Mariell Sletten
Lisa Yoosuphap Aarnes

Magnetic resonance imaging sequences' ability to identify and characterize abusive head trauma in pediatric patients: a literature review

RAT2900

Bachelor's thesis in Radiography
Supervisor: Albertina Rusandu
May 2024

Bachelor's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Circulation and Medical Imaging

NTNU
Norwegian University of
Science and Technology

Mariell Sletten
Lisa Yoosuphap Aarnes

Magnetic resonance imaging sequences' ability to identify and characterize abusive head trauma in pediatric patients: a literature review

RAT2900

Bachelor's thesis in Radiography
Supervisor: Albertina Rusandu
May 2024

Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Circulation and Medical Imaging

NTNU
Norwegian University of
Science and Technology

Table of contents

Abstract

Objective: Abusive head trauma is one of the most common forms of child abuse on a worldwide basis, and a condition that can cause severe neurological damage. This literature review aims to investigate which MRI sequences are most beneficial when identifying and characterizing abusive head trauma in pediatric patients.

Method: The current study conducted a literature search using the database PubMed to find relevant articles.

Results: In total, nine studies were included. The main findings in this literature review show that the sequences susceptibility weighted, diffusion weighted, and gradient echo are exceedingly effective when identifying multiple lesions resulting from abusive head trauma.

Conclusion: Several MRI sequences are valuable to use when identifying abusive head trauma. Nevertheless, further research will be necessary for more valid evidence. Although research expansion is required in this field, there are reasons to assume that magnetic resonance will be a huge part of diagnosing abusive head trauma in pediatric patients in the future.

Keywords: Abusive head trauma, magnetic resonance, sequences, shaken baby syndrome

Sammendrag

Formål: Voldelig hodetraume er et av de mest vanlige formene for barnemishandling på verdensbasis, og er en omfattende tilstand som kan føre til alvorlige nevrologiske skader. Denne litteraturstudien har som mål å undersøke hvilke MR-sekvenser som er mest gunstig å bruke ved identifisering og karakterisering av voldelig hodetraume hos pediatriske pasienter.

Metode: Litteratursøk ble gjort i databasen PubMed for å finne relevante artikler for denne litteraturstudien.

Resultat: Totalt ni studier ble inkludert. Hovedfunnene i litteraturstudien viser at sekvensene susceptibilitets-vektet, diffusjons-vektet og gradient ekko er svært effektive i å identifisere flere lesjoner som oppstår ved voldelig hodetraume.

Konklusjon: Det kan konkluderes med at flere MR-sekvenser er verdifulle å bruke ved identifisering av voldelig hodetraume. Likevel vil det være nødvendig med mer forskning i fremtiden for mer valid evidens. Til tross for at det trengs mer forskning på feltet, er det grunn til å anta at magnetisk resonans vil være en stor del av diagnostisering av voldelig hodetraume hos pediatriske pasienter i fremtiden.

Nøkkelord: Voldelig hodetraume, magnetisk resonans, sekvenser, shaken baby syndrom

1. Introduction

Child abuse is a worldwide concern. According to the World Health Organization, child maltreatment is defined as the abuse and neglect of a child younger than 18 years. This includes “[...] all types of physical and/or emotional ill-treatment, sexual abuse, neglect, negligence and commercial or other exploitation, which results in actual or potential harm to the child’s health, survival, development or dignity [...]” (World Health Organization, 2022). The main types of abuse are physical abuse, emotional abuse, neglect and sexual abuse. Physical abuse includes shaking, beating, biting and burning, and the most common finding associated with physical abuse are rib fractures. Emotional abuse, also known as psychological abuse, includes humiliation, verbal abuse, or acts that can scare the child so bad that it can have a negative impact on the child’s psyche in the future. Abuse in the form of neglect includes insufficient care of the child such as healthcare, supervision, education and basic needs such as food and clothing. Lastly, sexual abuse includes exposure to sexual content, genital contact in any form or sexual activities with a child that may not be able to comprehend the situation and therefore is not able to give consent (Gonzalez et al., 2023).

