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Kosterní traumata v případech týrání dětí

Skeletal trauma in cases of child abuse

Bakalářská práce

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Abstract

Child abuse is a very serious and common problem, which is important to diagnose correctly as any mistakes or wrong conclusions may have devastating consequences for both the child and its family. Particularly in cases of infant abuse or fatal injuries, where it is impossible to rely on interviewing the child, it is critical to be able to correctly interpret sustained injuries. With fractures being the second most commonly inflicted injuries, skeletal survey is an essential part of examination. This work offers a general review of skeletal injuries and their interpretation in relation to diagnosing child abuse.

Key words

child abuse, skeletal evidence, skeletal trauma, fractures, non-accidental injuries

Abstrakt

Týrání dětí je velmi vážným a rozsáhlým problémem, jež je důležité umět správně diagnostikovat, protože jakékoliv chyby či špatné závěry mohou mít katastrofální důsledky jak pro dítě, tak pro jeho rodinu. Zejména v případech týrání kojenců či zranění končících smrtí, kde se není možné spoléhat na zpověď dítěte, je důležité umět správně interpretovat utržená zranění. Jelikož jsou zlomeniny druhým nejčastějším projevem násilí na dětech, důkladná examinace skeletu je neodmyslitelnou součástí procesu diagnózy. Tato práce nabízí obecný přehled kosterních traumat a jejich výklad ve vztahu k diagnóze zneužívání dětí.

Klíčová slova

týrání dětí, kosterní důkazy, kosterní traumata, fraktury, zranění která nejsou důsledkem nehod

Contents

Introduction

Child abuse is a very serious and widespread problem in today's society, touching upon all socioeconomic classes, professions, ethnicities and levels of education and, provided the child survives the abuse, leads to lifelong repercussions such as physical or psychological health problems, often both (Stoltenborgh et al., 2013; Christian, 2015; Viola et al., 2016). Child abuse was first publicly recognised during the second half of the twentieth century, prior to which any mistreatment or inflicted injuries to children were mostly ignored or appraised as common discipline, due to society's view of children as possessions (Ross and Juarez, 2016). Abuse is defined as persistent physical or emotional ill-treatment, which results in potential or actual harm to a child's health, development, or dignity. We recognise four types of child abuse according to this definition: physical violence, sexual abuse, emotional abuse, and neglect (Torriani et al., 2012; Garrocho-Rangel et al., 2015; Viola et al., 2016), out of which neglect is the most prevalent type of maltreatment (Bhatia et al., 2014).

Among the aforementioned forms of child abuse, all of which can cause long-lasting trauma and none of which is to be considered more damaging than the other, physical abuse is the most evident. It occurs within the control of a parent or a person in a position of responsibility, power, or trust, and results in potential or actual bodily harm (Stoltenborgh et al., 2013). In 2013, the World Health Organization (WHO) released a report which stated that almost twenty-three percent of children suffer from physical abuse worldwide (Sethi, 2013).

Physical abuse is often manifested by visibly noticeable marks on the abused child but, even so, a diagnosis of abuse is not easy to make. It is not common practice to assume maltreatment when a child is brought hurt to the hospital and, even if abuse is suspected, it is difficult to diagnose. It takes a medical professional with extensive experience to determine whether a child in their care has been the victim of ill-treatment and nothing is ever certain until further investigation proves maltreatment to be the case. When determining if a child is being abused or not, three main factors come into play: how many injuries are present, their specificity for abuse, and the age of the injuries (Kleinman et al., 1996).

This work focuses on traces of physical abuse detectable on the skeleton through radiology or other imaging techniques, or post mortem by direct inspection of the bones. The reason I chose to further review this specific aspect of child abuse is because skeletal trauma is largely significant in diagnosing physical abuse and is far more complex than assessing visible

abrasions, bruises, and flesh wounds. The majority of evidence found on the skeleton are fractures, which are also the second most common injury caused by physical abuse (Ross et al., 2009). Other signs of physical abuse that can be found on a skeleton are for example surface marks left by weapons or dental injuries.

Any time an injured child appears in a medical facility, an exhaustive examination of traumatic injuries such as fractures is necessary (Ross et al., 2009). Up to twenty percent of inflicted fractures in children younger than three years may be mistaken for accidental at first (Flaherty et al., 2014); however, the majority of childhood fractures that are examined in hospitals are indeed the result of innocent accidents (Kemp et al., 2008) or indirect consequences of negligence (e.g., insufficient supervision or dangerous environment).

In any case, in order to satisfactorily diagnose abuse, it is always necessary to interview the child's parents or guardians and assess its home situation, for neither a single injury nor multiple fractures can be taken as definitively diagnostic of child abuse (Kemp et al., 2008). Any discrepancies in the parents' account of how their child injured themselves and the injury itself are to be treated with suspicion, and a thorough documentation of the injury as well as follow-up examinations are imperative. Any changes in the child's behaviour are also to be noted and carefully assessed (Christian, 2015).

Theoretical Part
1 Statistical documentation of child abuse

As has already been mentioned, child abuse is a severe, pervasive problem worldwide and, ever since it was first acknowledged and described in the middle of the twentieth century, many studies of child abuse have been conducted. According to international surveys, an alarmingly large number of children worldwide suffer from abuse, with twenty-five to fifty percent of children reporting abuse (Ragan, 2011) and over twenty-two percent reporting physical abuse. The most common type of abuse in children is mental abuse, with prevalence between thirty and thirty-six percent, while physical abuse is the second most prevalent with almost twenty-three percent (Stoltenborgh et al., 2013, 2015). The most researched type of abuse, though, is sexual abuse – mostly due to the fact that it often concerns older children and is therefore more easily remembered in adulthood (Creighton, 2004). Sexual abuse prevalence rate is approximately thirteen percent. The prevalence rates of mental and physical neglect are approximately eighteen and sixteen percent, respectively (Stoltenborgh et al., 2015). The exact figures can be found in *Table 1*.

Table 1. Estimated prevalence rates for self-reported abuse (adapted from Stoltenborgh et al., 2015).

Mental abuse	Physical abuse	Mental Neglect	Physical Neglect	Sexual Abuse
36.3 %	22.6 %	18.4 %	16.3 %	12.7 %

International studies indicate that child abuse prevalence rates are strongly influenced by cultural and economic factors. Because of varying views of abuse in different countries, statistics based on community surveys aren't exact - people in some countries may under-rate certain acts of abuse due to culturally more tolerant views of abuse. Economic factors include poverty rates, socioeconomic disadvantage, unemployment rates, and welfare receipt. It has been found that child abuse is more frequent in less-developed countries than in high-income countries, because disadvantaged communities present risk factors such as unemployment, low income, single parenthood, domestic violence, substance abuse, and poor mental and physical health (Viola et al., 2016; Anon). Even military deployment of one of the parents presents higher risk for child abuse (Christian, 2015).

