Contrast-enhanced ultrasound (CEUS) in pediatric blunt abdominal trauma

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Abstract

Baseline ultrasound is the first-choice technique in traumatic hemodynamically stable children, and is essential in the early assessment of unstable patients to detect hemoperitoneum or other potentially fatal conditions. Despite the technological advancements in new ultrasound equipment and the experience of the operators, it is not always possible to rule out the presence of parenchymal traumatic lesions by means of baseline ultrasound nor to suspect them, especially in the absence of hemoperitoneum. For this reason, in the last decades, basic ultrasound has been associated with contrast-enhanced ultrasound (CEUS) to evaluate the stable little patient in cases such as low-energy blunt abdominal trauma. Because it relies on second-generation contrast agents, the CEUS technique allows for better detection of parenchymal injuries. CEUS has been demonstrated to be almost as sensitive as contrast-enhanced CT in the detection of traumatic injuries in patients affected by low-energy isolated abdominal trauma, with levels of sensitivity and specificity up to 95%. A very important point in favor of CEUS is its capacity to help distinguish the healthy patient, who can be discharged, from the one needing prolonged monitoring, operative management or hospitalization. Finally, we also have the ability to follow-up on low-grade traumatic lesions using CEUS, always keeping in mind patients' clinical conditions and their hemodynamics.

Keywords Pediatric blunt abdominal trauma · Contrast-enhanced ultrasound · CEUS · Follow-up · Emergency radiology · Trauma imaging

Sommario

Il trauma rappresenta una importante causa di morbidità e mortalità infantile ed il trauma chiuso dell'addome è responsabile di circa l' 80-90% delle lesioni addominali. Il meccanismo traumatico è abbastanza simile a quello che si verifica nell'adulto, con significative differenze fisiologiche tra le due classi di età responsabili di un sempre maggior utilizzo del management non operativo in età infantile. In caso di trauma a bassa energia l'imaging può essere effettuato con la CEUS, una tecnica diagnostica in grado di evidenziare le lesioni traumatiche addominali con un' accuratezza diagnostica molto vicina a quella della TC con mdc. Tuttavia, per alcune lesioni traumatiche, come quelle che interessano le vie urinarie, la TC con mdc resta la metodica di scelta, in ragione della sua elevata sensibilità ed accuratezza, in grado di distinguere tra un leakage retroperitoneale o intraperitoneale, guidando quindi anche il management terapeutico. Il fegato è l'organo più comunemente interessato dalle lesioni traumatiche addominali, seguito dalla milza. Le lesioni renali e pancreatiche sono piuttosto rare. In questa review gli autori si propongono di presentare i reperti di imaging più comuni in corso di trauma chiuso dell'addome infantile con CEUS e relativo confronto con la TC.

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Introduction

Blunt trauma still remains the main cause of mortality and morbidity in pediatric patients, and can lead to permanent disability. Due to its volumetric disproportion to the rest of the body, the head is the most common site of injury, especially during the 1st years of life; the abdomen

is the second-most common site of injury [1–4]. One has to remember that the children are not “small adults,” because in the course of their growth they undergo several physical transformations. A deep knowledge of such transformations is needed to adequately manage a potential trauma involvement. Among these specific features, it is particularly worth remembering the lower thickness of the abdominal wall, the greater proximity of the internal organs to the abdominal wall, and a lower position of the abdominal organs than we see in adults, because the horizontal arrangement of the diaphragm muscle rolls those organs down. Each of these situations is a potential cause of serious damage to one or more internal organs, even after a low-energy trauma.

In children, as in other injured patients, it is mandatory to understand the dynamics of the traumatic event exactly: that is, to know if we are dealing with a high- or a low-energy accident. These two categories have different clinical and diagnostic management pathways.

The causes of a trauma are different according to the age of the patient: toddlers are more prone to domestic traumas. Among them, especially in small patients, we should remember the “beaten” or “shaken” child: in this case, the victim needs a complete physical evaluation to detect the presence of any previously unrecognized lesions. Children more often undergo sports trauma, whereas teenagers are often involved in sports and motorbike or car accidents.

In high-energy trauma, as in a vehicle or pedestrian accident, multi-organ involvement has to be suspected; therefore, it is necessary to study not only the abdomen but the whole body, including the cervical spine and the neck, to rule out the rare but dangerous vascular lesions of the great vessels.

In low-energy trauma, as usually happens during sport activity, single-organ involvement has to be suspected: a typical finding is the bruise, the superficial sign of the direct impact, as occurs in handlebar bicycle traumas [1–4].

Even if the patient is conscious, the anamnestic interview and the clinical examination can be difficult, especially in young patients. In the physical evaluation, the presence of bruises or wounds may suggest the severity of the trauma. It is important to remember that in younger patients, the absence of fractures does not exclude the possibility of injuries to internal organs, and that the presence of one or more fractures is an indication of trauma severity [5]. This can be explained by the higher elasticity of babies’ bones compared to adults’.

Given all these factors, diagnostic imaging plays an essential role in the management of a pediatric trauma.

