Ultrasound in pediatric intensive care unit

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Abstract

Title: Ultrasound in Pediatric Intensive Care Unit

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Objective

This narrative review provides an overview of the use of ultrasound in pediatric intensive care. It investigates point-of-care ultrasound (POCUS), which is a goal-directed approach for rapid clinical decision making and provides a multiorgan approach for assessment of complex disease states. This review is organized by integrating point-of-care ultrasonography for pediatric intensive care into the A-Airway, B-Breathing, C-Circulation, D-Disability resuscitation sequence in the primary assessment of critically ill patients after the paragon of the ABCD curriculum by Lichtenstein et al.

Methods

Data is collected by literature research on Pubmed and referencing literature of found articles. Educational literature is taken from chapters in edited books. Point-of-care ultrasound represents an extensively used tool by different fields, therefore taken literature spans various specialities including emergency medicine, anaesthesiology, intensive care, pediatrics, and cardiology.

Discussion

Point-of-care ultrasound in pediatric critical care is an emerging field and further studies are required. In relation to the ABCD assessment, research needs to be conducted for POCUS in pediatric patients with congenital malformations and patients after cardiac surgery. Different protocols and approaches for the same clinical presentation need to be compared in order to define a standard. Assessment of inferior vena cava is still controversial and requires a standard.

Conclusion

Point-of-care ultrasound in pediatric intensive care is the leading method for accurate assessment and timely intervention. It enhances decision-making, management, and intervention as an extension of traditional physical examination. Due to its established use in clinical practice and its development potentials, it should be integrated into medical school curriculum.

Keywords

Point-of-care ultrasound, Ultrasound, Pediatric intensive care, Pediatric critical care, Pediatric emergency medicine, Goal-directed echocardiography, Intensive Care

Sažetak

Naslov: Primjena ultrazvuka u jedinici intenzivnog liječenja djece

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Ciljevi

Spomenuti osvrt omogućava pregled korištenja ultrazvuka u pedijatrijskoj intezivnoj njezi. Istražuje „point of care“ ultrazvuk (POCUS), koji ima ciljani pristup brzog kliničkog odlučivanja i omogućuje multiorganski pristup za određivanje kompliciranih bolesti. Ovaj osvrt je organiziran tako da je POCUS uključen u pedijatrijsku intezivnu njegu kao dio ABCD slijeda (A-dišni putevi, B-disanje, C-cirkulacija, D-kratki neurološki pregled) tijekom oživljavanja u primarnom određivanju stanja kritičnih bolesnika nakon ABCD plana Lichtenstein-a i drugih.

Metode

Podaci su prikupljeni pretragom literature Pubmed-a i literature spomenute u određenim člancima. Edukacijska literatura je uzeta iz poglavlja uređenih knjiga. POCUS predstavlja alat koji se opsežno koristi u različitim poljima medicine te zbog toga spomenuta literatura obuhvaća različite grane specijalizacije poput hitne medicine, anesteziologije, intezivne medicine, pedijatrije i kardiologije.

Rasprava

POCUS u pedijatrijskoj intezivnoj njezi je polje u nastajanju i zbog toga su potrebne daljnje studije. U odnosu na određivanje ABCD slijeda, studija bi trebala biti provedena za POCUS u pedijatrijskih bolesnika s kongenitalnim malformacijama i bolesnika nakon operacije srca. Različiti protokoli i pristupi za isti klinički prikaz trebaju biti uspoređeni da bi se odredio standard. Metoda procjene donje šuplje vene je još uvijek kontroverzna i zahtjeva standard.

Zaključak

„Point of care“ ultrazvuk u pedijatrijskoj intezivnoj njezi je vodeća metoda za točnu procjenu i pravovremenu intervenciju. Poboljšava proces odlučivanja, upravljanja i intervencije kao dodatak tradicionalnom liječničkom pregledu. Zbog utvrđene koristi u kliničkoj praksi i potencijala za razvoj, trebalo bi biti uključeno u program medicinskog fakulteta.

Ključne riječi

„Point-of-care“ ultrazvuk, Ultrazvuk, Pedijatrijska intezivna njega, Pedijatrijska kritička njega, Pedijatrijska hitna medicina, Goal-directed ehokardiografija, Intezivna njega

Abbreviations

AAA	Abdominal aortic aneurysm
ABCD	Airway, Breathing, Circulation and Disability
ALARA	As Low As Reasonably Achievable
BCU	Bedside Cardiac Ultrasound
BP	Blood Pressure
CT	Computed Tomography
CXR	Chest X-Ray
EFAST	Extended Focused Assessment with Sonography for Trauma
FAST	Focused Assessment with Sonography for Trauma
FOCUS	Focused Cardiac Ultrasound
ICU	Intensive Care Unit
IS	Interstitial Syndrome
IVH	Intraventricular Haemorrhage
LUS	Lung Ultrasound
PICU	Pediatric Intensive Care Unit
TEE	Transesophageal Echocardiography
TTE	Transthoracic Echocardiography
RUSH	Rapid Ultrasound for Shock and Hypotension
US	Ultrasonography

Introduction

Ultrasound is a low-cost, non-invasive tool, which provides real-time, physiological, pathological and anatomical information. It narrows down the differential diagnosis as an extension of physical examination and allows rapid examination of critically ill patients. Ultrasound is radiation-free and follows the ALARA principle (as low as reasonably achievable) for radiation exposure. This is especially important for diagnostic imaging in children, where the accumulation of radiation must be prevented. Sedation can be avoided in children which is required in procedures like MRI.
Point-of-care ultrasound is a goal-directed approach which answers yes/no questions for rapid clinical decision making. It is a multiorgan approach, which allows assessment of complex disease states. The approach is not organ-based but problem-based, which is ideal for evaluation of critically ill patients. Furthermore, it is optimal for critical care because it allows serial imaging and follow-up and eliminates the need for transporting critical patient.

A considerable amount of literature can be found on ultrasound in adult patients, whereas in paediatric patients still further studies need to be conducted. Results of adult literature cannot easily be transferred because children cannot be seen as small adults. The difference lies not only in a smaller anatomy but also in different physiology and pathophysiology (1). For example, children have higher metabolism consumption rates leading to faster oxygen desaturation. In addition, POCUS examination in pediatric population covers a wider range than adult ultrasound because of different age groups with different physiologies and reference levels.

This narrative review makes a proposal for primary assessment in critical care after the paragon of ABCD curriculum by Lichtenstein et al (2). It uses the skeleton of ABCD resuscitation protocol and tries to tailor it to the needs in pediatric intensive care unit. The review is organized in the following way: In the first section the basics of ultrasound are explained in order to understand ultrasound applications in the second section. The second section elaborates the diagnostic application of point-of-care ultrasound. Each application is discussed according to technique, current evidence and pathology. The pathology passages follow a problem- based approach, which is more useful in critical care (2).

General

Ultrasound Fundamentals

Understanding of equipment and physics of ultrasound builds an important fundament for generating most accurate images and for mastering artefacts. Consequently, the following two paragraphs will shade some light on the technical side of this topic.

Physics

Ultrasound comprise mechanical pressure waves or sound waves, which are measured in cycles per second and denoted in Hertz (Hz). Sound waves per se can be perceived by the human ear until 20 kHz. As the term ultrasound already reveals, its sound waves exceed human hearing by ranging in frequency from 1 to 20 MHz. They are produced by piezoelectric crystals situated in the ultrasound beam. These crystals are compressed and expanded by an alternating electric field leading to vibration. The vibration generates mechanical pressure waves, which are transmitted from the transducer and reflected back by the tissue. The piezoelectric crystals do not only send pressure waves but reversely also receive reflected waves. The act of transmission and reflection itself is called pulse-echo principle, which is noteworthy for understanding the concept of different ultrasound modes described later. As a matter of principle, the transducer sends pressure waves in form of pulses into the body, where they penetrate different body tissues with their specific acoustic impedances. Based on these impedances, some of the pressure waves are reflected back as echo signals, some are refracted, some are scattered, some are absorbed and some continue to deeper planes. Scattering means that pulses are reflected diffusely in multiple directions, no echo signals return back to the transducer and the information is lost. The echo signals can be as well lost when the sound is absorbed by tissue, where the energy is transformed into heat. Different echo signals are produced by reflection from different distances of body tissue planes and return to the transducer. Following the echo range principle, it takes longer time for the reflection of more distant tissue. The range of returning signals is translated through a reversed piezoelectric effect into an image.