Generally speaking, in terms of geography, Europe and Asia present lower child abuse rates, while in South America, the estimates are the highest in the world (Viola et al., 2016). A

comparison between worldwide and European prevalence rates can be found in *Fig. 1.*, showing that the European numbers are slightly lower than the world average. With the exception of sexual abuse of females, though, these differences do not appear to be overly significant (Sethi, 2013).

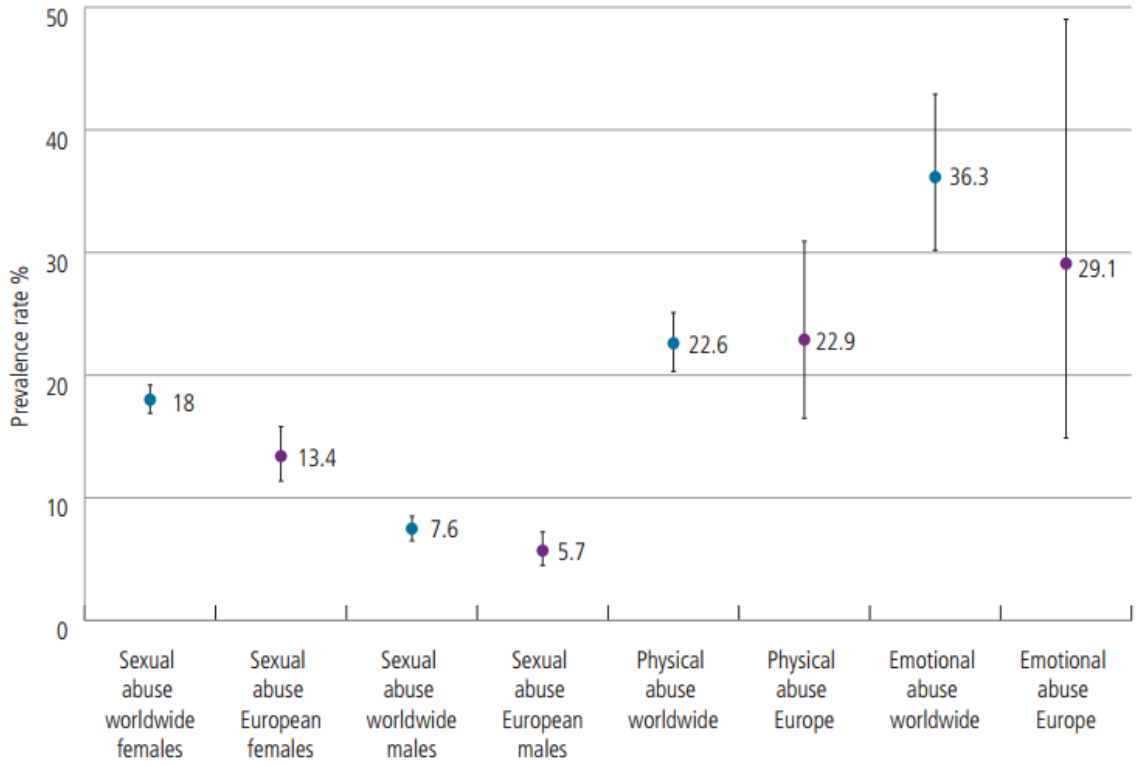

Fig. 1. A comparison between worldwide and European estimates of prevalence rates with 85% confidence intervals from self-report studies for sexual, physical and emotional abuse (Sethi, 2013).

While studies of child abuse in correlation with age and gender often report different conclusions, it is generally believed that such demographic aspects are not of any remarkable influence on abuse prevalence. Moving onto more concrete types of abuse, though, we can find differences. For example, females are at increased risk of sexual abuse compared to males, with prevalence for girls at over thirteen percent and prevalence for boys at almost six percent (Sethi, 2013; Stoltenborgh et al., 2013). On the other hand, males are sometimes considered to be more at risk for physical abuse (Collin-Vézina et al., 2013; Finkelhor et al., 2014). While the risk of serious inflicted injuries or even death is greatest for infants and younger children, with eighty percent of abuse inflicted deaths happening to children under the age of four, surveys show that the general prevalence of abuse increases in older age groups (Barth et al., 2013; Sethi, 2013; Christian, 2015).

According to the Ministry of Labour and Social Affairs, the number of abused children in the Czech Republic in year 2015 was 9,433 children under eighteen years of age, out of which 686 suffered from physical abuse and 745 were sexually abused. With eighty-three percent of sexual abuse cases being girls, they were significantly more frequently abused than boys. All the numbers can be found in *Table 2.*. The most frequent way abuse cases in the Czech Republic are reported is through the health care system or the child's school (MPSV ČR).

Table 2. Numbers of children under 18 suffering abuse in the Czech Republic in year 2015 (adapted from MPSV ČR).

Physical abuse	Mental abuse	Sexual abuse	Neglect
686	1,068	745	6,862

2 Methodology of examination and diagnosing abuse

2.1 Assessment of risk for child abuse

When an injured child is admitted to hospital, there are situations in which abuse should be considered and further skeletal survey is advised. One such situation occurs when the explanation for the injury is insufficient or not given at all. This mainly applies in cases of fractures that require a great amount of force, with explanations along the lines of "she rolled off the couch". Another such situation would be an instance in which a child with numerous injuries is said to be accident-prone or is suspected to have a medical condition, but obtains no new injuries while held in a controlled environment such as a hospital or foster care. The probability of abuse instantly grows because it rules out diagnoses that might cause spontaneous injuries (Kempe et al., 1984).

Further skeletal survey should also be conducted in cases of children younger than three years of age, especially those under twelve months, as accidental fractures within this age group are rare due to their flexible bones, as well as in cases of children with multiple fractures (Belfer et al., 2001). Lastly, other diagnoses which could potentially lead to an excessive number of fractures, such as osteogenesis imperfecta (brittle bone disease) or rickets (metabolic bone disease), should be considered before diagnosing abuse. A misdiagnosed fracture may have disastrous consequences for both the child and the family (Dwek, 2011; Paddock et al., 2017a).

2.2 Imaging techniques and assessment of skeletal injury

The first imaging technique used in suspected child abuse cases is radiography, as fractures are the second most common injuries in physically abused children (Pfeifer et al., 2016). However, fractures of a high specificity for abuse, especially recent ones, may sometimes remain undiscovered upon first examination because radiography is carried out before any changes visibly occur (Flaherty et al., 2014; Paddock et al., 2017b). A follow-up inspection may provide more insight, either uncovering additional injuries or giving us a more precise record of injuries already found (Kleinman et al., 1996). It is therefore advisable to use the best imaging techniques available in order to discover all fractures and interpret them correctly (Drubach et al., 2010).