The first imaging technique performed on a child who has sustained a low-energy trauma is ultrasound (US). Despite its own limitations, such as being strongly operator dependent and body-type dependent, it has several positive features, including its high availability, the lack

of radio-exposure, and its high sensitivity for very small amounts of hemoperitoneum [6–13].

In the last decades, the diagnostic accuracy of conventional ultrasound has greatly increased because of the introduction of contrast media. This technique has improved US sensitivity and specificity for the visualization of parenchymal lesions [6, 7, 13–15].

As Valentino et al. demonstrated [6], baseline ultrasound is characterized by a very low sensitivity in the evaluation of traumatic parenchymal lesions, especially in the absence of hemoperitoneum (about 45%); the authors showed that 25 patients without peritoneal fluid at US had false-negative results, whereas 20 patients who had a small peritoneal fluid collection had no post-traumatic injuries on CT, and were, therefore, considered false positives. As in our experience, these data confirm that the presence of a traumatic lesion cannot be excluded or confirmed only on the basis of the presence or absence of hemoperitoneum.

The scenario changes dramatically in the case of a high-energy trauma. In the case of a hemodynamically stable patient, total body contrast-enhanced CT is the gold standard exam to be performed.

In case of a hemodynamically unstable patient, “Focused Abdominal Sonography in Trauma” (FAST) or the Extended-to-thorax FAST (E-FAST) [15] should be performed during resuscitation maneuvers in the emergency room, to recognize the potential causes of “preventable” death in a very short time, such as pneumothorax (PNX), hemothorax, hemopericardium, or hemoperitoneum, as well as to evaluate the caval filling. Some studies, while supporting the usefulness of FAST, have emphasized its low sensitivity and specificity in depicting hemoperitoneum in patients aged 2 years [6, 12]. Only after the patient’s hemodynamic stability is achieved can total body contrast-enhanced CT be performed to correctly stage the disease.

The follow-up of an injured patient is another interesting scenario. In the case of low-energy trauma in children, the radiologist should perform the examination with no or the lowest levels of ionizing radiation. CEUS has been revealed to be very useful in such circumstances, allowing practitioners to adequately assess patients in a short time, while at the patients’ bedsides. Magnetic resonance (MR), if available, is also a valid alternative to the CT examination [13–20].

From an economic point of view, great savings could be achieved using CEUS in the follow-up of already studied injuries. To date, there are no studies of this practice in emergency contexts, although Lorusso et al. [17] performed a cost analysis comparing the use of CEUS to that of CT and MR in the characterization of liver lesions, which showed that the cost of a CEUS was half the price of other diagnostic exams.

CEUS technique

CEUS exam has to be performed after baseline US of the abdomen and pelvis [6, 12]. CEUS uses second-generation contrast agents (USCAs) and dedicated software operating at low mechanical index, which is able to recognize the resonance signals produced by the USCAs.

SonoVue® (Bracco, Milan, Italy) is the USCA used in Europe. This consists of stabilized gas microbubbles (1–7 µm), composed of perfluorocarbons or sulfur hexafluoride, encapsulated by a very resistant phospholipid shell. The high resistance of the shell to the mechanical effect of the ultrasound beam allows the contrast medium to have a long duration, so that it is possible to explore all the vascular phases in real time [21, 22].

The dedicated software is able to suppress the signals coming from stationary tissue, improving contrast resolution. It does so through real-time harmonic imaging scanning using a dynamic low mechanical index [23, 24], which allows the practitioner to differentiate between the signals of the background tissue and the gas-filled microbubbles without bursting the latter [25, 26].

The microbubbles emit harmonics at twice the insonation frequency by reflecting the ultrasound beam. The probe then separates the fundamental frequency from the second harmonic using inverted-phase pulse, and acquires the signal [11, 27].

Because the microbubbles are too large (10 µm) to pass through the vascular endothelium, USCAs remain intravascular (“blood-pool”), lacking any interstitial spread [18, 21].

As with the other contrast media, it is always necessary to obtain written informed consent from the patient’s parents or legal guardians before performing the procedure [6]. Even if USCAs are still off-label in children, several multi-centric studies have demonstrated their great safety in pediatric populations. USCAs are employed in most European and in many Asian countries, and they recently obtained FDA approval for echocardiography [13, 25].

Laboratory tests are not necessary, since this contrast medium is not excreted from the kidneys, but through the lungs during breathing [22]. The main contraindications are history of allergic reaction to the contrast agent itself, severe pulmonary hypertension, uncontrolled systemic hypertension and pregnancy status, and a known right-to-left shunt, but this last is currently considered controversial, with published recommendations for its removal.

The contrast medium is administered intravenously. The amount of contrast medium depends both on the weight of the patient and on the organs to be evaluated. In a patient of a younger age, for the evaluation of a single organ, or for the follow-up of known lesions, even half dose may be

enough. In older children, or in cases where it is necessary to evaluate multiple organs, USCA is administered in two split doses, whose amount is calculated using the following formula: age in years/20. The exam does not last more than 4–6 min; during the late phase it can be possible to obtain a visualization of active bleeding by visualizing the passage of microbubbles outside or in a damaged organ, and to rule out contained vascular injuries [6, 7, 13, 17–19, 21, 22].