The main factor for ultrasound-tissue interaction is acoustic impedance. It is the intrinsic property of a medium and is defined as the sum of tissue density times the speed of US wave propagation.

Shortly summarized in following equation:

$$Z = \delta \times c$$

Z= impedance, δ= density, c= velocity

The equation shows that speed is inversely related to tissue density. The higher the density, the lower the speed, the longer it takes for the signal to return. Vincent Chan and Anahi Perlas elaborate best on the features of impedance:

"Air-containing organs (such as the lung) have the lowest acoustic impedance, while dense organs such as bone have very high-acoustic impedance. The intensity of a reflected echo is proportional to the difference (or mismatch) in acoustic impedances between two mediums. If two tissues have identical acoustic impedance, no echo is generated. Interfaces between soft tissues of similar acoustic impedances usually generate low-intensity echoes. Conversely, interfaces between soft tissue and bone or the lung generate very strong echoes due to a large acoustic impedance gradient"(3).

The concept of impedance explains as well the use of gel. Gel is actually used to match the impedance at the boundary of skin because gel has a similar impedance like skin. What should be kept in mind is the assumption by default that ultrasound is travelling through homogenous tissue. The pressure waves however are weakened by attenuation through tissue and reflection, where some part of sound is not reflected. Each time the wave goes through tissue it is attenuated. In the case of a high frequency, the wave interacts with multiple areas of tissues, which provides a better resolution of the image. Due to the increased tissue interaction the signal weakens and does not get very far. In summary, a high frequency provides better resolution but the depth of penetrating tissue is less. Conversely, a lower frequency can penetrate deeper into the body but the image resolution is not as good. Consequently, the appropriate choice of probe with its specific transducer frequency is an important prerequisite for achieving the optimal image resolution.

Modes and Doppler

A-Scan, B-, and M-Mode

All modes follow the previously described pulse-echo principle. The difference lies in how many pulses are sent and how they are relating to time. An A-scan, where A stands for Amplitude, sends a single impulse which is plotted against time in a graph, whereas B-mode displays multiple impulses in a 2D picture. An A-scan is not commonly used anymore, whereas B-scan is the mainstay of ultrasound and used for generating M-modes. B-scan refers to brightness mode where echo signals are converted to intensity-modulated dots. The brightness of dot is proportional to the echo signal amplitude (4).

M-scan, where M stands for motion, can be simplified described as constantly refreshed B-scans, which generate moving images creating a film. The motion mode is created by selecting an area of interest as a sample, for example the distal tip of the mitral valve. The selection is then transferred into M-Mode, where the movement of the selected structure is evaluated over time. In this context, time does not refer to the time of a pulse signal to return to the transducer like in A-Mode but it delineates the movement of a structure over time. Therefore, M-Mode is an excellent tool for temporal resolution of motion pattern, especially in rapid moving heart structures (4). Furthermore, this echo display is especially useful for calculating the ejection fraction, which will be explained in later chapters.

Doppler

Doppler ultrasound is a very valuable tool for evaluating Hemodynamics, which is a Greek expression for blood flow through the human body. The basic principle of Doppler effect is the frequency change of waves with movement of its source. If the source is travelling away, the frequency decreases, if the source is approaching, the frequency increases. When applying this concept to sound waves, the frequency change is depicted in the change of pitch and volume. A well-known example of this phenomenon is the moving ambulance car. If an ambulance car is driving away, the frequency decreases. The sound of the ambulance horn is perceived with lower volume and pitch. Reversibly, if the ambulance car is approaching, the frequency increases leading to a higher pitch and volume of the ambulance horn. In ultrasound imaging, the transducer is sending and receiving pulses at the same time. In the case of static tissue, both frequencies would be the same. In moving red blood cells however, the frequency of the sent impulses and the received echo differ and provide therefore information about velocity and distance of red blood cells and consequently the blood flow. This information can be displayed as sonogram or with colour spectrum. The relationship can be expressed mathematically by

$$v = \left(\frac{c}{2}\right) x \, \frac{\Delta f}{f0} \qquad \Rightarrow \qquad \Delta f = (2\, f0\, v\, cos\theta)/c$$

Δf = Doppler shift, f_0 = transmitted beam, v = blood velocity, c = sound speed in tissue

From this equation it can be deducted in which the angle the probe should be positioned. In case of a perpendicular angulation, the Cosine of 90° would be zero and no Doppler shift can be measured. Accordingly, a perpendicular position of probe would make the impression, that there is no blood flow. Angulation consequently should always be less than 60°. A zero angle would be the optimum as it captures the direction of blood flow.

The information of Doppler effect can be presented in an audible, spectral or colour format. Audible Doppler only provides the sound of the Doppler shift. Regarding colour display, different colours are allocated to the direction of blood flow. Blue colour depicts that red blood cells move away from the probe and red colour stands for blood movement towards the probe. This colour designation aids in differentiating venous from arterial circulation.

Equipment

Different Probes

The ultrasound transducers differ based on their piezoelectric crystal arrangement, footprint, and frequency. The piezoelectric arrangement defines the shape of the beam by the organization of rays. In a linear array, the rays are organized in a parallel fashion. In curved and phased array the rays are close together near the probe and spread out far from the probe. These ray orientations create accordingly different shadows. This plays a role for example in lung ultrasound, where the posterior shadows of ribs differ with the choice of transducer: the linear transducer generates parallel shadows of the ribs, convex and phased array transducer produce divergent shadows. The linear and convex transducer have a wider footprint than the phased array transducer. The phased array transducer is therefore of advantage for cardiac imaging, which is ideal for positioning it between the ribs. Despite the narrow window, the display is great. Linear transducers have due to their wider footprint and parallel array orientation with equal spacing near and far a better lateral resolution. In addition, they provide high-frequency waves with a spectrum of 5 to 10MHz, which leads to a better axial resolution. This is based on that axial resolution is related to the depiction of two objects one in the near field and one in the far field, which is better identified with higher frequency. Convex transducers are also called curvilinear transducers due to the curvilinear ray positioning and exhibit a lower frequency of 2 to 5Mhz. As described earlier high frequency has a shorter depth of penetration. Consequently, linear transducers are ideal for scanning shallow structures, whereas curvilinear and phased array transducers penetrate deeper into the tissue and are the instrument choices for abdominal ultrasound. Apart from cardiac and abdominal imaging, the phased array transducer is utilized as well for cranial imaging.

Artefacts

Artefacts are based on the machine's presumptions that ultrasound travels only uniformly in a straight line, like a single pulse from the probe to the tissue and back to the probe, and that attenuation is uniform. Artefacts include shadowing, posterior acoustic enhancement, defocusing artefacts, mirroring artefacts and reverberation artefacts. Shadowing occurs when sound is not transmitted through a surface, like in the example of lung ultrasound where the scanning of ribs generates shadows. Posterior acoustic enhancement means that structures behind a medium are reflecting even stronger. This occurs when attenuation through the medium is decreased like in the case of fluid. Therefore, soft tissue behind a filled bladder is acoustically enhanced and much more echogenic. Defocusing artefacts stand for bending of sound beams at a fluid interface, which causes deep focusing artefacts like in the case of lateral cystic shadowing. Mirroring artefacts occur when structures are reflected from certain tissue. An example is hepatization in lung ultrasound, where the diaphragm reflects structures of the liver giving the false appearance of liver tissue in the area of lungs. Reverberation artefact causes increased depth throughout the image. This sort of artefact is not just a mere artefact, but builds the principle of lung ultrasound.

Patient Preparation and Difficulties

The preparation for a good examination is a crucial point in order to gain the compliance of paediatric patients. The key to success is to put the child at ease. Measures include warming the gel, positioning the child on the parent's lap or performing the ultrasound while feeding. Especially in neonates, the maintenance of body temperature needs to be monitored closely as the body surface area is higher and the loss of temperature more likely. Aseptic precautions are achieved by hand washing and transducer cleansing between examinations. Difficulties can occur in case of obese patients or in case of abdominal distension.