In addition to radiography, there are other, more precise imaging techniques that can be used to identify abuse-related injuries. The two most commonly used are computed tomography (CT) and magnetic resonance imaging (MRI). CT is used to assess complex fractures of the extremities, rib fractures as well as skull fractures, which would be otherwise difficult or impossible to discern on a less sensitive radiograph (Pfeifer et al., 2016; Paddock et al., 2017a). MRI, which can provide us with additional information about soft tissue injuries, may be helpful in cases of suspected fractures that do not show on radiographs, e.g., occult hip fractures (Pejic et al., 2017).

However, no matter how well documented, no injury by itself is absolutely diagnostic of abuse, though some are more significant than others - for example, rib fractures are extremely significant indicators of abuse, especially in young children, and are considered almost diagnostic (Hobbs, 1989; Carty, 1993) as they very seldom occur accidentally. There are also injuries, which are more significant in certain ages than others. For example, femoral fractures in children under one year are more often than not due to abuse since there aren't many ways children that young can cause themselves such injuries (Paddock et al., 2017b). Once they start running, it is more feasible for children to fracture their femurs, and the significance of these fractures decreases.

Skeletal survey itself naturally has its limitations when it comes to determining and documenting child abuse; therefore, it plays only a partial role (Belfer et al., 2001; Ross et al., 2009). As has already been mentioned, thorough investigation of the reported circumstances of the injury, unbiased witness reports, as well as further inquiries into the child's family

situation are necessary. It is advisable to obtain an uninterrupted recount of the circumstances surrounding the injury from the child's caregivers because, though perpetrators of child abuse scarcely ever admit to their actions, they may implicate themselves due to inconsistencies in their stories (Christian, 2015).

3 Fractures

3.1 Fracture dating

A bone fracture is a medical condition where the bone is broken, its tissue discontinued, as a result of stress inflicted upon the bone, be it through impact, pulling, or grabbing (Ubelaker and Montaperto, 2011). Due to the heterogeneity of bone tissue, every bone responds to the same kind of stress differently, e.g., long bones are dissimilar to flat ones; the bones of an older child are unlike those of a toddler.

Consequently, depending on the bone and the type of stress inflicted, each fracture is different. From a single line fracture to multiple complicated bone fractures, each takes a different amount of time to finish the mending process. Normally, the more complicated and serious the fracture, the longer it takes for it to heal, especially if the bone is displaced or a re-fracture hinders the process. The speed with which a fracture heals is also directly dependent on the age of the injured child, though no evidence has been published to support this widely accepted claim (Hobbs, 1989; Paddock et al., 2017a). Generally, infants and toddlers heal more quickly than older children or teenagers.

Due to the fact that acute bone fractures in children are difficult to detect on a radiograph, it is important to take note of indirect indicators of injury such as periosteal reaction or callus formation in order to successfully determine fracture age (Pickett, 2015). However, some fractures heal without periosteal reaction and are therefore hard to detect even during the healing window (Carty, 1993).

Fracture dating is a difficult and often subjective procedure, even for experienced professionals, but a general set of rules and a broad time frame do exist (Paddock et al., 2017a). All fractures heal in stages (Hobbs, 1989) with the first visible changes occurring approximately ten days after the bone is fractured. The approximate healing process is described in *Table 3.*, which shows a general time frame for fracture healing. At first, a periosteal reaction becomes apparent as the bone thickens in the area of the injury due to

subperiosteal bleeding; then over the course of the next week, the fracture loses its definition and a soft callus forms. Around the one month mark, the fracture develops into a hard callus, and then in the following months the fracture finishes healing and remodelling.

Table 3. Dating of fractures in children (adapted from Carty, 1993).

Approximate time frame	**Stages of healing process**
10-14 days	periosteal new bone formation
14-21 days	loss of fracture line definition, soft callus
21-42 days	hard callus
3 months up to 1 or 2 years	remodelling

The healing of diaphyseal and rib arc fractures follows a similar set of rules. Periosteal new bone formation appears after ten to fourteen days, though there have been cases in which periosteal reaction appeared as early as four days. At the eight-week mark, hard callus appears and, for the next three or more months, the bone undergoes the process of remodelling (Paddock et al., 2017a).

Different rules to those summarised above apply to isolated metaphyseal fractures, because they often heal without periosteal reaction, instead slowly fusing onto bone. These injuries heal completely within four to six weeks, meaning that, by the four-week point at which they are normally identified, they are often almost fully healed. Neither vertebral nor skull fractures can be reliably dated (Paddock et al., 2017a).

Fracture dating in infants follows a different time frame, which has been derived from studies of infant clavicular fractures secondary to delivery. It has been ascertained that subperiosteal new bone formation develops between seven to ten days after the injury, its character evolving with fracture age, as single-layered periosteal new bone is more often to be seen in younger fractures, and more solid and multi-layered new bone formation is present in older injuries. Callus forms between ten to fifteen days, hardening and decreasing with fracture age (Walters et al., 2014).

The more recent the fracture is, the more precisely it can be dated (Pickett, 2015; Paddock et al., 2017a). When multiple fractures are present, it is often possible to determine whether they occurred at approximately the same time or whether they are of different ages (Offiah et al., 2009). This precision is also important to distinguish between fractures caused by a difficult

delivery or a caesarean section (e.g., metaphyseal or clavicular fractures) and those resulting from abuse (Walters et al., 2014).

The time gap between a primary injury and a re-fracture at the same place can also be determined. If the second injury happens after the original fracture has already healed, it is defined by a discernible fracture line leading through an already-developed callus (Hobbs, 1989). However, if the re-fracture transpires during the healing process, it leads to asymmetrical bleeding and obvious signs of repair (Carty, 1993).

3.2 Multiple fractures

Multiple fractures in a young child are significantly indicative of abuse, unless an appropriate history of accidental trauma, such as motor vehicle accident, is provided. The prevalence of multiple fractures in abused children under one year of age is between seventy and eighty-three percent (Leaman et al., 2016). The significance of a single fracture therefore rapidly rises once it is accompanied by another fracture (Carty, 1993). As evidenced by practice, experts even often believe that multiple fractures are virtually diagnostic of abuse, though it is necessary to exclude bone diseases such as osteogenesis imperfecta or rickets (Cannell and Holick, 2016).