Because of the inherent features of this contrast agent, it is not possible to use it to study the excretory phase of the kidneys. Therefore, the agent is not suited to the assessment of any excretory system lesions.

USCAs are generally well tolerated; the rate of adverse reactions is very low (about 0.014%) [7, 25–28]. There is no thyrotoxic or nephrotoxic effect; therefore, they can be safely applied in cases of acute or chronic renal failure because they do not have a renal excretion. Their employment is not authorized on pregnant or breast-feeding women [7].

As far as the timing of the examination is concerned, one should remember that the kidneys have the earliest and most transient enhancement because they lack glomerular filtration, whereas the spleen is initially inhomogeneous and then becomes persistently and homogeneously enhanced (up to 6 or 8 min); the liver and the pancreas behave intermediately, showing an intensifying enhancement. As a consequence, the examination usually starts with the kidneys, and then moves to the liver, the pancreas and finally the spleen. Our protocol consists of two split doses of SonoVue, followed by 10 mL of saline water: the first dose is used to explore the right kidney, the liver and the pancreas, and the second for the left kidney and the spleen. However, in many cases, we focus directly on the organ suspected or known to be injured. Because of the lack of blood circulation in lacerations, we found that all circulatory phases are useful for the detection of traumatic injuries, with the exception of the very first part of the arterial phase, when contrast enhancement is not yet evenly distributed in the parenchyma.

In the liver, the initial arterial phase usually lasts about 40 s, or slightly less. The venous and the late or homogeneous phases usually last about 4 min. The kidneys show different degrees of enhancement in the cortex and the pyramids. The cortex immediately enhances very intensely, while the pyramids enhance diffusely from the periphery to the center over about 30 s. The homogeneous phase of the kidneys generally lasts 2–2.5 min. The spleen has the longest lasting irregular arterial phase, with a confusing “zebra” pattern of early enhancement before the homogeneous phase, which sometimes arrives close to the minute mark. The homogeneous phase may be very long, lasting up to 6 min or more.

Following the injection of SonoVue, we usually start by examining the kidneys on both sides because of their quick

enhancement pattern. There is generally enough time to examine the kidneys thoroughly before moving on to the spleen or liver. We scan the kidneys both transversally and longitudinally from the onset of enhancement of the pyramids and throughout the homogeneous phase.

On the right side, after the kidney we usually move on to explore the pancreas and the liver after a second injection of SonoVue. Liver exploration starts as soon as the parenchyma shows even enhancement following the early arterial phase. In a trauma setting, it is useful to use less contrast medium for the liver than usual, since too much contrast may cover very thin lacerations. The homogeneous phase lasts long enough that we can examine the pancreas at the same time.

On the left side, the spleen is examined after the kidneys because its enhancement continues about 1.5–2 min after the kidney, leaving ample time for a thorough examination. The spleen acts as an efficient filter for the microbubbles, leaving the splenic veins very hypoechoic after 2–3 min; this feature helps to distinguish the veins from lacerations due to their tubular shape and the fact that a few microbubbles can always be seen passing through them.

CEUS finding is positive when a perfusion defect of a solid organ is found; in this case, we find a hypoechoic parenchymal area with irregular border, with or without interruption of the organ capsule. In case of a main vascular injury, the absence of perfusion in part or the whole of an organ is observed.

In our protocol (see the flowchart provided in the text), when a CEUS examination is positive, contrast-enhanced CT has to be performed to stage the disease and to evaluate other potential lesions not visible on CEUS, such as urinary tract and mesenteric damage [7, 13].

Traumatic lesions

The most used injury severity classification for traumatic lesions is that of the American Association for the Surgery of Trauma (AAST), which is based on surgical findings, and is not always directly related to the need to perform a surgical treatment. Children have a greater vasoconstrictive response than adults, so that their bleeding tends to be self-limiting. Therefore, conservative management is recommended in a hemodynamically stable patient, despite hemoperitoneum. The main factor responsible for operative management is hemodynamic instability or the possibility of its happening [6, 7, 13, 29].

Contrast-enhanced CT remains the first-choice technique in the evaluation of a traumatic patient because of its ability to stage the disease according to the AAST classification. In the evaluation of a patient with a low-energy trauma, CEUS showed optimal results, which are comparable or slightly inferior to those of CT ones in some studies [6, 13, 23].

At CEUS exam, normal parenchyma appears homogeneously hyperechoic without any distortion of the echotexture, and the parenchymal vascular structures are clearly recognizable. Solid organ injuries are represented by a parenchymal non-enhancing defect, sharply demarcated from the well-enhanced healthy tissue, which is more evident during the venous phase. In this phase, the relations with the capsule are more easily recognizable, and it is possible to evaluate the presence of any active bleeding as an intraparenchymal or extracapsular hyperechoic blush [22, 30].