Point-of-care Ultrasound

Emergency medicine and intensive care fall into the same category of critical care regarding the primary assessment. Despite the same category, point-of-care ultrasound in intensive care unit differs. Longer hospital stays allow repeated scanning. Therefore, US in ICU is not only used for diagnostics but also for monitoring and goal-directed therapy. The surplus of time available in comparison to emergency medicine allows elective scans in collaboration with other specialities. In addition, ultrasound is very useful for procedural tasks in intensive care, especially in pediatric population where vascular access is difficult to obtain due to small anatomy. This review suggests how point-of-care ultrasonography can be integrated into the A-Airway, B-Breathing, C-Circulation, D-Disability resuscitation sequence in the primary assessment of critically ill patients in the pediatric intensive care unit. The ABCD curriculum suggests as first step the primary assessment for life-threatening conditions. The second step includes ABCDE resuscitation, which addresses procedural application and therapy management of ultrasound. The third step involves "Head-to-TOE" secondary assessment. The fourth step includes among others loco-regional anaesthesia, drainages, and pre-/intra-/postoperative applications. The fifth step consists of monitoring (2). In this review the first step is elaborated despite the fact that further steps involve procedural and therapeutic interventions and monitoring, which are specific to intensive care. To address all steps would extend the scope of this review. Therefore, the decision was made to concentrate on point-of-care ultrasound for investigating life-threatening situations.

Airway

The first step in the primary assessment includes the examination of the airway. Airway management includes assuring patency of airway and lung ventilation. The trachea needs to be investigated for tube displacement, lesions or emphysema, and adjacent hematomas or masses. The stomach is examined for assessment of the prandial status as a risk factor for aspiration (2). The principal goal is the maintenance of airway patency for optimal oxygenation and ventilation as hypoxia causes brain damage after several minutes. Airway management in critically ill patients poses particularly a challenging task because of their reduced physiological reserve and complex conditions (5). In addition, the airway management in children differs from adult patients. Higher metabolism consumption rates in children lead to faster oxygen desaturation. In case of crying children, the desaturation occurs even faster (6). In addition, children are more prone to upper airway obstruction due to a larger occiput-to- body ratio, which causes the neck to be flexed in a supine position. This can be prevented by putting the patient in sniffing position and by elevating the thorax with putting sheets under the patient's shoulders. In case of obstruction, a jaw thrust needs to be performed.

Point-of-care questions include: Is the airway patent? If not, what is the cause of the obstruction? A-pattern and lung sliding on lung ultrasound confirm patency. No lung sliding, lung pulse, and A pattern would indicate a possible obstruction or airway displacement. The culprit for the obstruction can be found by ultrasound examination by assessing airway displacement or a mass or hematoma adjacent to the trachea. In the case of air obstruction, ultrasound can be used for guiding cricothryoidotomy. In the breathing section different lung patterns and indirect intubation management by assessing lung sliding will be explained in detail. In this section, the focus lies on the direct intubation management by visualising the endotracheal tube and excluding oesophageal intubation.

Technique

The transducer of choice is the linear transducer, which achieves the best resolution for superficial structures due to high frequency. The probe is positioned horizontally at the cricothyroid level with the indicator showing to the patient's right. The trachea is seen in the midline as hypoechoic semi-lunar structure girdled superiorly by the thyroid gland. The hyperechoic line inferior indicates the air interface between lumen and tracheal cartilage. The air in the trachea appears as a black bullet from which the term "bullet sign" is derived. The oesophagus can be identified posterolateral to the trachea. The oesophagus is normally collapsed and either seen as smaller structure next to the trachea or not at all. In case of oesophageal intubation, the oesophagus appears similar to the trachea. This is described as "Double tracheal sign".

Evidence

Lin et al conducted in their the systemic review that bedside ultrasound is **"**a useful adjunct tool in confirming tracheal tube placement in critically ill pediatric patients, but further studies are needed to assess its accuracy in a randomized multicentre setting" (7). Kristensen et al state that "ultrasound helps in intubation management by making sure the tube is placed correctly and by localising cricothyroid membrane if intubation turns out to be difficult"(8). As well Adam J O'Brien and Robyn M Brady agree that "real-time ultrasonography can immediately confirm correct positioning of an endotracheal tube or, conversely, inadvertent oesophageal intubation" (9).

Prandial Status

The examination of the stomach may appear to fit better in the abdominal section and its importance might be questionable at the first sight. However, the assessment of the prandial status is important to evaluate to prior urgent intubation and deep sedation for the estimation of the aspiration risk, considering that aspiration increases mortality and morbidity (8) (10). According to Perlas et al medical comorbidities like advanced renal or hepatic dysfunction, critical illness and opiate consumptions delay gastric emptying (11). These conditions and the need for intubation occur frequently in intensive care, therefore the assessment of prandial status will be elaborated.

Technique

The transducer of choice is a curvilinear low-frequency abdominal probe. Given a pediatric patient under 40 kg, the antrum is positioned more superficial and a linear high-frequency transducer is preferred (10). If the patient is stable enough, the patient should be positioned in a right lateral decubitus position. In case the patient is not stable enough, the semi-recumbent position with 45° head elevation is recommended. The probe is positioned sagittal in the subxiphoid window and swept from the right to the left subcoastal margin. The goal is to visualise the most distal portion of the antrum. Perlas et al recommend using a standardized plane at the level of the aorta (11). Aorta and IVC as landmarks are located posterior to the antrum. The interpretation of the ultrasound image is best described by Perlas A. and Van de Putte P., who state: "When the stomach is empty, the antrum is either flat or round with juxtaposed anterior and posterior walls. When it is round or ovoid, its appearance has been compared with a''bull's eye'' or ''target'' pattern ". They furthermore report that validity and reliability of gastric sonography have been proven by studies, however the differentiation between different gastric contents is still an area to explore. The next question arising is how to best integrate this examination into clinical daily practice (12).

Breathing/Lung Ultrasound

Introduction

The next step in the ABCDE assessment ladder is B for breathing, which stands for the evaluation of respiratory performance and investigation of causes for dyspnea and hypoxemia. Lung ultrasound evolved over the 3 last decades and provides a rapid, real-time tool with a surprising accuracy. Only recently Wimalasena et al reviewed lung ultrasound again and confirmed that it is a very useful tool in emergency medicine and critical care in the hands of an experienced practitioner (13). It can be considered particularly useful in children because of better imaging acquisition achievable due to the thinner chest wall and smaller thoracic width (14). While artefacts originally had been considered as a disturbance for gaining appropriate quality of ultrasound images, pulmonary ultrasound is based on the interpretation of artefacts. Amongst others, reverberations particularly build the backbone of lung ultrasound and are produced by the reflection of ultrasound wave on air, rather than on anatomical structures.

Indication for pulmonary ultrasound constitute following point-of-care questions: Is pneumothorax present and was the placement of the endotracheal tube successful? Is subcutaneous emphysema present? Are A-lines, B-lines or C-lines present? Furthermore, the presence of pulmonary edema or an interstitial syndrome is evaluated. A special indication for neonatal intensive care unit builds the diagnosis of respiratory distress and transient tachypnea in newborn, which is an exciting field for future research.

Technique

Equipment

Mostly used is the curvilinear (2-5Mhz) transducer, which provides a good image and is used as well for abdomen and heart examination. The use of the same transducer allows a fast and comprehensive examination in an unstable patient. This transducer is the probe of choice for evaluating fluid, which makes it ideal for diagnosing interstitial syndromes, pleural effusion, and consolidations. The phased array transducer has the same flexibility but generates a worse image quality. The linear transducer (5-10MHz) has the best resolution for shallow structures but the depth is limited to 8 cm. Due to this characteristic, the linear probe is ideal for scanning of pleura and pneumothorax. It also should be mentioned that newer machines eliminate artefacts, the fundamental principle, on which lung ultrasound is based. Therefore, old machines with minimal post-processing are recommended or post-processing settings in newer machines need to be adjusted beforehand.

Approach

The examination comprises two phases: a quick screening scan in the case of resuscitation and a comprehensive exam later. The first phase consists of a screening examination of the airway and breathing after intubation. Firstly, the anterior chest is examined for the occurrence of pneumothorax and the right placement of the endotracheal tube at the fourth intercostal space slightly medial to the midclavicular line. The next point of interest is the most posterior aspect of the chest at the base of the lung, where the lung meets the diaphragm. In this location pleural effusion and hemothorax are investigated, which are located according to gravity at the lowest possible point. In the comprehensive examination 11 regions of the thorax excluding the cardiac region are scanned. At the anterior aspect, the superior and inferior halves between parasternal, midclavicular and anterior axillary line are investigated. On the lateral chest, the superior and inferior halves between anterior and posterior axillary line are examined. The positioning of the patient can help with the examination. Pleural effusion is easily detected in a sitting patient, while pneumothorax is better seen in supine position. In a ventilated patient, the lateral decubitus position is recommended.