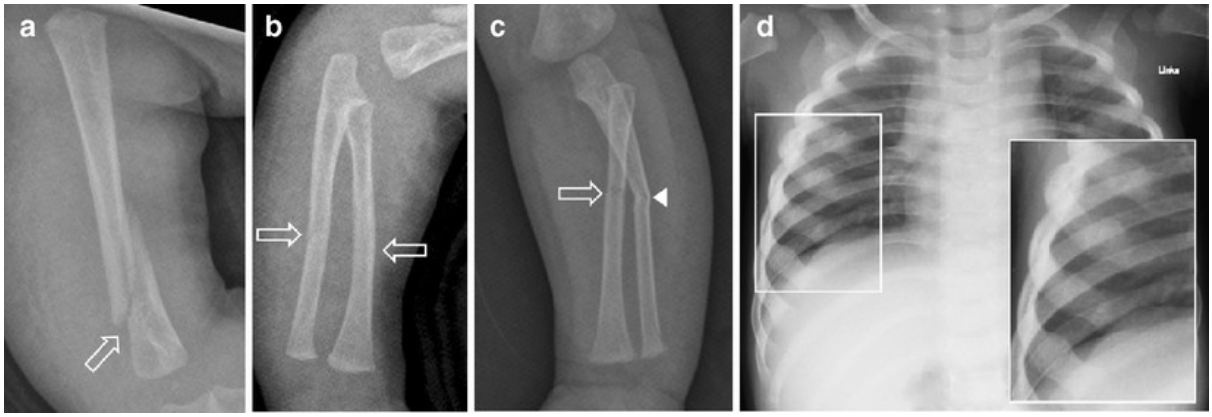

Fig. 2. A seven-month-old abused girl with multiple fractures of different ages. ***a*** *Oblique diaphyseal fracture of the right humerus.* ***b*** *Transverse fractures of the right radius and ulna.* ***c*** *Transverse fracture of the left radius (arrow) and a buckle fracture of the left ulna (arrowhead).* ***d*** *Multiple healing anterior rib fractures (Offiah et al., 2009).*

Especially suggestive are multiple fractures in different stages of healing, which point towards repeated instances of trauma during a certain time span and are highly indicative of abuse (Hobbs, 1989; Carty, 1993), since they cannot be explained by one traumatic event or

an accident (Leaman et al., 2016). For example, an eight-month-old infant brought to the hospital for being fussy with no obvious cause or explanation was suspected to have been abused once an oblique mid-shaft fracture of the left femur, a buckle fracture of the proximal left femur, and a healing buckle fracture of the proximal right tibia were discovered (Thomas et al., 1991). These multiple injuries of different ages, for which the parent couldn't provide any reason, were strongly indicative of mistreatment.

4 Periosteal new bone formation

4.1 Characteristics

The formation of new periosteal bone often accompanies injury or irritation that causes bleeding under the periosteum, which is the outer layer of a bone (Bisseret et al., 2015). It usually takes ten days to two weeks for the periosteal reaction to become visible as the periosteum rises from the shaft, and its severity depends on the extent of subperiosteal bleeding (Hobbs, 1989; Carty, 1993). However, not all fractures cause this reaction.

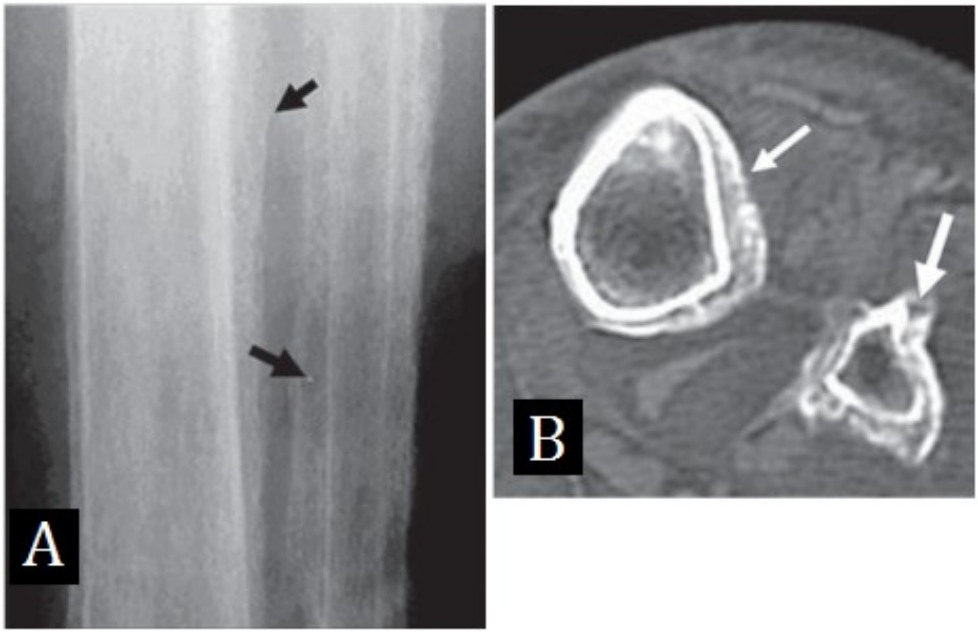

Fig. 3. Solid periosteal reaction. A: Conventional radiography shows periosteal reaction in the tibia and fibula (black arrows). B: Axial computed tomography shows the circumferential involvement of the periosteal reaction (white arrows) (adapted from Nogueira-Barbosa et al., 2010).

Periosteal reaction manifests itself as a thickening of the outer layer of the bone or a squaring off of the edges of a disrupted metaphysis. It may also expand from the fracture along the

bone shaft, even covering the whole bone. This, together with cracks along the newly formed periosteal bone, generally signifies repeated trauma (Carty, 1993). However, in infants under the age of five months, a smooth and often bilateral subperiosteal new bone formation is normal. It is most often found along the humerus, femur, and tibia, doesn't extend beyond the diaphysis of the bone, and is related to the fast growth of infants (Dwek, 2011). On the other hand, an abuse-inflicted injury often extends to the metaphysis (Hobbs, 1989).

Periosteal reaction is often much more easily identifiable than some other fractures because, while young bones are largely made of radiologically imperceptible cartilage, periosteal reaction shows very prominently in the growing bones of children. This is because periosteal reaction is less adherent and far more active than in adult bones. It is therefore visible even through less sensitive imaging techniques (Kempe et al., 1984; Hobbs, 1989; Bisseret et al., 2015).

Periosteal new bone formation in children may have different causes, a traumatic bone injury being second in prevalence to a normal physiologic reaction from growth. Its significance must be therefore determined by further assessment (Bisseret et al., 2015). The traumatic causes include: direct trauma to a child's developing bones, resulting in a fracture; grabbing or pulling of the arms and legs; using limbs as handles for rattling the child; and shaking the child by its torso, with its limbs swinging about uncontrollably (Hobbs, 1989; Carty, 1993).