Parenchymal lacerations are represented as linear or branched hypoechoic bands, perpendicular to the organ capsule; at CEUS, their relationship with the capsule, which may be interrupted or not affected, is clearly visible. The intraparenchymal hematoma appears as a heterogeneous hypoechoic area with ill-defined contours; subcapsular hematoma is usually seen as a non-enhancing lenticular area surrounding and shaping the parenchyma. Active bleeding is visualized in the early stage or the late stage as microbubble extravasation within the peritoneal or retroperitoneal space [13]. The absence of organ perfusion is suggestive of a complete avulsion of the vascular pedicle.

Liver

The liver is involved in 10–30% of blunt abdominal trauma, both with isolated and multi-organ lesions. Lesions are often asymptomatic, and non-operative management is adopted in 70% of cases. Hemoperitoneum occurs in around 2/3 of the cases when the organ capsule is involved; when the lesion involves the posterior surface of the liver, the so-called “bare area” not wrapped by peritoneum, the blood expansion occurs in the retroperitoneal space. Hepatic parenchymal lesions can involve biliary ducts, causing a biloma [3, 4, 31].

CEUS evaluation of the liver is limited in some not easily accessible areas, such as the liver dome, because of its relationship with the lung bases, and the lateral and lower segments in relation to patient’s lack of collaboration and to the interposition of ribs and of intestinal gas.

The liver is characterized by a double vascular supply, so that, after the arterial phase will follow the portal (40–120 s after contrast injection) and the sinusoidal (or late) ones (120–300 s after contrast injection) [3, 7].

The study during the venous phase, which lasts about 2 mins, is more suitable for the evaluation of any lesions; in fact, after this phase the image deteriorates, making it very difficult to distinguish between healthy parenchyma and injured parenchyma.

At baseline ultrasound, recent lesions appear as slightly hyperechoic linear or irregular areas; the presence of perihepatic collection is usually clearly depicted, but the relationship between the lesion and the capsule is not always well demonstrated. At CEUS, the lacerations are well

depicted as a slow attenuation zone into the hyperechoic parenchyma, and the relation with the capsula is easy to see as even little amount of perihepatic fluid (Figs. 1, 2). The subcapsular hematoma typically compresses the liver's outer profile, thus allowing it to be differentiated from perihepatic fluid. In some cases, it is possible to see the presence of hyperechoic spots due to active bleeding in the anechoic lesion or out of the Glissonian capsule [3, 32–34]. Traumatic hepatic vascular lesions are rare in children, but when they occur, they appear as non-enhancing areas after contrast medium injection.

According to previous work by Miele et al. [31] and to our more recent experiences [13, 35], CEUS has great potential in the staging of hepatic lesions after a mild isolated abdominal trauma. Valentino et al. [36] reported their experience in a study performed on 69 patients who had sustained a blunt abdominal trauma, where they performed sonography, contrast-enhanced sonography and CT. While baseline ultrasound was able to reveal four of seven liver lesions with a sensitivity of 57.1%, CEUS exam was able

to reveal seven of seven liver lesions, as CT exam did, with a sensitivity of 100%.

In another study by Valentino et al. [37] performed on 133 hemodynamically stable patients, the authors emphasized the high accuracy of CEUS compared to the baseline US performance, proposing it as the first-line technique for the early evaluation of patients with blunt abdominal trauma.

Durkin et al. [38] reported their experience with CEUS evaluation of traumatic pseudoaneurysms in 101 children affected by isolated or combined hepatic and splenic blunt or penetrating trauma. CEUS was performed routinely 5–10 days after the injury. In this study, CEUS detected liver and splenic pseudoaneurysms with 83% sensitivity, 92% specificity, 71% positive predictive value and 96% negative predictive value. These values were lower with respect to CE-CT, but CEUS was revealed to be superior to conventional ultrasonography in the follow-up of traumatic pseudoaneurysms.

In our experience [13] with a young boy affected by a sport trauma, CEUS was able to detect the hepatic lesion, the capsular involvement and the extra-parenchymal bleeding; in

Fig. 1 Liver trauma. **a** Baseline US and **b** CEUS demonstrate two parallel course lacerations of right hepatic lobe. CEUS allows for better definition of margins and the extent of the lesions. **c** Contrast-

enhanced CT on axial plane, **d** on coronal and **e** on sagittal reconstructions confirms the lacerations of the liver parenchyma and clearly depicts the relationships with hepatic vessels

Fig. 2 Liver trauma. **a** Baseline US shows an ill-defined area of inhomogeneity in the echostructure of the hepatic parenchyma. **b** CEUS better defines the site and the extent of liver laceration. **c** Contrast-enhanced CT on axial plane, **d** and on coronal reconstruction perfectly confirms CEUS findings

another case, it demonstrated an intra-lesional active bleed very well. All these data were fully confirmed at contrast-enhanced CT exam.

The treatment of hepatic lesions in children tends to be as conservative as possible, with patients' hemodynamics as the fundamental indicators guiding its management [38, 39] (Fig. 3).