Pleural Line and Lung Sliding

The transducer is placed longitudinally with the indicator directed towards the head. Ribs superiorly and inferiorly serve as reference point for the identification of pleural line. The next step is the identification of the pleural line, which is crucial for the examination. The pleural line is a hyperechoic line along the chest wall formed by the parietal and visceral pleura, which exhibits lung sliding. This to-and-fro movement presents gliding of visceral pleura on parietal pleura, which is caused by inspiratory excursion of the lung toward the abdomen. According to the physiological lung expansion, lung sliding is less prominent in lung apices and more prominent in pulmonary bases. Physiological lung sliding needs to be differentiated from pathological lung pulses. Lung pulses are identical to lung sliding but short, rapid, minute to-and-fro movements due to arterial pulsation and heart movement. Lung pulses indicate a nonventilated lung and that there exits a pleural contact but lack of lung expansion. Lung sliding and lung pulse can be differentiated by using M-Mode. Compared to the normal seashore-sign in lung sliding, lung pulses generate in M-Mode a pattern, which is alternating between the seashore- and stratosphere-sign. This is due to the collapsed lung vibrating in a pulse-like fashion because of the lung's proximity to the beating heart. Colour Doppler can be as well used for assuring lung sliding, where exhibiting flashes of colour indicate normal lung sliding.

ABC and further Signs

A-lines, A for air, are horizontal and equidistant lines, that result from sound reverberating or bouncing between the pleura and the transducer. B- lines are vertical artefacts. They are normally present, but the presence of more than 3 indicates a pathological process. They are laser-like hyperechoic lines, moving with the pleura during the respiratory cycle and follow the transducer array. Normally, the width of normal interalveolar/interlobular septa cannot be depicted by the dimensions of US wavelength. In the case of thickening due to a pathological process however, they are large enough that US waves are conducted and cause a ring down artefact reverberation. B-lines repeat the anatomical distribution of interstitial disease processes: ARDS and infant respiratory distress syndrome are seen as patchy B- lines, pulmonary contusion as focal B-lines and cardiogenic pulmonary edema as diffuse B-lines. C-lines, where C stands for consolidations are soft tissue-like regions, which are in direct contact with visceral pleura and underlie the pleural line. They are mostly of intermediate echogenicity, but can as well present as hypoechogenic. C-lines vary with specific aetiology: small multiple C-lines indicate acute respiratory distress syndrome. Well-demarcated C-lines can be either wedge-shaped indicating pulmonary embolism or round in shape suggesting malignancy. Atelectasis represents with irregular border and consolidation with air bronchogram.

M-mode displays the sea-shore sign and the stratosphere- or barcode- sign. The sea-shore sign demonstrates that visceral pleura is gliding on parietal pleura: the chest wall appears due to horizontal lines as ocean waves. A grainy appearance beneath pleural line is created by a reflection artefact and appears as a sandy beach. The stratosphere-sign or barcode-sign registers only horizontal lines and indicates that the US beam is reflected by air beneath pleural line.

Spine sign and hepatization of lung are signs for pleural effusion or consolidation and will be explained later with pleural effusion.

Pathology

Indirect Intubation Management and Pneumothorax

The detection of pneumothorax is the most important application of LUS. It is lifesaving and performed in few minutes. In addition, pulmonary ultrasound is used to monitor the size of the pneumothorax. Indirect intubation management refers to assessing the right position of the endotracheal tube by investigating ventilation and not directly the trachea. It comprises bilateral scanning of the anterior chest for lung expansion like the investigation for pneumothorax. Synchronous bilateral lung sliding suggests adequate tracheal position of tube and excludes pneumothorax. In case lung sliding is present on the right side but lung pulse is present on the left side of the chest, the left lung is not ventilated. The causes therefore include mainstem intubation, bronchial foreign body or mucous plug. If lung sliding and lung pulses are absent, pneumothorax should be considered. Pneumothorax is presented on lung ultrasound by the absence of lung sliding and B-line caused by the separation of pleural layers by air. The presence of lung points is 100% specific. It is the transition zone from the normal lung to lung affected by pneumothorax. Therefore, if lung sliding is not present on the anterior chest wall, the next step is to locate the lung point at the posterior wall. In M-mode the barcode-sign and stratosphere-sign are seen both together in pneumothorax, where the visceral pleura detaches from the parietal pleura.

The evidence for diagnosing pneumothorax with pulmonary ultrasound is mostly based on studies in adult patients. Further studies for pediatric population need to be conducted. In 2005, Lichtenstein et al concluded that lung sliding rules out pneumothorax, lung point rules in pneumothorax and LUS for evaluation of pneumothorax has high feasibility, high sensitivity, and rapidity, with a simple technique and a short learning curve (15). In 2006, Zhang et al found out that bedside clinician performed US in trauma patients was more sensitive and more accurate than CXR in detecting pneumothorax and that the time needed for diagnosis of pneumothorax was significantly shorter with US compared to CXR (16). The International Consortium for POCUS recommends LUS when pneumothorax is a differential diagnosis and reports level A evidence that LUS is more accurate for pneumothorax than supine CXR (17).

Subcutaneous Emphysema

Other causes for the absence of lung sliding include pulmonary emphysema. It is shown as multiple hyperechoic vertical artefacts originating at multiple levels within the chest wall. Subcutaneous emphysema creates a significant barrier for examination. If ribs or pleural line cannot be identified and the air cannot be removed out of the scanning plane by pressure on the transducer, another imaging modality like chest radiograph must be chosen.

Pleural Effusion

Fluid accumulates according to gravity at the lowest level of the thoracic cavity unless there are pleural adhesions, which are less common in children. Therefore, Volpicelli et al (17) recommend scanning for pleural effusion at the posterior axillary line at the level of the diaphragm, where pleural effusion is located in the posterior costophrenic recess. In an atelectatic patient it should be considered that the diaphragm can be located more superiorly towards the axilla. Pleural fluid is shown as an anechoic layer overlying lung parenchyma without A-, B-, C-lines being present. The fluid functions as acoustic window and makes vertebral shadows more visible, titled as spine sign. The type of effusion is characteristic for the underlying pathology: An anechoic echotexture refers to transudate and hemothorax. Transudate appears as homogenous fluid, whereas the appearance of hemothorax depends on the debris within. Floating particles in a hemothorax is titled "plankton sign". Air bubbles indicate that a hemothorax coexists with the pneumothorax. An exudate presents as echoic, where empyema produces a lobulated appearance.

Evidence for pleural effusion is well studied in adult as well as in pediatric patients. In adult-specific literature Lichtenstein et al pointed out that the sensitivity of POCUS for identifying pleural fluid has been shown to be 92 % with a specificity of 93–97 % (18). Kocijancic et al demonstrated that LUS is more sensitive than lateral decubitus CXR in the detection of small pleural effusions (19). The International Consortium for Point-of-Care Ultrasound reported that LUS is more accurate than supine CXR and is as accurate as CT. When a CXR identifies both opacities and effusion, an LUS should be obtained because it is more accurate than CXR in distinguishing between opacities and effusion (20). Regarding pediatric-specific literature, Hajalioghli et al stated that chest CT may be replaced by POCUS with or without chest radiography in evaluating complex effusions/empyema (21). Furthermore, Calder and Owens established that LUS performed better than CT or magnetic resonance imaging in showing spectated effusions and/empyema (22).

Consolidation

Consolidations are pathological conditions where the lung parenchyma is filled with water, like in pneumonia or in atelectasis. This is indicated by C-lines, subpleural soft tissue-like masses differing in size and shape with poorly defined borders. Surrounding B-lines differentiate pneumonia and atelectasis from other disorders. In the beginning multiple small C-lines are amongst B- lines. Well organized types of pneumonia exhibit better conducting property enabling better visualisation of parenchyma details like vessels and airways.

Pneumonia can be differentiated from atelectasis by a dynamic air bronchogram and fluid bronchogram. Atelectasis is suggested by a static air bronchogram due to air trapped distal to the obstruction. Furthermore, the bronchovascular structure is oriented in parallel compared with the tree-like pattern in pneumonia. The dynamic air bronchogram in pneumonia demonstrates how secretions move with respiration in larger airways after forming primarily in alveoli. The fluid bronchogram seen in post-obstructive pneumonia displays airways, which are flooded with fluid and lack air movement. Bronchi appear as blood vessels but can be identified by their hyperechoic walls and absence of blood flow on Doppler imaging.