5 Shaken Baby Syndrome

5.1 Characteristics

Shaken baby syndrome (SBS) is a specific form of child physical abuse, which can occur either as an isolated incident or as an accompaniment to other forms of abuse or neglect. SBS is described as injuries inflicted by violent shaking of an infant by the extremities or torso, which causes excessive acceleration and deceleration of the head (Lancon et al., 1998; Mian et al., 2015). The most common age in which SBS is diagnosed is between 10-16 weeks (Squier, 2011).

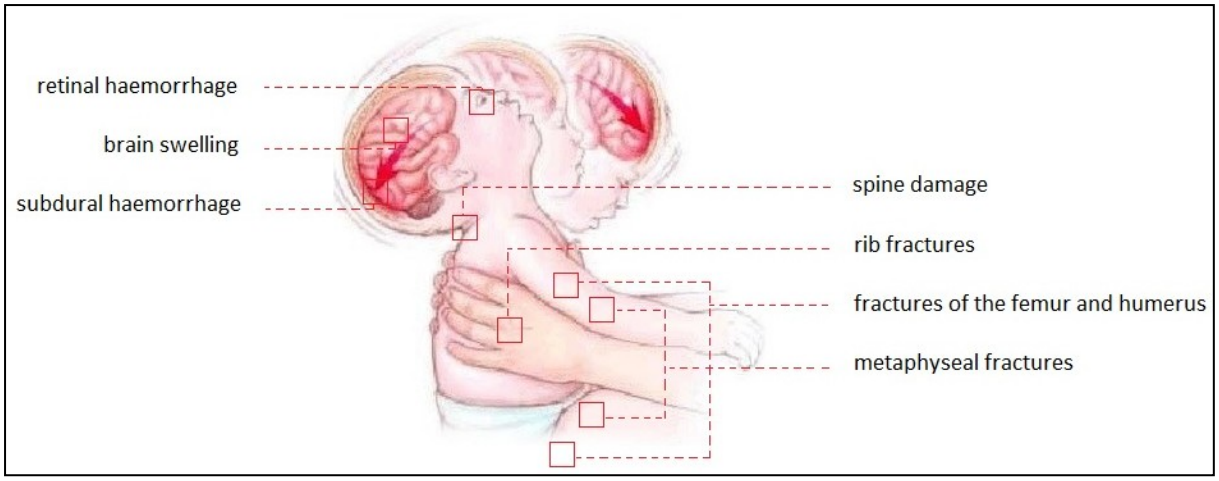

Fig. 4.Common injuries in cases of Shaken Baby Syndrome (adapted from Dake, 2014).

Typical SBS injuries include traumatic brain injury, the child's brain impacting against the skull as a result of their body being shaken, with the head swinging back and forth. Due to the relative weakness of neck muscles in comparison to the weight of the head, infants are particularly at risk for serious brain and spinal injuries (Pfeifer et al., 2016). The three most important injuries to be found in cases of SBS, which are called 'the triad' are subdural haemorrhage, brain swelling and retinal haemorrhage. Subdural haemorrhage is bleeding into the subdural space, which is forcibly created during an impact as the cells of the dural border layer split open. Retinal haemorrhage appears in fifty up to a hundred percent of SBS cases and is the result of alterations in intracranial, intrathoracic and intra-abdominal pressure. Brain swelling is the most important factor in determining morbidity and mortality in cases of head trauma as it may obstruct arterial blood flow (Duhaime et al., 1998; Matschke et al., 2009; Squier, 2011).

Fractures typical for SBS are rib fractures, caused by thoracic compression; fractures of the femur or humerus, in accordance with how the child was held; and metaphyseal fractures as a result of flailing arms (Lancon et al., 1998; Mian et al., 2015).

5.2 Epiphyseal and metaphyseal fractures

Epiphyseal and metaphyseal fractures are often present in child abuse cases and therefore should be taken seriously. They are sometimes considered to be almost diagnostic of abuse - especially in infancy - as an extreme amount of force must be applied to the child's extremities and rarely ever occur during what could be considered normal handling of the child, with the recognised exception of a difficult delivery. They occur at the ends of the long

bones, usually very close to the growth plate and appear either as incomplete fractures or bone fragments detached from the metaphysis (Dwek, 2011; Paddock et al., 2017b).

Unlike accidental fractures that usually happen at the junction of the diaphysis and metaphysis, abuse-inflicted injuries of the metaphyseal bone occur in the most immature part of the bone - closest to the growth plate. The detachment of an ossified bone chip, a ring, or even a whole plate from the metaphysis is called avulsion, and it may show as a bucket-handle or a corner fracture on a radiograph. Bucket-handle and corner fractures are essentially one and the same, only viewed from a different angle (Dwek, 2011).

Epiphyseal fractures occur through physis and are often accompanied by displacement of the epiphysis. They are normally extremely difficult to visualise on a radiograph, as epiphysis is rarely ossified in younger children, and are often misinterpreted. The use of more sensitive imaging techniques is advisable (Dwek, 2011).

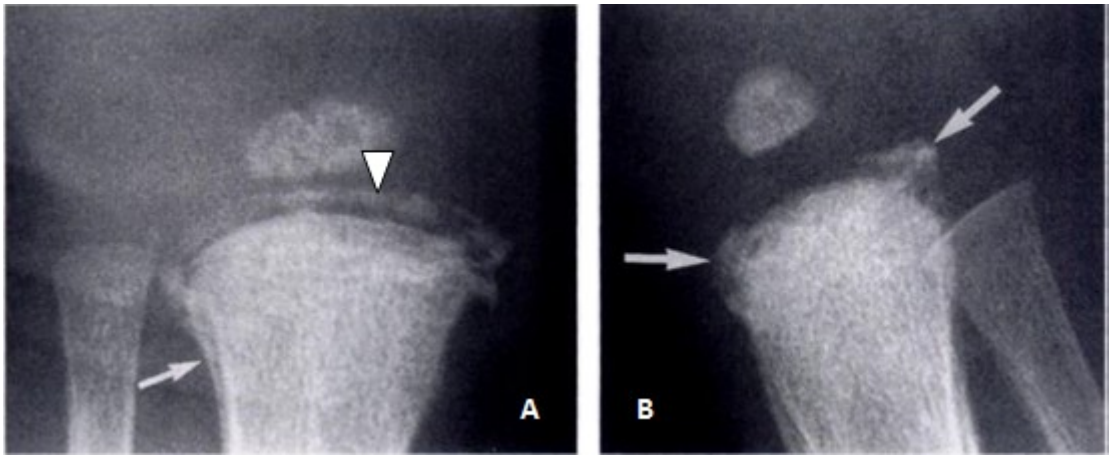

*Fig. 5. A three-week-old female with **A** a bucket handle fracture of the tibia (arrowhead) and subperiosteal new bone formation (arrow) and **B** corner fractures of the tibia (arrows) (adapted from Kleinman et al., 1996).*

Metaphyseal and epiphyseal fractures are often caused by acceleration and deceleration as a child is shaken by its body, arms, or legs. Since these fractures are commonly found without any association to head or intracranial injuries, however, SBS cannot be the sole cause of metaphyseal and epiphyseal fractures - twisting, gripping, or pulling forces applied to the child's limbs are also a frequent cause (Hobbs, 1989; Lancon et al., 1998; Paddock et al., 2017a). Shaking usually causes symmetrical fractures as the child is often grabbed by both sides of its torso or both upper or lower limbs, resulting in bilateral injuries. Singular

fractures, in contrast, are more likely to happen due to a direct trauma to the limb (Carty, 1993). Metaphyseal and epiphyseal fractures - be it singular or symmetrical - are most commonly found in the child's: distal femur; proximal and distal tibia; and proximal humerus (Paddock et al., 2017b).