This literature review will focus on the physical abuse of children, more specifically on abusive head trauma. The review will include different studies of children with either confirmed or suspected abusive head trauma, and the magnetic resonance imaging (MRI) sequences that are used to identify related lesions. Computed tomography (CT) is used in the initial workup of a patient with suspected head trauma, where a non-contrast head CT is performed. However, if the patient needs further examination of the brain, an MRI scan is provided to define the extent of the injuries (Franklin et al., 2023). CT uses ionizing radiation, while MRI uses a strong magnetic field. CT comes with the risk of radiation exposure, which may adversely affect the child's future health. Therefore, this thesis will focus on the utilization of different MRI sequences and their potential to substitute or complement other neurological imaging techniques.

1.1 Abusive head trauma

Abusive head trauma (AHT), previously known as “shaken baby syndrome”, is a non-accidental head injury and is the most common form of child abuse characterized by violent shaking and/or blunt impact to the head of an infant or child younger than 5 years.

Injuries caused by this type of trauma can have profound and frequently fatal impacts on a child´s brain, affecting both the skull and intracranial components (Hung, 2020). AHT is a worldwide "leading cause of traumatic death in infants and young children" (Cheon & Kim, 2022). As AHT is a global concern, it becomes crucial to share clinical and biomechanical data to improve and increase the efficiency of detecting and preventing AHT in children, as well as improve the treatment of AHT.

Dr. John Caffey came across six different cases in 1946, where infants had unexplained long-bone fractures and chronic subdural hematoma (SDH). His observation formed a medical entity around child abuse. Since then, different terms have been used to describe brain injuries in infants and young children. "Battered child syndrome" was used by Kempe et al. in 1962 and was suggested to be used for children "[...] with a combination of multiple fractures, SDH and bruises" (Cheon & Kim, 2022). "Whiplash shaken infant syndrome" was formed by Caffey in 1974, and described children who suffered from retinal hemorrhages, neurologic injury and SDH as a result of abuse. The term "shaken baby syndrome" (SBS) was also used for a long time to describe inflicted traumatic brain injuries on young children. In 2009 it was recommended by the American Academy of Pediatrics Committee on Child Abuse and Neglect that the term "abusive head trauma" was more appropriate to describe traumatic injuries to the brain as a result from abuse (Cheon & Kim, 2022). The reason being that the injuries are not only a result from violent shaking, but can also result from suffocation, blunt impact, strangulation, as well as dropping and throwing a child. AHT therefore describes the type of injury rather the mechanism of them (Joyce et al., 2024). While AHT describes brain injuries resulting from multiple traumas, SBS often only describes brain injuries resulting from violently shaking an infant or small child. The injuries from SBS include subdural hematoma and unilateral/bilateral retinal hemorrhages, which we also see with AHT. The term "abusive head trauma" therefore includes the term "shaken baby syndrome" but is not specifying the mechanism of the injury.

1.2 Biomechanics

The biomechanics of AHT consists of either direct forces to the head or violent shaking or encompasses a combination of the two. The direct forces applied to the baby's head is referred to as "impact loading". The consequences of this may manifest as skull fractures and parenchymal contusions (crushing injuries) (Cheon & Kim, 2022). However, “impact loading” injuries are more common in older children and less in infants and young children with AHT. When talking about the biomechanics of violently shaking the baby, we refer to it as “impulse loading”. This is a non-impact force, which means that the baby is not exposed to a direct force but is abused by forces that are “[...] produced by alternating angular acceleration and deceleration of the cranial vault [...]” (Cheon & Kim, 2022). The violent shaking can therefore cause the infant's brain to move more as it is not fully developed yet. Infant’s heads are also large and heavy compared to the size of their torso, and their neck muscles are not strong enough to support a heavy head (Hung, 2020). The injuries that can result from violent shaking are subdural hematoma (SDH), intracranial and retinal hemorrhage, parenchymal injury, and diffuse axonal injury. Diffuse parenchymal injury is a type of parenchymal injury, and it is not specific for abusive head trauma. However, it is highly recommended to consider the possibility of AHT when there is an association with subdural hematoma and retinal hemorrhage (Cheon & Kim, 2022). When suspecting AHT in children, imaging plays a very important role in the evaluation. Imaging can give an accurate diagnosis of the injuries, as clinical presentation may lack specificity.

1.3 Abusive head trauma lesions

Injuries stemming from abusive head trauma predominantly appear as internal injuries, and can only be identified by neurological imaging techniques, such as MRI. Some of the most common injuries in pediatric patients that have been exposed to AHT are subdural hematoma, different types of hemorrhages and parenchymal injuries. Other injuries that may result from AHT are diffuse axonal injuries, cerebral swelling and infarct.