According to Copetti et al, the sensitivity to detect pneumonia in pediatric patient is higher than in adults due to better accessibility and noncalcified bones. Furthermore, a consolidation more than 1 cm exhibits a specificity of 98% (14). In 2008, Copetti and Cattarossi published a landmark article that compared diagnostic accuracy of point-of-care lung ultrasound with CXR in children with suspected pneumonia and found out that LUS is as reliable as CXR (23). In 2012, Shah et al conducted a prospective observational cohort study with increased sample size and concluded clinicians are able to diagnose pneumonia in children and young adults using POCUS with high specificity. The International Guidelines from 2012 very strongly recommend using lung ultrasound in the diagnosis of pneumonia. It was stated that LUS is as accurate as CXR in the diagnosis of pneumonia in pediatric patients. Lung ultrasound should be used as well for the detection of lung consolidation, because it can differentiate consolidations according to pathologies like pulmonary embolism, pneumonia, or atelectasis, based on visualization of air bronchogram. In mechanically ventilated patients, LUS is more accurate than portable CXR in detection of consolidation. However, LUS does not rule out consolidations that do not reach the pleura (20). In 2015, Pereda et al conducted a meta-analysis evaluating LUS for the diagnosis of pneumonia in children. Following a sensitivity of 96% and specificity of 93% of LUS, they support

LUS as an imaging alternative for the diagnosis of childhood pneumonia and advocate for the training of pediatricians in LUS (24).

Alveolar-Interstitial Syndromes

The hallmark finding of interstitial lung disease comprises multiple B-lines, which indicate the presence of increased extravascular fluid in the lungs and/or thickening of interstitium. In interstitial syndromes, there is more air than fluid in the lung, in consolidations conversely is more fluid than air (25). An interstitial syndrome is present if more than 3 B-lines are seen, which are no more than 7 mm apart. This finding needs to be present in 2 or more out of the above described 11 scanning regions. Interstitial syndrome can be caused by pulmonary edema due to heart failure or other causes like pulmonary contusion, pneumonia and in pediatric population commonly bronchiolitis. The distribution and amount of B-lines vary with the underlying pathology. B-lines of cardiogenic edema appear firstly in dependent regions and spread with progression of edema over the whole lung field. In severe pulmonary edema, multiple B lines converge to a “white lung”, the equivalent of ground glass appearance on CT scan.

The absence of B- lines excludes cardiogenic pulmonary edema with a sensitivity to 100% which is very useful for the clinical work up of a patient with dyspnoea (26). At the first sight cardiogenic edema might be related more to adult patients, but it should be considered, that a respectable proportion of patients in PICU are post cardiac surgery patients.

Circulatory examination

The section circulatory examination elaborates on goal-directed echocardiography, vascular ultrasound, and abdominal ultrasound. The assessment of the hemodynamic status is crucial in the management of critically ill patients. Point-of-care ultrasound offers a tool for hemodynamic assessment by providing immediate information about cardiac function and fluid status. This helps to identify the nature of cardiovascular compromise, to evaluate if the current therapy is working and gives direction for future intervention. In the section vascular ultrasound, the focus lies on caval vein assessment for volume responsiveness and fluid status. Investigation of aortic dissection and aneurysm and deep vein thrombosis will be mentioned only briefly as it occurs less likely in the pediatric population. Abdominal ultrasound will be discussed with respect to assessment for free fluid.

Focused Cardiac Ultrasound

Introduction

Focused cardiac ultrasound (FOCUS) comprises goal-directed echocardiography. According to Jennifer R. Marin et al FOCUS includes the evaluation of the heart as well as the inferior vena cava (IVC) (27). It is a limited focused clinician-performed evaluation, which can be performed by a critical care physician. FocUS does not replace the full cardiac examination of a cardiologist and does not intend to detect cardiac anomalies, but should be performed to answer focused questions and should be interpreted according to the clinical presentation of the patient (28). This refers only to transthoracic echocardiography considering that transesophageal echocardiography requires more training. FOCUS assesses the heart performance by displaying its rhythm, contractility, volume and ratios. It is interpreted with respect to clinical available information like arterial pressure, central venous pressure, use of vasopressor/inotropic drugs, ventilator setting, and urine output. Indications include cardiac related presentations like shortness of breath, chest pain, syncope, hypotension, shock, new murmur, and cardiac arrest (27). This examination can be an integral part of multiorgan ultrasound protocols like FAST or FALLS. Walley et al state however, that significant valvular abnormalities, wall motion abnormalities, LV aneurysm, RV hypertrophy, cardiac masses, thrombus, diastolic dysfunction, or a dilated ascending aorta with potential dissection should be examined with comprehensive echocardiography and not with point-of-care echocardiography (29).

Technique

Machine Setting and Transducer

General ultrasound evaluation is performed from the right side of the patient like in physical examination and history taking. Due to the left position of the heart, echocardiography is conventionally performed by cardiologists from the left side. As part of a multiorgan examination however, it is suggested to perform echocardiography as well from the right side in order to prevent time delay by changing the position of the ultrasound performer. The orientation of indicator-to-patient and indicator-to-screen results often in confusion due to different conventions (30). The

approach of the cardiologist is to flip the image on the machine setting in order to create an image more similar to the anatomy of the heart, which is thought to be more useful for evaluation of congenital anomalies. Critical care physicians recommend using the abdominal setting on the machine and trying to create a cardiology consistent image by rotating the probe for 180° in relation to probe positions used by cardiologists. This technique prevents time-delay and confusion in a multiorgan time-limited examination.
The transducer of choice is a low frequency (2-5 MHZ) phased array or microconvex probe, whose small footprint allows fitting between the ribs.

Standard Views

Standard views of echocardiography include subxiphoid, parasternal long- and short- axis and apical four- chamber view.

Subxiphoid View

The subxiphoid view is the most accurate window for the detection of pericardial effusion because it allows the evaluation of posterior pericardium where the effusion starts. In addition, it is the preferred window in cardiac arrest, because the probe position does not interfere with the resuscitation process. As congenital cardiac diseases have a higher occurrence in paediatric population, the ratio of postcardiac surgery patients after correction of cardiac anomalies is higher in pediatric care units. Consequently, it is of importance to know how to recognize hemopericardium in postcardiac patients with the subxiphoid view, which allows the best visualisation. The probe lies compared to other probe positions in a flat angle of 15° inferior to xiphoid process pointing towards the left shoulder. In a cardiology setting, the probe indicator would be directed to the patient's left, while in a general imaging orientation it should be directed to the patient's right, resulting in the same image on the screen. The view uses the liver as acoustic window and visualizes all four chambers of the heart. The apex of the heart, a left-sided structure, is seen on the right side of the screen and right-sided structures are viewed on the left side of the screen and adjacent to the liver (30).

Parasternal Long-Axis View

The probe is placed in the 3rd-4th intercostal space just left to the sternum above the the nipple line, compared to adults where the transducer is positioned in the 2nd-3rd intercostal space sternum (1). The probe position in this view is perpendicular and the indicator directed towards the patient's left hip. This view allows particularly the evaluation of left ventricular function, which is important for the diagnosis and management of heart failure. One of the assessment methods is fractional shortening (FS), which measures the change in the left ventricular short axis diameter with M-mode (28). The fraction of left ventricular shortening can be calculated by the following equation:

$$\text{Fractional shortening} = \frac{\text{End diastolic dimension - End systolic dimension}}{\text{End diastolic dimension}} \times 100\%$$

A fractional shortening of more than 30% is normal. The limitation of this technique is that M-Mode echocardiography does not display the specific movement and thickening of wall regions, but only displays generalized contractility. Nevertheless, the subjective visual approximation also was proven to be accurate in comparison to other assessment methods. In a systematic review, McGowan et al compared visual assessment with Simpson's method and wall motion index and concluded that none of these would over- or underestimate the left ventricular function (31).

Parasternal Short-Axis View

This window is also known as Fishmouth view due to the appearance of the mitral valve. It serves for the assessment of ventricular contractility and valvular function, which is achieved by rotating the probe about 90° towards patient's right hip. During the process of rotation, the mitral valve, pupillary muscles, and tricuspid valve are displayed.