5.3 Rib fractures

Rib fractures are the most common abuse-related injuries in infants and are usually very dangerous, as lower rib fractures in particular are frequently associated with major intra-abdominal trauma (Ross et al., 2009; Paddock et al., 2017a). The prevalence of rib fractures in abused children is between 8.7 and 14 % (Barber and Kleinman, 2014).

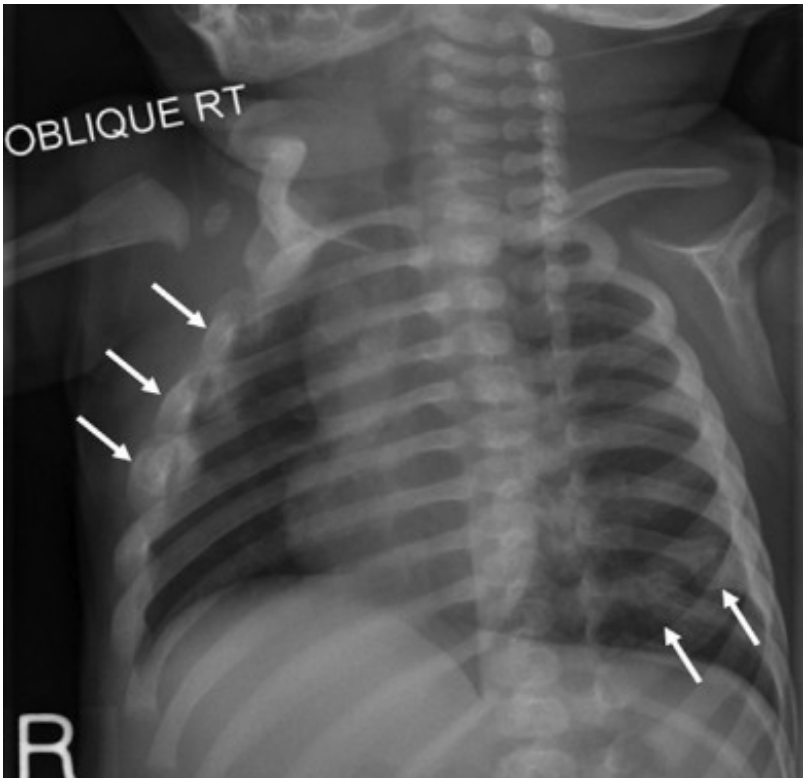

Fig. 6. Right oblique radiograph showing healing fractures of the posterior arcs of the left 8th and 9th ribs and anterior arcs of the right 2nd to 4th ribs (adapted from Paddock et al., 2017a).

Multiple lateral rib fractures may be explained by non-abusive trauma such as a traffic accident (Dwek, 2011), while inflicted rib fractures often appear bilaterally due to the circumstances under which they are usually inflicted (Hobbs, 1989). They are often compression injuries, but may also result from a direct blunt force trauma to the chest, which

is a frequent cause of anterior rib arc fractures. Posterior rib fractures, on the other hand, are often associated with difficult deliveries (Paddock et al., 2017a). Careful fracture dating is essential in excluding injuries secondary to birth trauma.

While rib fractures are generally ascribed to SBS in infants, in older children, the cause can be anything from kicking, stomping, or punching - or a combination thereof - to impact with a hard object (Hobbs, 1989). It is important to keep in mind that, due to the greater plasticity of young children's ribcages, the bones have a tendency to deform before they break; therefore, the force inflicted has to be extreme in order to cause a fracture. Rib fractures are rarely seen even in cases of major chest trauma like serious motor vehicle accidents (Worlock et al., 1986; Offiah et al., 2009; Paddock et al., 2017a). For example, cardiopulmonary resuscitation of children normally cannot cause rib fractures as it does not require strong enough force. Consequently, it is not a valid explanation for rib fractures (Hobbs, 1989).

It is difficult to see the fracture line of a recent rib injury on a radiograph; therefore, it is prudent to repeat the examination in cases of suspected rib fractures after ten to fourteen days, by which point a callus will have formed and the injury will be more noticeable (Hobbs, 1989; Carty, 1993). The use of more sensitive imaging techniques such as CT or MRI is also advisable.

6 Skull injuries

6.1 Characteristics

Skull fractures appear in various forms - from a singular un-branched line, which is the most common in both accidental and inflicted injuries, to complex injuries. Induced skull fractures are typically multiple and usually cross a suture line, but only with the proffered history can the cause be reliably ascertained, as no fracture pattern is indicative of physical abuse. Factors important to assess the true cause of the injury are the height, angle, and object from which the child has supposedly fallen, e.g., falls from less than one metre are not likely to cause a fracture (Barber and Kleinman, 2014; Paddock et al., 2017a). Other types of skull fractures include depressed fracture of the bone, an indentation caused by blunt force trauma, which is often fatal because of the force necessary to cause such an injury; and expanding fracture, i.e., a growing separation of bone in the fracture line. Generally, the width of an expanding fracture is greater in inflicted than in accidental injuries (Hobbs, 1984; Lancon et al., 1998).

The most frequently fractured bone in a child's skull, either inflicted or accidentally damaged, is the parietal bone, followed by the much less commonly injured occipital bone. Skull fractures are often associated with abusive head trauma in infants and are usually found in children who possess other injuries such as metaphyseal, rib, spinal, and scapular fractures (Barber and Kleinman, 2014; Barber et al., 2015).