1.3.1 Subdural hematoma (SDH)

A subdural hematoma (SDH) is an unusual collection of blood under the dura mater, which is one of the protective layers of the brain tissue (Pierre & Kondamudi, 2023). SDH in pediatric patients is mostly caused by trauma to the head, whether it is accidental or intentional. When the trauma is intentional, it is often referred to as “shaken baby syndrome” because the injuries “[...] correlates with the back-and-forth motion of the brain in the skull [...]” (Pierre & Kondamudi, 2023). The brain is held by fragile bridging veins, and these veins can rupture as a result of the violent and repeated movements of the brain, leading to a subdural hematoma. Infants are vulnerable to SDH as they do not have strong neck muscles to support the head during such movements.

1.3.2 Hemorrhages

A hemorrhage is loss of blood from a damaged blood vessel. The bleeding is acute, and can range from minor or significant. A hemorrhage can occur externally, such as from a traumatic wound, or it can occur internally. When the bleeding is internal, it requires a clinical suspicion that is obtained through laboratory testing, diagnostic imaging, the patient's history and physical, as well as monitoring the patient’s vital signs (Johnson & Burns, 2023). A hemorrhage can occur on various parts of the body, depending on the trauma. When the hemorrhage occurs in the brain, a ruptured vessel will bleed into or around the brain. When the bleeding occurs within the skull, it is called an intracranial hemorrhage. Intracranial hemorrhage often occurs due to chronically elevated blood pressure, which can weaken the arterial walls (Johnson & Burns, 2023). Trauma is a major cause of intracranial bleeding. Retinal hemorrhages are another type of hemorrhage, located in the retina. Retinal hemorrhages can range from small dots to a massive hemorrhage, and its location, size and distribution give information about the etiology (Kanukollu & Ahmad, 2023). When trauma is involved, the hemorrhages can be both unilateral or bilateral, depending on the trauma. “The shaken baby syndrome shows bilateral diffuse multilayered hemorrhages in infants and children” (Kanukollu & Ahmad, 2023). The injuries that cause retinal hemorrhages in young children exposed to abusive head trauma, are caused by repeated acceleration and deceleration. Additional to the retinal hemorrhages, the trauma can also cause intracranial injury as well as fractures to the ribs and long bone metaphysis.

1.3.3 Parenchymal injuries

Parenchymal injuries may arise from direct trauma, such as shaking, impact of forceful insult, or it can occur through neurometabolic processes, such as oedema, cell death or metabolic failure (Oates et al., 2021). The injuries can also be divided into primary or secondary parenchymal injuries. An example of a primary parenchymal injury are contusional injuries. Parenchymal contusion may develop due to direct trauma, such as blunt force impact to the head.

1.3.4 Diffuse axonal injury

Diffuse axonal injury (DAI) is a damage to the nerve fiber of a neuron in the brain. The nerve fiber is known as the axon. The occurrence of the damage is a result of head trauma involving acceleration or deceleration. DAI "[...] poses the most important prognostic factor for mortality, disability or persistent vegetative state following head trauma" (Luc et al., 2021). As a consequence, it is a possibility that DAI can cause physical, cognitive or personality changes, impacting the patient's future productivity, social functioning and quality of life.

1.3.5 Cerebral swelling

Cerebral swelling, also known as cerebral edema, is when the brain is swelling up due to a traumatic brain injury. If left untreated, cerebral edema can be severely damaging to the brain, potentially leading to fatality. When the volume of brain tissue increases, the brain tissues will swell with edema. The clinical presentation will vary, "[...] ranging from asymptomatic to severe autonomic dysregulation, coma, and death" (Nehring et al., 2023).

1.3.6 Infarct

A cerebral infarct may not appear immediately following a head injury but emerges several days after the incident. Infarcts can prolong the recovery time and therefore increase the length of stay at the hospital or rehabilitation facilities for the patient. Infarcts are also "[...] often associated with at least temporary if not permanent motor, sensory and speech deficits" (Ransom et al., 2003). According to Ransom, there was a study about traumatic brain injury in children under the age of 6 in 1999, revealing that these patients with cerebrovascular infarct had decreased motor and mental function after the injury (Ransom et al., 2003).