Apical view

The apical view allows the comparison of the four cardiac chambers in regard to their size and function. The transducer is positioned at the cardiac apex, which is located in fifth intercostal space and can be confirmed by palpation of apex beat. The indicator is directed towards the right side of the patient. For decreasing lung artefacts and bringing the heart closer to thoracic wall, the patient is turned into lateral position lying on his left side.

Pathology

Pericardial effusion and tamponade

Pericardial effusion has a broad spectrum of presentation from an incidental finding to a life-threatening cardiac tamponade. Especially for the diagnosis of cardiac tamponade, which can lead promptly to circulatory collapse, ultrasound is of high clinical importance. Ultrasound is more sensitive in the detection of cardiac tamponade than signs on physical examination. Only one of the classic signs of Beck's triad (distended jugular veins, muffled heart sounds and low blood pressure) is present in 30% (1). Causes of pericardial effusion are multiple and can be divided into inflammatory and non-inflammatory. Inflammatory include bacterial, viral, HIV infections and others. Non-inflammatory causes can be among others neoplastic and trauma. The process can be acute or chronic. In an acute process, the fibrous pericardial sac cannot adapt to the fluid accumulation and less amount of fluid is necessary for developing a cardiac tamponade.

In the subxiphoid window pericardial effusion is seen as an anechoic line surrounding the heart, which starts posteriorly. Cardiac tamponade is displayed as a circumferential anechoic line, which compresses the heart. The heart appears hyperdynamic and displays scalloping. Scalloping describes the process that the right ventricle collapses during early diastole and the right atrium during late diastole. Klugman and Berger concluded in "Echocardiography and Focused Cardiac Ultrasound" that right atrial collapse is more sensitive than the right ventricular collapse for indicating cardiac tamponade as the right atrium is more compliant than the ventricle (28). One pitfall should be kept in mind that epicardial fat pads can be falsely interpreted as pericardial effusion. The difference is that epicardial fat is seen anteriorly and presents an echogenicity within its mass. Pericardial effusion contrary starts posteriorly and inferiorly and appears anechoic.

The assessment of pericardial effusion constitutes one of earliest ultrasound applications and its value is confirmed by several studies (27). Via et al strongly recommend FOCUS for the assessment of pericardial effusion in critically ill pediatric patients in "International Evidence-Based Recommendations for Focused Cardiac Ultrasound" (2014)(32). In addition, Levitov et al confirm in "Guidelines for the Appropriate Use of Bedside General and Cardiac Ultrasonography in the Evaluation of Critically Ill Patients—Part II: Cardiac Ultrasonography " from 2016 as well the evidence of ultrasound in cardiac tamponade for pediatric patients (33).

Cardiac arrest

Another interesting example of the different physiology in children is that cardiac resuscitation might be more promising in children than in adults. While in adults cardiac standstill has a very bad prognosis, in children there is still a probability that the cardiac function can resume, which Steffen et al presented in a case study (34). Levitov et al further stated that cardiac arrest in children is mainly due to respiratory causes. Therefore, a fast oxygen delivery can change the outcome in comparison to adult cardiac standstill. The rationale why Levitov et al do not recommend bedside cardiac ultrasonography (BCU) for irreversible causes of cardiac standstill highlights as well the unique potential in children to recover from severe myocardial insult. According to Levitov et al., there is the chance that an initially akinetic heart might ultimately recover. Cases exist where myocardial function continued after extracorporeal membrane oxygenation (ECMO) and days of absent function (33).

The recommended window is the earlier explained subxiphoid view. M-Mode offers the best evaluation for asystole to follow motion of cardiac wall over time. The compression and artificial respiration however must be put on hold for this evaluation (1).

Marin et al find literature for pediatric patients limited (27). Via et al affirm with very good consensus the panel for the 2010 international pediatric basic life support and ALS recommendations, which state that ‘‘FocUS may be considered to identify potentially treatable causes of a cardiac arrest when appropriately skilled personnel are available, but the benefits must be carefully weighed against the known deleterious consequences of interrupting chest compressions.’’ (32, 35). Regarding bedside cardiac ultrasonography for irreversible causes, Levitov et al do not recommend BCU for diagnosis of irreversible pulseless electrical activity in cardiac arrest, because the efficiency is compromised by a low level of BCU penetrance and a low number of expert operators in pediatric critical care (33).

Vascular US

Caval index, IVC/ Aorta ratio and fluid responsiveness

Hemodynamic monitoring is a crucial part of critical care. It is critical for the assessment of volume status and fluid responsiveness, which gives directions not only for diagnosis but also for further clinical management. The clinical signs for hypovolemia/shock include increased capillary refill time more, decreased blood pressure, increased lactate level and decreased urine output. These are

only surrogate markers of tissue-end-perfusion. General appearance, dry mucous membranes, and sunken eyes are vague clinical signs for dehydration, which vary with the subjective impression of the clinician. Ultrasound examination would in comparison offer a non-invasive method, which enables imaging of real-time physiological changes. Many studies in adult population have been conducted and integrated into clinical practice in contrast to pediatric patients. There exists a lack of studies and the existing results are contrary. One point is that the inferior vena cava (IVC) changes with age in normovolemic children compared to adults, which poses the need for more studies researching age-specific IVC measurement (36). IVC measurement in mechanically ventilated patients, common in paediatric intensive care, requires further validity.
A current parameter of fluid status assessment is the collapsibility of the inferior vena cava. Collapsibility is a marker for intravascular volume status, estimated by visual assessment or by measuring the caval index. There exist several arithmetic formulas for the caval index, the most commonly one used is the following:

collapsibility index = (IVC max diameter- IVC min diameter)/IVC max diameter

This is based on the physiological principle that the AP diameter of IVC is minimal during inspiration due to negative thoracic pressure and maximal during expiration when positive intrathoracic pressure presses volume back to the low-pressure abdominal venous system. Faiza Al-Talaq and Vicki E. Noble use pediatric POCUS for fluid status assessment by measuring the caval index and the IVC/Aorta ratio. Decreased volume status is defined by inspiratory collapsibility of more than 50 %. IVC/Aorta ratio of < 1 and an increase to ≥ 1 after fluid challenge serves as an indicator for dehydration (37). The IVC/Ao ratio is as well supported by the study of Chen et al in the emergency department (38). Levine et al performed a non-consecutive cohort study in Rwanda in 2009, where they evaluated ultrasound as an assessment tool for severe dehydration. They found that the measurement by IVC/aorta ratio was reliable for detecting severe dehydration. However, the number of participants of their study was too small in order to determine ultrasound as a superior method compared to others. This study is often cited. Nevertheless, it must be mentioned that these study results apply only for severe dehydration, which is rare in tertiary hospitals in developed countries as compared to the rural hospital in Rwanda, where this study had been conducted. In a consecutive study in 2014, Levine investigated again the use of IVC/aorta ratio for diagnosing dehydration in a resource limited area. This time it was performed by district nurses and the patients' age was limited to 5 years of age. In this case, the IVC/aorta ratio did not prove as an independent tool for assessing dehydration. Accountable factors may be that nurses could not perform the ultrasound as required or that pediatric patients in this age group had been more difficult to examine. They would not keep still and would cry more, which change the IVC diameter due to increased abdominal and intrathoracic pressure (39). Marin et al stated as well that "Standard measurements of the IVC/aorta are not well established for all age groups. Serial exams may be more useful to guide resuscitation than an exam at a single point in time. " (27). Fluid responsiveness is as well an important issue in critical care. Gan et al found out in a systematic review that the only variable for predicting fluid responsiveness in children is respiratory variation in aortic blood flow peak velocity (40).

Technique

For identifying the IVC (inferior vena cava) and aorta, the vertebral bodies serve as landmark. The aorta and IVC are located anterolateral to the vertebral bodies. The IVC lies to the patients right, the aorta to the left. The same arrangement is displayed on the screen. The IVC can be distinguished from the aorta by thinner walls, being compressible and not displaying pulsations. Nevertheless, in small children aortic pulsations may be transmitted to the IVC due to the proximity of aorta and IVC and IVC's thinner vessel walls. The aorta differs from the IVC further by exhibiting echogenic walls and by branching pattern. An important characteristic for the IVC is its respiratory variation.