Spleen

The spleen is the second-most frequently injured organ in a blunt abdominal trauma, after the liver. In fact, it is involved in 25–30% of cases, as an isolated lesion or as part of a multi-organ involvement [7, 40].

Spleen involvement is much more frequent in children than in adults, because the organ is bigger and protrudes from the rib cage, so it is more exposed to traumas [3].

The spleen is also the most vascularized organ of the body: in fact, around 350 L of blood flows through it every day, which is why its injury can lead to a massive hemoperitoneum [3].

From a technical point of view, it is always not easy to visualize the whole organ by means of ultrasound, especially the upper pole and the subphrenic region, because of its overlay by the left lung during inspiration; furthermore, the

artifacts from the caudal ribs and from the gas within the splenic flexure may also reduce its visibility [6, 40].

One has to remember that at baseline ultrasound, recent parenchymal lesions are not easy to visualize, even if they are large ones, because the echogenicity of fresh blood is very similar to that of the normal parenchyma, so that the most evident sign of splenic lesion is perisplenic or pelvic fluid collection [3, 7].

The vascular pattern at CEUS exam is the same as that observed at the CT. The arterial phase starts at 12–20 s and it has a long duration; in this phase, there is typically peculiar irregular enhancement, which is called a “zebra” because of the movement of the contrast media within the red pulp and the white pulp. For this reason, it is quite difficult to recognize any tissue lesions during this phase [41, 42].

The best time to look for any type of traumatic lesions is during the venous phase, which starts 40–60 s after contrast-media injection. In this phase, there is a homogeneous enhancement of the healthy parenchyma with a long duration (about 5–7 min) [6, 40–43]. After that, the parenchyma loses homogeneity and the search for any lesions becomes more difficult.

As for the liver, typical findings of splenic injuries include subcapsular hematoma, appearing with a lenticular shape along the organ profile, and lacerations, which have

Fig. 3 Liver injury treated with packing. Contrast-enhanced CT. **a** axial plane, **b** coronal reconstruction show the extensive lesion of the hepatic parenchyma, which also affects the organ capsule. **c** CEUS

follow-up 1 day after the packing. **d**, **e** CEUS follow-up 1 month later shows progressive reduction and demarcation of the traumatic lesion, with improvement of the parenchyma structure

different shapes. They can be linear, branched or complex (Figs. 4, 5, 6), until the catastrophic event of a shattered spleen [40]. Lacerations can be associated with the presence of hemoperitoneum if the splenic capsule is interrupted, although hemoperitoneum is most frequent when the hilum region is involved. In this case, we can also find the involvement of the retroperitoneum, because the blood drains along

the splenorenal ligament into the anterior pararenal space surrounding the pancreas [4, 44, 45].

Otherwise, in case of capsular integrity (25% of cases), we can find subcapsular or intraparenchymal hematoma [3, 4, 44, 45].

In our experience, it is also possible to detect an infrequent but potentially lethal vascular lesion such as

Fig. 4 Splenic trauma. **a** Baseline US does not show any alterations in lesions of the splenic parenchyma. **b** CEUS clearly shows a fracture of the lower pole of the spleen

Fig. 5 Splenic trauma. **a** Baseline US shows a structural inhomogeneity of the spleen, with no evidence of traumatic injury. **b** CEUS clearly shows an incomplete tear (I degree) of the lower pole of the spleen

Fig. 6 Splenic trauma. **a** Baseline US shows an extensive structural inhomogeneity of the spleen. No areas of injury are clearly defined. **b** CEUS highlights a large irregular lesion at the middle third of the organ, involving the splenic capsule

pseudoaneurysm, which is depicted as a saccular deformation of the vascular profile where microbubbles are collected.

Catalano et al. [41] described the different appearance of splenic lesions by CEUS, confirming its superiority to baseline ultrasound. The hemoperitoneum was visualized using both techniques. They also reported some findings that were undetectable on baseline ultrasound, such as splenic hypoperfusion in 11% of positive cases on both CEUS and contrast-enhanced CT, contrast medium pooling in 21% of cases on both CEUS and contrast-enhanced CT, and contrast extravasation in 11% of cases on contrast-enhanced CT and 5% on CEUS.

In our experience [13], when performed on 73 children affected by a minor trauma, CEUS demonstrated high diagnostic accuracy, with the ability to highlight the same number of lesions displayed by CT.

Oldenburg et al. [45] reported the case of two children involved in a minor blunt trauma in which traumatic splenic lesions were diagnosed by CEUS and confirmed by CE-CT. The findings were then followed up by CEUS, highlighting its ability to monitor minor lesions without using ionizing radiations.

In our other studies [35], when performed on a population of 256 patients with a history of low-energy blunt abdominal trauma who were not selected by age (7–82 years), CEUS

identified 34/35 splenic injuries with CT as the standard of reference; the missed lesion measured 1 cm.