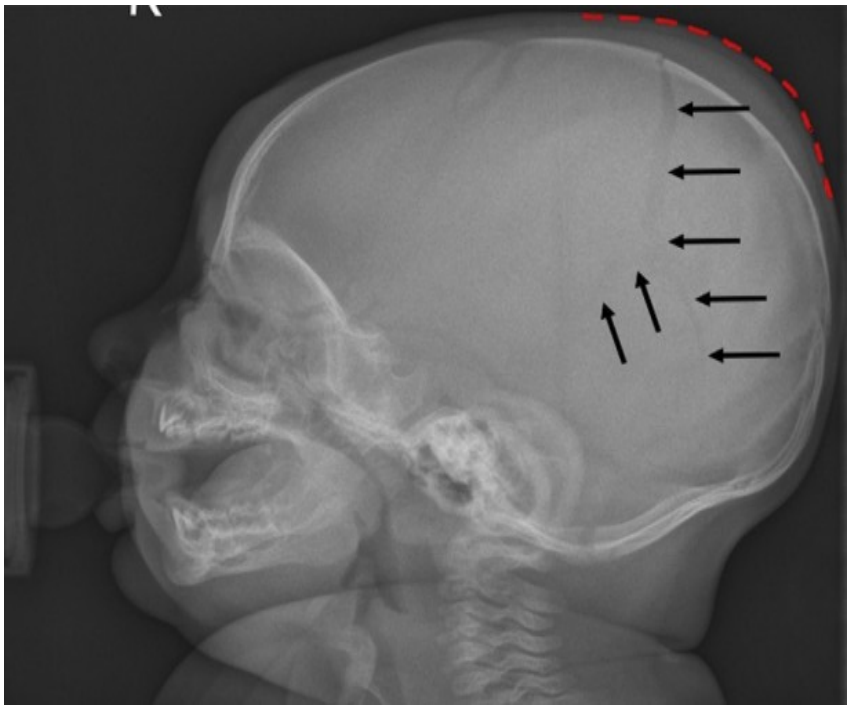

Fig. 7. Skull radiograph of an 11-week old male infant showing swelling of the scalp (dashed red line) and a wide, branching parietal bone fracture (black arrows) (adapted from Paddock et al., 2017a).

6.2 Causes

A great deal of force is needed to fracture an immature skull, since it is very pliable and usually deforms before it breaks. Consequently, skull fractures are often accompanied by various degrees of brain injury from the significant trauma. In abused children younger than two years old, head injury is actually the most frequent cause of death (Keenan et al., 2003; Ross et al., 2009). The most common cause of skull fractures is an impaction force from the child falling and hitting its head on something hard or a hard object hitting the child’s head. Rarely does a skull fracture happen as a result of someone stamping on the head (Paddock et al., 2017a).

Accidental falls and impacts almost never generate enough force to fracture a child's skull. One possible accidental cause is a motor vehicle accident, where a child is run over, which has been found to have similar consequences to battering. Another possibility, which it is necessary to exclude when diagnosing abuse in infants, is an injury secondary to delivery - from which both linear and depressed skull fractures have been reported (Hobbs, 1984; Paddock et al., 2017a).

7 Uncommon fractures

Other injuries signifying child abuse include uncommon fractures such as scapular fracture, fracture of the sternum, clavicle, spine, or pelvis. Uncommon injuries are usually highly indicative of abuse, since they are otherwise very rare - their prevalence has been estimated to be between 2.4 and 5.5 % (Barber et al., 2015).

7.1 Scapular fractures

Scapular fractures are very significant in determining abuse (Barber et al., 2015), because they generally do not occur unless significant force has been applied (Paddock et al., 2017b). They are often found in infants who suffer from other typical inflicted fractures; therefore, they seem to be the result of indirect forces (Barber and Kleinman, 2014). Scapular fractures are also known to be related to cranial trauma resulting from high-impact forces (Steyn et al., 2014).

Fig. 8. CT of a 6-week old girl showing a healing right scapular fracture (arrow) (Sanchez et al., 2015).

7.2 Clavicular fractures

Clavicular fractures, while not very frequent, are of a lower significance when determining child abuse. They most often occur in children and individuals younger than twenty-five years. Generally, a fracture of the distal or proximal clavicle is more abuse-specific than a mid-shaft fracture, which is the most common one. Clavicle fracture healing is often accompanied by a significant callus formation (Pecci and Kreher, 2008; Barber et al., 2015).

The most common cause of clavicular fracture is an impact from falling on the shoulder, with the arm by the side - most frequent in contact sports (Pecci and Kreher, 2008). In cases of fractured clavicles in infants, it is critical to date the injuries as, during delivery, the clavicle is often broken. The incidence of such injury ranges from 0.2 to 4.4 %, and the fracture most commonly happens at mid-shaft (Ross and Juarez, 2016; Paddock et al., 2017a).

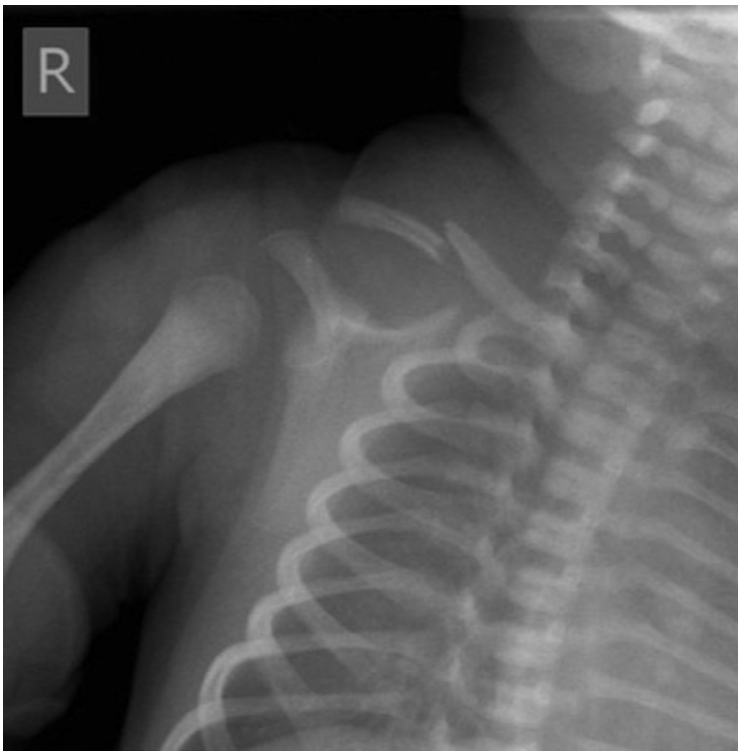

Fig. 9. Radiograph showing displaced fracture of the right mid-shaft clavicle of an 8-day-old infant. Fracture is consistent with fracture secondary to delivery (adapted from Paddock et al., 2017a).

7.3 Spinal injuries

Inflicted spine fractures are often compression or impaction injuries, for example when a child is forcibly thumped down on its bottom or legs on a hard surface. This may result in the

fracture of a vertebral body (Carty, 1993; Barber et al., 2015). Isolated vertebral fractures are not very common but may sometimes be the only manifestation of physical abuse in young children; therefore, spine radiographs are advisable when child abuse is suspected, particularly in children younger than two years old (Henry et al., 2016; Paddock et al., 2017a). A significant correlation of spinal injury with intracranial trauma has been noted, the occurrence sometimes described as being as high as seventy-one percent (Barber and Kleinman, 2014).

