relationship of imaged structures and medical use is limited to ophthalmology.