Valentino et al. [36] identified the rapid decrease of splenic vein contrast agent as a specific disturbance factor in the evaluation of the splenic parenchyma at CEUS. In fact, the spleen acts as an active microbubble filter, resulting in a slight perfusion of splenic vessels. This peculiarity can make the differential diagnosis between venous vessels and lacerations difficult. To avoid this problem, Valentino recommended performing a second bolus of USCA when in doubt.

In our experience, the limitation of CEUS imaging interpretation can be due to incorrect timing of the vascular phase or to the presence of splenic clefts. The differential diagnosis between splenic clefts and lacerations is not always easy; nevertheless, we have to remember that splenic clefts arise from the capsule and have a smooth contour, whereas lacerations have irregular margins, do not always reach the capsule, and are often associated with hematoma or perisplenic fluid [6, 42].

The importance of the immune function of the spleen, especially in the pediatric population, has shifted the trauma management towards a conservative approach, always according to patient's hemodynamics [6, 45, 46].

Velmahos et al. [47] reported their experience in a study including 388 adult patients affected by high-grade splenic

lesions. Among them, 164 patients (42%) were immediately treated with surgery, while the remaining 224 had indications for a NOM. The reported failure rate was 8–38%. Patients with contrast blush, pseudoaneurysm and AAST lesion $\geq$ III were considered at high risk for NOM failure.

The proximal or selective embolization of the spleen [48] can preserve its immune function, and should be performed in case of active arterial bleeding or pseudoaneurysm. The proximal embolization, when vascular lesions are not identifiable, reduces the intrasplenic arterial pressure ($\sim 50\%$), limiting the possibility of splenic infarcts; nevertheless, it is characterized by a theoretical risk of bleeding at a distance because it is not performed on the bleeding site. Selective embolization of the injured vessel (focal bleeding) does not reduce splenic arterial pressure and can produce an infarcted (moderate-extended) area. Angiography should be considered for patients with AAST ≥ 3 degree of injury, the presence of contrast blush, moderate hemoperitoneum or evidence of active bleeding.

Kidneys

The kidneys are the third-most involved organs in blunt abdominal trauma, and parenchymal lesions are usually caused by a direct impact, while decelerative forces can cause vascular and/or urinary tract injuries [3, 4, 49, 50].

Clinical evaluation of renal trauma in pediatric patients is often difficult; the presence of bruises in the left or right upper quadrant or costal rib fractures can help indicate a renal involvement, although the typical and more specific symptom is hematuria. This, however, may also be completely lacking even in the event of major trauma. Gross hematuria is the most valuable sign of renal trauma, found in more than 95% of cases, but is not always related to the severity of the trauma. It is more frequent in penetrating trauma than blunt trauma, and it is rare in trauma due to decelerative forces [3, 49–51].

Technically speaking, both at CEUS and at US, the evaluation of the right kidney is facilitated by the presence of the liver. The evaluation of the left one is often invalidated by the presence of splenic flexure and pulmonary bases. Another limit inherent to US examination is the incomplete assessment of the retroperitoneum [51].

Kidney evaluation by CEUS is a well-tolerated and reproducible technique; it is safe because is not nephrotoxic and can obviate the need for computed tomography or magnetic resonance imaging during the follow-up in selected cases [49–51].

At CEUS exam, the cortex usually enhances very quickly and very intensively, while the pyramids enhance from the periphery to the center in about 30 s. [7, 35]. The optimal timing for kidney assessment is up to 2.5 min. For the evaluation of a single kidney, a single bolus of 2.5 mL is enough;

when the study involves the two kidneys, they have to be explored separately with two different boluses [7].

The most common renal injury is parenchymal contusion, which is an organ bruise characterized by microscopic areas of hemorrhage and surrounding edema. This lesion is often missed at sonography exam. The involved kidney may appear larger than the healthy kidney, and it is possible to see a slightly echoic area. Renal lacerations appear as linear low-attenuation areas in the context of highly echogenic renal parenchyma, limited to the cortex or affecting the collector system. Hematoma may be present as subcapsular or perinephric collection (Fig. 7). Subcapsular hematoma is limited in its extension by the renal capsule, causing a mass effect on the renal profile (Fig. 8). Some studies report that in the presence of a deficit of renal perfusion due to the compressive effect of a large subcapsular hematoma, it is advisable to intervene even in the absence of active bleeding within it [3, 4, 53].

At CEUS, a perirenal collection appears more evident compared to the baseline ultrasound; it is located within the perirenal space, and when large, can dislocate the kidney [54, 55].

In a series of 25 children affected by a renal and ureteral trauma, Siegel et al. [52] demonstrated that the extent of a perirenal or periureteral fluid collection is not related to the severity of the parenchymal lesion. On the other hand, the arrangement of interfascial fluid in the anterior pararenal and along the psoas muscle is related to renal fracture and avulsion pedicle [3].

In the case of traumatic vascular injury, the kidney appears partially or totally hypo-anechoic [3, 55]. As for the other organs, focal contrast material extravasation suggests active hemorrhage [3, 7].