The best imaging can be achieved by using a low-frequency curvilinear transducer. However, a phased array transducer can be used as well. The most common views are the transverse subxiphoid view and the longitudinal subxiphoid view. The transverse subxiphoid is generated by placing the probe perpendicular to the patient's body with the indicator pointing toward the patients right. The longitudinal view is achieved by rotating the transducer for 90° with indicator directed towards the patient's head. The inferior vena cava is identified in a subxiphoid longitudinal plane as it passes through the liver parenchyma, traverses the diaphragm and enters the right atrium. The caval index is measured in the longitudinal view. Dynamic assessment consists of measurements of vessel diameter during inspiration and expiration using M-mode. Nevertheless, Finnerty et al recently suggested after examining 39 healthy medical students, that the best window for IVC measurement is B-mode in longitudinal subxiphoid (41). The IVC/Aorta ratio is obtained by visualising the descending aorta in its subxiphoid location in the transverse plane at the level of the renal arteries., measuring the maximum size during systole, and comparing it to the IVC.

Abdominal Aortic Aneurysm and Aortic dissection

Abdominal aortic aneurysm (AAA) and aortic dissection are quite rare in the pediatric population, but should be kept in mind. A suspicion should be raised particularly in patients with congenital cardiac anomalies, Marfan syndrome, hypertension and trauma. Point-of-care questions for investigation of AAA and aortic dissection address whether aortic dissection is present, whether the aortic diameter is more than 3cm and the diameter of iliac arteries is more than 1.5cm (37).
For this examination a curvilinear or phased array transducer is used as well. The aorta is displayed in a longitudinal view when it leaves the diaphragm and the superior mesenteric artery is branching off. Then the aorta is followed up until it branches into the iliac arteries. This corresponds to the distance from the subxiphoid area to the umbilicus.

Deep Venous thrombosis

In adults, an integral part of vascular ultrasound examination poses the screening of deep vein thromboses in limbs, iliac and subclavian vein. Pediatric thromboembolism is rarely found and plays consequently a minor role in point of care ultrasound. In cases of high suspicion due to coagulopathy, malignancy or prolonged immobilization, screening for deep vein thromboses is recommended.

Role of Doppler in Circulatory Examination

Audible Doppler is very useful in assessing peripheral pulses. In case peripheral pulses cannot be palpated, this small device can assist in the examination. The application is very easy and self-explanatory. As explained in the general chapter, the angulation should be less than 60°.
Colour Doppler is very useful for distinguishing the inferior vena cava from the aorta when assessing the caval index or the IVC/Aorta ratio. In addition, it is used for detecting valvular abnormalities, where change of colour can indicate backward jets.

Abdominal Ultrasound

In the frame of primary assessment, abdominal ultrasound focuses on the detection of free fluid or blood. It is an integral part of the FAST (Focused assessment with sonography for trauma) and EFAST (Extended focused assessment with sonography for trauma) protocol. As the name already indicates, both are protocols for the examination of trauma patients. The difference between FAST and EFAST is the extension in EFAST, which include lung investigation for pneumothorax. The binary point-of-care questions to be answered in FAST protocol include: Is free fluid or blood present in the abdomen? Is free fluid or blood present in the pericardium? Is free fluid in the thorax present? Is a pneumothorax present? After discussing the examination of free fluid in the thorax and pericardium, and pneumothorax earlier, the following will concentrate on the investigation of free fluid or blood in the abdomen. Free fluid however is not only assessed in trauma patients but also in patients with a likelihood of shock. For this examination a low-frequency curvilinear transducer is recommended due to its deeper penetration into the abdomen. In smaller children the phased-array transducer may be more appropriate due to its smaller footprint. Fluid accumulation obeys the principle of gravity and follows the anatomical gutter in the abdominal cavity. Ultrasound imaging for free fluid comprises Morrison's view in the right upper quadrant, the splenorenal view in the left upper quadrant and the suprapubic view. Most likely fluid accumulates in Morrison's pouch, in smaller children however the fluid accumulation occurs more likely in the pelvis. By using gravity, the Trendelenburg position, elevating patients' legs for about 10-15°, can improve detection of free fluid in the abdominal cavity. The reverse Trendelenburg position by elevating the upper body above the level of the lower body helps in imaging fluid in the suprapubic and subxiphoid view.

Morrison's View

This view illustrates Morrison's pouch, a hyperechoic line between right kidney and the adjacent liver. The transducer is oriented longitudinally with indicator directed towards the patient's head. The scanning begins at the costal margin at the midaxillary line and continues until kidney and liver can be visualized. From this point the right kidney is scanned completely in all directions. Fluid accumulation in Morrison's pouch can be visualized if it exceeds 250ml. This however leads to the conclusion, that a small amount of fluid cannot be detected in the very early phase, which should be kept in mind.

Splenorenal View

As the name already indicates, this window visualises the space between the spleen and the left kidney in the left upper quadrant. The transducer is oriented longitudinal and positioned posterior to the midaxillary line. The technique is similar to Morrison's view by scanning the complete left kidney in all directions. The anatomic difference lies in the more superior and posterior position of the left kidney. The fluid accumulates superiorly to the kidney beneath the diaphragm, medially and in the splenorenal recess. For detecting a potential fluid accumulation, it is obligatory to visualize the diaphragm by orienting the probe more cephalad.

Suprapubic view

In this window, the goal is to investigate, if free fluid is present in the rectovesicular pouch in males or Douglas pouch in females. The transducer is positioned transversely directly superior to the pubic symphysis and directed towards the patient's feet until the bladder is visualised. If the bladder is completely seen on the image, the probe is rotated for 90° directed longitudinally with the indicator showing to the patient's head. If fluid is present, it should be seen behind or adjacent to the bladder.

In the case of examination of trauma patients, the investigation for further hematomas would continue in the parenchymal, subscapular, pre- & retroperitoneal spaces.

Protocols and Sonodynamics

SESAME Protocol

SESAME-protocol is the abbreviation for "sequential emergency sonography assessing mechanism or origin of severe shock of indistinct cause". Dr. Lichtenstein, devoted to the development of bedside ultrasound, developed this protocol for diagnosing reversible causes of cardiac arrest. According to Dr. Lichtenstein, "the SESAME protocol does not need any validation: each of the applications has been duly validated." (42). SESAME, in particular, provides a very good protocol with as little time consumption as possible, which is a major advantage considering that only 10 seconds during pulse check constitute a very narrow time window for the ultrasound examination (43). A technical prerequisite is that a narrow machine with seven seconds start-up time, no buttons to set and a microconvex probe are available (42). If cardiac arrest does not respond to electric shock, this protocol tackles reversible causes. The first step is to rule out pneumothorax. The next step would be the examination for a deep vein thrombosis. Lichtenstein states that this on-off marker is more sensitive for the evaluation of pulmonary embolism than visualisation of the right ventricle. In the case of pediatric patients, where thromboembolism is less likely, importance and sequence of this step should be discussed further. The third step is to perform abdominal ultrasound to assess free fluid and rule out haemorrhage. The next step assesses the pericardium for excluding cardiac tamponade. The fifth and last step consists of the visualisation of the heart.

FALLS Protocol

FALLS (fluid administration limited by lung sonography) protocol, also contributed by Dr. Lichtenstein, is used for circulatory failure of unknown cause and differentiates the four types of shock (42). For this protocol, a microconvex transducer is recommended. The first step of the examination is to rule out obstructive shock. This is accomplished by excluding pneumothorax, and pathology of the right ventricle or pericardium. Next, cardiogenic shock is ruled out by the absence of B-lines. If obstructive and cardiogenic types of shock are excluded, fluid therapy is started. The remaining possibilities left are hypovolemic and septic shock. In case of hypovolemic shock, the clinical condition of the patient should improve with fluid administration. In case of no improvement, the possibility of septic shock requires performing additional lung ultrasound. Further examination investigates if A-lines have changed to B-lines, which would correspond to an interstitial syndrome. Interstitial syndrome would indicate that the interstitial compartment is saturated with fluid and that septic shock is likely.

Sonodynamics for Hypotension

Hypotension in children is defined as systolic blood pressure (BP) below 5th centile for age. Because children possess the capability to compensate longer a declining BP than adults and prevent cardiovascular collapse, hypotension as a clinical sign is more severe. In fact, hypotension in shock indicates a late stage. However, in case of hypotension, ultrasound can serve as a useful adjunct for examination and management (44, 45). Due to the value of ultrasound for the management of hypotension, Elbarbary et al suggested following “sonodynamic” sequence: Gross evaluation of heart, analysis of vena cava and evaluation of interstitial fluid in the lungs (46, 47).