1.4 Magnetic resonance imaging sequences

A prerequisite for a properly planned MRI examination is to provide an answer to the clinical question. It is essential to have a correct understanding of the problem itself as well as knowledge of the sequence properties. There are different variants of sequences available for clinical use, based on different contrast mechanisms, resolution and acquisition speed (Chavhan, 2016). The ability of MRI to produce soft tissue contrast has made it highly relevant in neurological imaging. The various pathologies are highlighted by appropriate choice of pulse sequences and pulse sequence parameters. A pulse sequence defines how the radio frequency is pulsed, which generates detectable signals, which further use magnetic gradient fields that form spatial codes of these signals (Jackson et al., 1997).

The sensitivity of magnetic resonance imaging in the central nervous system comes from the dependence of MRI contrast and signal-to-noise ratio (SNR) on several intrinsic and extrinsic parameters. The most important internal parameters concern T1 weighted, T2 weighted, proton density and velocity of moving protons. In addition, more advanced techniques such as diffusion weighted imaging (DWI), susceptibility weighted imaging (SWI) and Fluid attenuated inversion recovery (FLAIR) are among the most important in neurological imaging. The external parameters are determined by the radiographer performing the examination and include echo time (TE), repetition time (TR), field-of-view, slice thickness and resolution (Jackson et al., 1997).

In other words, there are a number of available MRI sequences to choose from in neurological imaging, and it is unclear whether all these sequences add value in the investigation of abusive head trauma. Based on these theoretical foundations, the aim of this literature review is to examine *how different sequences of magnetic resonance imaging can contribute to identify and characterize "abusive head trauma" in pediatric patients*.

2. Method

In order to answer the research question, a literature review was conducted.The rationale for employing this method was to acquire pertinent data regarding MRI diagnostics in AHT, including an assessment of which MRI sequences would be most beneficial. The searches were performed in a medical database.

2.1 Literature search

An English language structured literature search of original articles published between the years 2000 to 2024 was undertaken. The availability of research articles was limited, therefore a 24 year time period was justified by gaining access to a sufficient amount of research within the topic. Scandinavian language articles were also approved in search.

PubMed was the only database used in this literature review. Several keywords were used in the searches, and they were connected with the conjunction "AND" to obtain relevant articles. These following keywords were used: "abusive head trauma", "magnetic resonance", "sequences" and "shaken baby syndrome ". Also "full text" was selected as an option. The literature search increased the sensitivity by examining the reference lists in the obtained literature. However, none of the articles in those reference lists were included in this review.

Table 1: Overview of the search process done in PubMed

Date	Keywords	Results	Abstracts read	Articles read	Included articles
21.02.2024	Abusive head trauma	4090	N/A	N/A	N/A
21.02.2024	Abusive head trauma *AND* MRI	351	32	15	7
22.02.2024	Shaken baby syndrome *AND* MRI	84	7	3	1
07.03.2024	Abusive head trauma *AND* MRI *AND* sequences	21	2	2	1

2.2 Inclusion and exclusion criteria

To be included in this literature review the articles had to meet certain inclusion criteria; Inclusion: 1) peer reviewed article, 2) the article written in English or Scandinavian, 3) the article included magnetic resonance as neurological imaging technique, 4) abusive head trauma is reported as outcome. If the articles that met the inclusion criteria also included additional characteristics that may interfere with the outcome of this review, certain criteria were made to exclude those articles: 1) the article concerns child abuse without neurological damage, 2) the article evaluated neuroimaging techniques (CT, ultrasound) which is not relevant to the current practice, 3) articles who mixed child and adult data. A total of nine articles fulfilled all these criteria, and each one of these were included in the review.

2.3 Ethical considerations

The work presented must adhere to requirements of research ethics. While the chosen methodology is not associated with similar high risks to laboratory/other forms of research, one needs to reduce or eliminate violations In this study, this is done by using articles assessed by peers. In this way, the risk of ethical violations are minimized, as they must comply with ethical guidelines created by the World Health Organization. In addition, all articles mentioned in the review are credited to the authors.