Among CEUS' limitations in kidney evaluation, we have to consider its complete inability to highlight the injuries of the urinary tract as urine leakage or urinoma, because the contrast agent is not excreted by the kidneys [3, 7]. However, owing to the high contrast resolution of CEUS, a traumatic urinary tract involvement can be suspected if one or more deep lesions affecting the collector system are detected. In our experience with a young girl affected by a minor trauma presenting with hematuria, the CEUS finding of a deep renal parenchymal lesion confirmed the clinical suspicion of involvement of the excretory tract, which was then disclosed by CE-CT.

Valentino et al. [37] highlighted the good performance of CEUS in depicting renal trauma; they missed only two minor kidney lacerations, then discovered on CE-CT, without changing the management of the patients. No major lesions were missed on CEUS, unlike in the experience reported by Poletti et al. [56, 57]: in this study, performed on 210 hemodynamically stable adult patients, the authors underlined the diagnostic improvement of CEUS

Fig. 7 Renal trauma. Contrast-enhanced CT on axial plane (**a**) and on coronal reconstruction (**b**) performed at the onset; laceration of the renal parenchyma with a large amount of hemoretroperitoneum. CT also shows the thrombosis of the renal vein. CEUS controls, at 10 days (**c**) and at 20 days (**d**), show the progressive reabsorption of the hematoma, well differentiated from the renal parenchyma, whose vascularization is preserved

Fig. 8 Renal trauma. **a** Baseline US shows a structural inhomogeneity of the anterior kidney profile. A clear lesion of the renal parenchyma or a perirenal hematoma is not clearly detectable. **b** CEUS highlights an extensive perirenal blood collection, quite distinct from the normal renal parenchyma

in visualizing traumatic lesions compared to basic ultrasound, also reporting a fair number of false negatives at CEUS respect to CT, even for significant lesions. It should be considered that this study was performed exclusively on adult patients, and that a child is certainly more suitable for ultrasound evaluation owing to their physical structure.

In our experience with renal trauma [7], CEUS was able to correctly identify 28/28 renal parenchymal lesions, regardless of the presence of perirenal or retroperitoneal

hematoma; CT confirmed all the cases identified as positive at CEUS.

AAST classification divides kidney traumas into five classes of increasing gravity. From a management point of view, the traumatic lesions that usually undergo a NOM treatment are those included into the first three classes (those lesions not affecting the urinary system or the vascular component) [3].

The management of a renal trauma tends to be conservative: renal segmental infarction not involving the collecting systems results in a focal area of renal scarring; the management of renal collecting system injury, if the leak is confined, is non-operative, although sometimes the placement of a stent can be adopted.

Operative treatment is performed in cases of hemodynamically unstable patients, multi-organ injuries, or when a complete destruction of the pyelo-ureteral junction or a lesion of the artery or renal vein with devascularization of the kidney occur [3, 52, 53].

Pancreas

Pancreatic traumatic injuries are relatively uncommon, occurring in 2% of blunt traumas; isolated injuries are rare and most pancreatic lesions are seen in association with other parenchymal lesions, such as the liver, spleen and duodenal vertical portion. The portion most frequently affected by traumatic injuries is the body of the pancreas, due to its close proximity to the spine, making it exposed to compressive traumas.

An example of a typical traumatic mechanism of childhood is the bicycle handlebar trauma, where the body of the pancreas is squashed precisely between the handlebars and the spine [3, 4, 58]. In these cases, according to our experience, the lesion can often be isolated. Injury to the head or tail results from a blow to the flank, often in the course of a polytrauma.

Because of the pancreas' retroperitoneal position, the symptomatology is nonspecific and the diagnosis is often difficult and late. Complications related to pancreatic trauma increase with diagnostic delay. In fact, missed pancreatic lesions lead to complications in 20–30% of cases and mortality in about 20%; mortality is quite high, from 70 to 80%, when there is also involvement of the aorta, upper mesenteric artery or vena cava. Common risk factors for morbidity and mortality are the presence of ductal injury and delayed laparotomy [2, 56–59].

The increase in serum amylases and the presence of a bruise or wound in the epigastric region may make one suspect the presence of a pancreatic lesion.

The accurate assessment of pancreatic injury is critical, and its diagnosis is often performed with CE-CT scan completed by MR cholangiography for the evaluation of the ductal system [58, 59].

In a series of pediatric cases, Korner demonstrated that CEUS had a better chance of highlighting a traumatic injury, because the tissues are thinner than in adults [40]. At CEUS exam, the pancreatic lesion is appreciated as an anechoic area without contrast enhancement in the context of the hyperechoic, strongly contrasted glandular parenchyma (Fig. 9).

Transection results in complete separation of pancreatic fragments, with hypo-anechoic fluid between two segments [4, 60].

Indirect signs of traumatic involvement include focal or diffused glandular swelling, unclear organ profiles, the presence of periglandular collection, and focal or diffuse hyperechogenicity of the parenchyma.

The inherent hyperechogenicity of the healthy parenchyma makes it possible to better visualize the presence of strongly anechoic peripancreatic fluid.