Gross cardiac evaluation rules out pericardial effusion and gross cardiac anomalies. On a closer look ventricular function is investigated by answering following questions: Does the left ventricle appear dilated? Is the function of the left ventricle compromised? Is the right ventricle dilated? Is the performance of the right ventricle impaired? Dilation or decreased performance of the left ventricle could indicate cardiogenic shock. The state of the right ventricle aids in the differential diagnosis of hypovolemic, cardiogenic or obstructive shock. A dilated right ventricle can indicate obstructive shock by pulmonary embolism or pneumothorax (29). It furthermore can refer to pulmonary hypertension, which can be evaluated by measurement of tricuspid regurgitation (46). The analysis of the vena cava consists of its size and its collapsibility during inspiration (36) (46). According to Elbarbary, an IVC collapsibility of 20% in ventilated patients and 50% in spontaneously breathing patients indicates hypovolemia. Furthermore, a flat IVC, meaning that its diameter is small and it collapses spontaneously, suggests hypovolemia and fluid responsiveness. A fat IVC in contrast, indicates no fluid responsiveness, hypervolemia or pulmonary hypertension. A flat IVC in combination with a small, hyperkinetic heart points towards cardiac tamponade (47). Similar to the FALLS protocol, Elbarbary et al integrate lung ultrasound for differential diagnosis. It is stated that A-line rules out pulmonary oedema and the combination of a hypokinetic left ventricle, B-line pattern on LUS and low oxygen saturation indicates cardiogenic pulmonary edema, which requires administration of inotropes and avoidance of fluids (46).

Disability

Cranial Ultrasonography

D for disability refers to cranial ultrasound which includes the assessment of optic nerve enlargement and neonatal assessment.

Optic Nerve Enlargement

Enlargement of optic nerve sheath diameter is an indirect sign of increased cranial pressure. Komut et al investigated the measurement of optic nerve sheath diameter by bedside ocular ultrasonography in the emergency department and concluded that it is a useful method for patients with suspected intracranial event (48). Le et al found that a sensitivity of 83% and a specificity of 38% is insufficient for medical decision making in children with suspected rise in intracranial pressure (49). As a conclusion from these diverging results, it can be suggested that until the

measurement of optic nerve sheath diameter is validated, it can serve as a screening tool for increased intracranial pressure. Le et al defined the abnormal cut-off value as greater than 4.0 mm in patients younger than 1 year and greater than 4.5 mm in older children. The point-of-care questions consequently address these cut-off measurements for the diameter of the optic sheath.
A linear high-frequency transducer is placed on the closed eyelid of the patient. For the best result, the transducer is placed opposite to the optic nerve. On the ultrasound image first the anterior chamber is seen, then the lens and the posterior chamber. Beneath the hyperechoic line, due to posterior acoustic enhancement by the vitreous body, the optic nerve is visible. The measurement commences 3mm posterior to this hyperechoic line. A mean value needs to be calculated after measurement of the optic nerve sheath diameter in both eyes.

Cranial Ultrasonography

Cranial ultrasonography can be used as bedside technique in neonatal intensive care units. It is age limited because the fontanelles serve as acoustic window. Traditionally scanning is performed through the anterior fontanelle, which closes between 12- 14 months. The posterior fontanelle closes up to 6 months. Cranial ultrasonography is less suitable for infratentorial structures because of the highly echoic tentorium. Considering that intraventricular haemorrhage (IVH) is a major neurological complication of prematurity, its investigation is included in the ABCD assessment. Intraventricular hemorraghe is more common in preterm babies, where cerebrovascular autoregulation is impaired and germinal matrix vasculature fragile. The immature vessels cannot withstand the fluctuating cerebral blood flow and hemorraghe occurs. Risk factors include consequently a rapid change in blood pressure and blood volume, coagulopathies, respiratory distress and hypoxic-ischemic events. Furthermore, it is associated with ICU specific therapies. Doymaz et al state that ECMO is a risk factor for intracranial hemorraghe in newborn with persistent pulmonary hypertension (50). Furthermore, IVH is exacerbated by anticoagulation. Brunhild Halm and Adrian A. Franke suggest in a case report that IVH should be kept in mind as a differential diagnosis for preterm babies presenting with anaemia.
IVH is visualised by placing a high-frequency linear transducer parasagittal over the anterior fontanelle with the indicator pointing towards the patient’s head. Hemorraghe can be visualised in the caudothalamic groove inferior to lateral ventricle, between the thalamus and the caudate nucleus. In grade I the hemorraghe is limited to the germinal matrix. Grade II includes

intraventricular hemorraghe echogenic lesion in lateral ventricle without dilatation. Grade III involves ventricular dilatation where ventricular lining can appear echogenic reflecting ventriculitis. Grade IV encompasses parenchymal hemorraghe.
McCrea and Ment state that prematurely born children with Grade 1-2 face the risk for developmental disability and with Grade 3-4, they have a high risk of developing cerebral palsy and mental retardation (51). The management of IVH is limited and involves managing sequela and avoiding progression with preventing further blood pressure fluctuation and hypoxia.

Discussion

In this review more than one approach is represented in some instances. Different approaches were represented in case of direct and indirect intubation management, the intersecting FALLS protocol for shock and Sonodynamics for hypotension, and the controversial assessment of fluid status. Further studies need to be conducted to compare different approaches in order to find a common ground for standards, which enable POCUS to be integrated into guidelines. In addition, further studies need to prove their validation for their application in pediatric population.
Levitov et al did suggest not to use BCU for evaluation and definitive diagnosis in congenital heart disease. In addition, it is suggested that it is done with pediatric cardiology specialist (33). Regarding the high prevalence of congenital heart disease in pediatric intensive care unit, this might be reconsidered for monitoring patients after surgical correction of cardiac anomalies.
Regarding the ABCD curriculum, the question may arise what happened to the E in the ABCDE. "E "stands for exposure and according to the curriculum, it refers to "Exclude missing findings" in order to prevent life-threatening lesions.
FALLS protocol, SESAME protocol, ABCD curriculum, lung ultrasound: Dr. Lichtenstein can look back on many years of experience with point-of-care ultrasound. He makes a big contribution to the development of protocols and to the ABCD curriculum. In fact, he contributed with extensive research and longstanding experience, especially to lung ultrasound. In general, he advocates minimalistic equipment like using only one button. However, this trend of avoiding technological advancement like Doppler might present a limitation (2, 42).
In general, point-of-care ultrasound is seen to have great development potentials. The ultrasound machines are decreasing in size allowing the use of ultrasound as an extension of physical examination. Furthermore, acquired point-of care ultrasound skills are proven to be quite accurate.

Mandavia et al state that “emergency physicians can be taught focused ultrasonography with a high degree of accuracy” (52). Pershad et al found out that pediatric emergency physician sonographers can accurately perform emergency physician–directed Focused Echocardiography in the evaluation of the critically ill pediatric patient (53).

Several publications exist about the appropriate training for residents. the current trend is to integrate point-of-care ultrasound into the curriculum during medical school (54, 55). Therefore, the initial idea for this narrative review was to provide a basic overview for other medical students, which might serve as an inspiration.

Conclusion

Point-of-care ultrasound is the leading method of ultrasound in the pediatric intensive care unit. It is proven that it is not only a fancy idea but a basic skill (56). It provides accurate assessment for clinical decision making and management. Real-time imaging allows time-saving intervention, which is crucial in the treatment of critically ill patients. POCUS in pediatric critical care represents an emerging field. Point-of-care ultrasonography has great development potentials and should be integrated into the curriculum of medical school.

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Biography

Katharina Anna Leipfinger was born in Bavaria, the South of Germany, and did her A-levels at Gymnasium Gars. Before she enrolled into School of medicine at University of Zagreb, she obtained a bachelor of arts at the Royal Conservatoire of Scotland. Preceding her medical studies, she volunteered for one month in neonatal care in a rural hospital in India. In addition, she volunteered for three months as a nurse's assistant in surgery at the University Teaching Hospital Butare in Rwanda. Besides her studies, Katharina is working as a second assistant in the Traumatology and Orthopaedics Department at the Hospital Barmherzige Brüder in Munich. She appreciated being a student instructor for history taking and physical examination as she enjoys making an impact by sharing knowledge. Currently, Katharina is doing her clinical elective in the Accident and Emergency department at Charing Cross Hospital in London. Her next clinical elective will take place at the Unfallkrankenhaus Berlin in the Department of Intensive Care. She sees in point-of-care ultrasound high potential and is interested to continue to explore this area in her future career.