Fig. 10. Lateral spine radiograph of a 21-month-old female showing a subtle depression of the superior endplate of thoracic vertebrae T5 (arrow) in keeping with fracture, and also possibly of T4 and T6 (numbered) (adapted from Paddock et al., 2017a).

7.4 Pelvic fractures

Pelvic fractures in young children are very rare and are often associated with other injuries. The prevalence of pelvic fractures in children younger than ten years has been approximated to between 0.1 and 0.4 %, which is extremely rare. The most common site of pelvic fracture is the ischio/pubic ramus (Bixby et al., 2014; Paddock et al., 2017b).

The immature pelvis is very flexible and able to absorb great impact before fracturing. Pelvic fractures therefore almost always result from a major trauma such as a pedestrian being hit by a motor vehicle, which is the cause in between thirty-nine and seventy-eight percent of cases (DeFrancesco and Sankar, 2017). In older children, inflicted fractures of the pelvis are associated with high-force blunt trauma or physical restraint having been applied to the area during a sexual assault (Bixby et al., 2014; Paddock et al., 2017b). The majority of these children are girls (Offiah et al., 2009).

8 Fractures in the shafts of long bones (diaphyseal)

Diaphyseal fractures have low specificity for child abuse, because they are generally very common in both accidental and inflicted injuries (Dwek, 2011). Inflicted diaphyseal fractures are caused either by indirect trauma, such as swinging a child by its arms or bending its limbs, or by direct trauma, such as a blow to the extremities or a fall on an extended limb (Hobbs, 1989; Paddock et al., 2017b). Fracturing a diaphysis of an immature bone requires a great deal of force; therefore, children who are not yet walking or have just started to do so, are rarely the victims of such force accidentally - femoral fractures in particular are significantly associated with child abuse in pre-ambulant children (Lancon et al., 1998; Paddock et al., 2017b).

According to studies, twenty percent of femoral fractures in children between one and two years old are inflicted. The diaphyseal fracture of the femur is the most common femoral fracture in both abused and non-abused children and can be caused by the child tripping while running (Thomas et al., 1991; Kemp et al., 2008). Diaphyseal fractures of the humerus, spiral/oblique fractures in particular, in children younger than fifteen months with a suspicious history are also highly suggestive of abuse (Paddock et al., 2017b).

Causes of diaphyseal fractures are various. The spiral/oblique fractures result from a twisting force, while transverse fractures are caused either by direct blows and levering forces or by the child falling on an outstretched extremity. Both spiral/oblique and transverse fractures occur in abused children with equal frequency (Dwek, 2011; Paddock et al., 2017a).

Inflicted diaphyseal fractures are often associated with buckling. A buckle fracture is a compression injury, which causes the bone to bend (or buckle, henceforth the name) towards

the fractured side. It is most likely to occur at the diaphyseal-metaphyseal junction when a child is forcibly brought down on its outstretched leg on a hard surface (Carty, 1993; Lancon et al., 1998).

Fig. 11. Acute spiral fracture of the right femur in an 9-month-old infant (Paddock et al., 2017b).

9 Oral injuries

Because a child's head, face, and oral cavity are exposed and easily accessible, oral injuries are very common in abused children, with over fifty percent of abused children suffering such injuries. The most visible and frequent injuries to the oral cavity are tooth fractures, which are found in thirty-two percent of cases, while fractures of the mandible or maxilla occur in eleven percent of abused children. Despite the significant prevalence of oral injuries in abused children, only one percent of suspected abuse cases are reported by dentists (Costacurta et al., 2015; Garrocho-Rangel et al., 2015).

Dental injuries include fractured, displaced, or avulsed teeth, which may result from hard objects being forced into the child's mouth. Examples of such objects include silverware,

household utensils, or a bottle pushed into the child's mouth during feeding (Kellogg, 2005; Costacurta et al., 2015).

Another sign of dental trauma is discoloration. Discoloration of the teeth may stem from various causes, the most cited one being pulpal necrosis, partial or total death of dental pulp due to long-term interruption of the blood supply as a result of physical trauma (Kellogg, 2005; Costacurta et al., 2015). Another type of discoloration is so-called 'pink change', which is noticeable post-mortem and is the result of haemorrhage in the pulp chambers during asphyxia. Pink change, however, is not a reliable indicator of the cause of death (Lewis and Rutty, 2003; Cunha, 2009).

Mandibular fractures are the most common facial fractures in children, be they accidental or abuse-inflicted. Mandibular and maxillary fractures most often occur in the condyles, mandibular ascending ramus, and mandibular symphysis, with possible displacement of bone fragments. Physical trauma may also result in imperfect positioning of the teeth when the child's jaws are closed, so-called dental malocclusions (Zimmermann et al., 2005; Costacurta et al., 2015).

Conclusion

The purpose of this review is to show the importance of skeletal review in cases of suspected physical child abuse and summarise which skeletal injuries are significant in its diagnosis. It is clear that abuse determination is a very complex process which includes more than just the expertise of a paediatrician or a radiologist, requiring the cooperation of a psychologist or a social worker as well. Investigation based solely on skeletal review is therefore inconclusive most of the time.

Skeletal review can still provide us with very important evidence, though, as some fractures are evidently more significant than others when it comes to inflicted injuries. Their significance depends on their prevalence in abused children as well as their prevalence in children that weren't abused. While certain fractures may often be found in cases of inflicted injury, their high occurrence in accidental injuries as well makes their significance unremarkable. The most important fractures are therefore those that are significantly more frequent in abuse cases than in accidents. Generally, uncommon fractures are also usually of

a high importance for determining abuse, but due to their rare occurrence, there are not many studies describing their characteristics specific to abuse.

Furthermore, fracture interpretation is greatly dependent on a child's age and its resulting weight and mobility, as some injuries are almost impossible to obtain accidentally for small children that have yet to learn walking or running. The speeds and forces required to inflict some of the more serious injuries are often out of the realm of possibility for these children.

Fracture dating is also a very complex discipline, since it strongly depends on both the type of the fractured bone and the age of the patient. It is not always consistently described in literature - some articles being more specific than others.

Numerous correlations have also been found between specific bone fractures and other soft tissue or organ injuries like severe head trauma. This seems to be an area that might be of particular interest when establishing the cause of death for a person, whose body has deteriorated and soft tissue is no longer available. The field of injury interpretation is still in its infancy and is being applied in new ways. In the future, I personally would like to pursue the significance and interpretation of skeletal traumas and other injuries in murder cases.

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