3. Results

The literature review ultimately incorporated nine studies, all conducted in the USA. Five of the articles were retrospective studies, and the remaining four were either a cohort, analytical, prospective, or pilot studies. There were a total of 354 participants with either proven or suspected AHT. The articles´ primary emphasis centered around identifying and characterizing AHT using the most advantageous MRI sequences. One article specifically used shaken baby syndrome as a expression, however it was still included as the injuries identified were similar to AHT and its classifications. Three of the articles contain favorable results of retinal and intracranial hemorrhage with susceptibility weighted imaging (SWI). Five articles the effectiveness of diffusion weighted imaging (DWI) in identifying various infarcts, subdural hematoma (SDH), diffuse axonal injury (DAI), and brain swelling. T2 weighted sequences also showed good results in detecting both intracranial and retinal hemorrhage, cerebral swelling and SDH. The main findings across all articles indicate that these three MRI sequences (SWI, DWI and T2) are all particularly effective in identifying several lesions that occurred by AHT. Table 2 presents an overview of the characteristics of the nine included articles, while Table 3 provides detailed results and findings. Subsequently, each study will be described individually.

Table 3: Characteristics of the included articles

Article (year)	Study Design	Age range (*mean*)	Number of participants in groups	MRI-sequences	Type of MRI-scanner used
Thamburaj et al. *(2019)*	Retrospective	EX: 9,1 months CG: 31,1 months	EX: 26 CG: 14	SWI standard	Siemens MAGNETOM Aera 1,5 Tesla & MAGNETOM Skyra 3 Tesla
Flom et al. *(2013)*	Cohort	DC: 3,9 months VC: 5,2 months	EX: 34 (DC: n=9, VC: n=25) CG: 53 (VC: n=53)	Sagittal T1, axial T1, axial T2 FSE, coronal T1 IR, axial DWI, axial PD, axial GRE, SWI angiography	GE Healthcare Signa HDxt 1,5 Tesla
Zuccoli et al. *(2013)*	Retrospective, single institution, observational	EX: 10,9 months	EX: 28	Axial SWI standard Axial SWI high-resolution orbits	GE Healthcare Signa HDxt 1,5 Tesla & Signa 3 Tesla HDxt
Zimmerman et al. *(2007)*	Analytical	EX: 0,75-48 months	EX: 33	Sagittal T1 SE, axial T1 SE, axial T2 FSE, coronal T2 FSE, axial T2 GRE, axial DWI	Siemens 1,5 Tesla
Biousse et al. *(2002)*	Retrospective interventional	EX: 7 months	EX: 26	Sagittal T1, axial T1, axial T2, T2 GRE, DWI	UV
Kralik et al. *(2017)*	Prospective	EX: 4 months (median)	EX: 24	Ultrafast MRI: axial T2, coronal T2, axial DWI, axial EPI T2* Standard MRI: sagittal 3D T1, axial T2 FSE, coronal T2 FSE, axial T2 FLAIR, axial DWI, axial SWI	Siemens Avanto 1,5 Tesla & Verio 3 Tesla

McKinney et al. *(2007)*	Retrospective	EX: 10,1 months	EX: 15	Axial T1, axial T2, T2* GRE, FLAIR, DWI	1,5 Tesla & 3 Tesla MRI-scanners
Beavers et al. (*2015*)	Retrospective	EX: 4 months	EX: 77	Axial T1, axial T2, FLAIR, GRE, T1 post-contrast	1,5 Tesla & 3 Tesla MRI-scanners
Franklin et al. (*2023*)	Pilot	EX: 3,67 months	EX: 24	Coronal & axial T2 HASTE, sagittal T1, axial SWI, axial T2 FLAIR, axial DWI	Siemens 1,5 Tesla & 3 Tesla

Abbrevations: EX = experimental intervention, CG = control group, UV = undisclosed variable, SWI = susceptibility-weighted imaging, DC = derivation cohort , VC = validation cohort, DWI = diffusion-weighted imaging, SE = spin echo, FSE = fast spin echo, GRE = gradient echo

Table 4: Results and findings in the included articles

Article	MRI-sequences of interest	Identifying AHT-lesions/Findings	Fundamental characteristics of diagnostic imaging test
Thamburay et al. *(2019)*	SWI	Retinal hemorrhage	Sensitivity: 50% Specificity: 100% PPV: 100% NPV: 32%
Flom et al. *(2013)*	T2, GRE, T1 IR	Intracranial hemorrhage	Sensitivity: 100% Specificity: 83%
Zuccoli et al. *(2013)*	Standard SWI HRO-SWI	Retinal hemorrhage	Sensitivity: 75% / 83% Specificity: 100%
Zimmerman et al. *(2007)*	DWI	Diffuse supratentorial brain swelling, watershed infarction, parieto-occipital venous infarction, DAI, focal superficial injury	UV
Biousse et al. *(2002)*	DWI	SDH, parenchymal lesions	UV