The evaluation of the ductal compromise remains a prerogative of MRI or CT scan; however, the visualization of a very deep parenchymal lesion with peripancreatic fluid collection may suggest a ductal involvement.

In a case report by Valentino et al. [55], the authors outlined their experience with a 5-year-old boy with a pancreatic handlebar trauma. The child had a physical and laboratory examinations that suggested a pancreatic injury, but a negative baseline ultrasound. In this patient, contrast-enhanced CT diagnosed the presence of a grade II pancreatic lesion, and was followed by MRI for ductal assessment. Non-operative management was chosen in response to the results of CT and MRI. In this case, the follow-up was performed by CEUS, highlighting its ability

Fig. 9 Pancreatic trauma. **a** Baseline US shows an incomplete laceration of the pancreatic parenchyma in the isthmus region. **b** CEUS confirms the lesion of the pancreatic isthmus, highlighting a full-thickness fracture and better delineating the relationships with the surrounding vessels, in particular the splenic vein

to perform a complete examination safely, quickly (in 4–6 min) and at patient's bedside.

In our experience with an 8-year-old boy who had sustained a pancreatic handlebar trauma, a basic ultrasound was performed at first, showing an inhomogeneity at the level of the body, which required an integration with CEUS. The latter clearly demonstrated a complete transection of the pancreatic gland at the level of the body, with peripancreatic fluid. The exam was then completed by CE-CT scan, which confirmed CEUS findings. The child underwent a conservative management process; during the follow-up, he developed a mild pancreatitis and the formation of two small pancreatic pseudocysts, at first monitored by CEUS and then by MRI examination to evaluate the evolution of the pancreatic cysts [45, 61, 62].

In this case, the CEUS examination proved to be accurate, with a high sensitivity and specificity in the relief of the lesion comparable to that of the CT, and allowed the clinician to perform an accurate follow-up on the 1st day at the patient's bedside. The possibility of performing the examination in the presence of a relative often reassures the little patient, reducing stress and increasing collaboration.

Lv et al. [63] reported their experience with 22 patients affected by blunt pancreatic trauma and examined by CEUS, comparing CEUS findings with those of contrast-enhanced CT. The results of this study demonstrated the very high diagnostic accuracy of CEUS, which was quite comparable to that of CT scan (about 95.5%), enabling the detection of 21 out of 22 lesions.

The management of a pancreatic duct lesion is controversial both in the adult and in the child. Non-operative management is the treatment of choice in children, to preserve the whole parenchymal function, especially in cases of integrity of the biliary duct [4, 64–66]. Other authors believe that a distal pancreatectomy for transections occurring to the left of the spine (grade III of AAST) is the treatment of choice, because it is definitive with an acceptable morbidity, or requires at least the placement of a stent. Lesions affecting the proximal part of the duct are of greater severity (grade IV), and because of their deep location, surgical treatment is more complex; therefore, they are managed more often by the positioning a stent, avoiding surgery [3, 67].

Wales et al. [64] performed a multi-institutional review comparing operative with non-operative management for grades II and III blunt pancreatic injuries in 167 patients younger than 18 years. Of these, 57 patients underwent distal pancreatectomy, 95 were managed non-operatively, and 15 patients were treated with drainage placement only, and were studied separately. In this study, it was emphasized how patients undergoing resection had a shorter time to goal oral feeds and a lower rate of pseudocyst formation, while in the non-operative group, the healing time was longer and complications were frequent. The authors

concluded that when the main duct is involved, the benefits of performing a surgical resection are greater than those of non-operative management. It is clear that the integrity of the pancreatic duct makes the difference in the management of the patient for whom the precise evaluation of the pancreatic duct is mandatory [64–67].

Conclusions

In a low-energy trauma, basic ultrasound still remains the first-line examination to perform. However, in the recent years, CEUS has been shown to be an effective technique in detecting parenchymal lesions in such a case, especially in the pediatric population.

CEUS allows the clinician to discriminate between those patients who can be discharged in safety from those needing diagnostic monitoring, thus avoiding frequent exposures to ionizing radiation. In this way, inappropriate hospitalizations or re-evaluations are avoided, with a reduction in stress for the little patient and their family members, as well as a reduction in costs.

When a traumatic organ lesion is depicted with CEUS, it is essential to perform a complete evaluation with CE-CT to evaluate those prognostic factors and those lesions that can be not be evaluated by it, such as renal excretory system injuries, intestinal lesions, bleeding, pseudoaneurysms, etc.

In the case of a high-energy trauma, the management is different and depends on the hemodynamic condition. CE-CT still remains the first-choice technique for the assessment of a trauma patient, whether pediatric or adult.

Like us, other authors, such as Valentino or Manetta, have emphasized the usefulness of CEUS in the follow-up of already studied lesions in cases of both high- and low-energy trauma. CEUS can be as accurate as CT in the identification of lesion site, and allows the clinician to follow the repair process through to its complete resolution. One advantage is that during the follow-up phase, the lack of urgency and the knowledge of the lesion site enable the performance of a more detailed baseline examination.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent For this type of study (review article) individual informed consent is not required.

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