Kralik et al. *(2017)*	DWI T2	Intracranial hemorrhage No sedation needed >2 minutes examination 100% diagnostic quality	Sensitivity: 50% Specificity: 100% PPV: 100% NPV: 31%
McKinney et al. *(2007)*	DWI T2* GRE FLAIR	Hypoxic-ischemic encephalopathy Interhemispheric and convexity SDH Cerebral swelling	UV
Beavers et al. *(2015)*	GRE, T2	Retinal hemorrhage	Sensitivity: 61% Specificity: 100%
Franklin et al. *(2023)*	T2 HASTE, T1, DWI, T2 FLAIR, SWI	Skull fracture Intracranial hemorrhage Scalp hematoma	Sensitivity: 83,3% Specificity: 100% Sensitivity: 93,75% Sensitivity: 66,5% Specificity: 96% PPV: 93,75% NPV: 74,38%

Abbrevations: SWI = susceptibility-weighted imaging, DWI = diffusion weighted imaging, HRO = high resolution orbits, DAI = diffuse axonal injury, UV = undisclosed variable, GRE = gradient echo, SDH = subdural hematoma, PPV = positive predictive value, NPV = negative predictive value

3.1 Article 1

Thamburaj et al. (2018) looked at the utility of susceptibility-weighted imaging in detecting retinal hemorrhages in AHT. 26 children with AHT and 14 children without a history of trauma (controls) were included in the study. T-test showed no significant age difference between the groups (p=0,31), indicating that the age range does not significantly impact the results. Two radiologists identified the SWI-images, and by consensus, retinal hemorrhage in the right eye was found in 9 cases (34,6%) and 8 cases (30,7%) in the left eye. Regarding the control group, a false positive retinal hemorrhage was identified by one of the radiologists. In order to reliably assess the degree of radiologists´ agreement for the presence or absence of retinal hemorrhage among the groups, the assessment tool inter-rater agreement was used. It showed 0,80 on the right eye and 0,78 on the left eye. Furthermore, 80,7% of the children with AHT had a funduscopic examination available.

3.2 Article 2

In their study, **Flom et al.** (2015) explored ways to optimize the development of a screening MRI for children with AHT. The study first included a derivation cohort of 9 children with AHT, before 78 children were included in the validation cohort (25 children with AHT). Seven pulse sequences were used in the derivation cohort, and after an assessment by a neuroradiologist and a neurosurgeon, the following three sequences proved to have a high sensitivity for intracranial bleeding: axial T2, axial GRE and coronal T1 inversion recovery (IR). Both readers found axial T2 and GRE abnormal in 25/25 cases, and that coronal T1 IR was abnormal in 23/25 cases.

3.3 Article 3

Another article dealt with SWI and its ability to detect retinal hemorrhages in AHT. **Zuccoli et al.** (2013) evaluated the problem statement and used the gold standard dilated fundus examination (DFE) as a comparison. A regular standard SWI in addition to high-resolution orbits SWI (n=15) was used. For the further comparison, RH was identified by DFE in 21 patients. Standard SWI identifies RH in 13/21 (62%), and high-resolution orbits SWI identified RH in 12/15 (80%).

3.4 Article 4 & 5

Both **Zimmermann et al.** (2007) and **Biousse et al.** (2002) looked at diffusion-weighted MRI in AHT. A total of 59 pediatric patients were included. The result by Zimmermann et al. (2007) clearly shows that DWI is a favorable sequence to use as five imaging patterns were found using it. This is substantiated by Biousse et al. (2002) in their study who compares parenchymal brain lesions seen on conventional MRI with DWIMRI. The patients were divided into two groups: with and without retinal hemorrhage. In the group without RH, 14% showed more extensive lesions on DWIMRI than conventional MRI. In the group with retinal hemorrhage, DWIMRI showed lesions that were larger than on conventional MRI in 76%.

3.5 Article 6

Kralik et al. (2017) aimed to compare unsedated ultrafast MRI (ufMRI) versus standard MRI (stMRI) for the identification of intracranial trauma in pediatric patients with possible AHT. The ufMRI brain protocol consisted of T2 HASTE, T2* and DWI, and showed 100% diagnostic quality by additionally achieving advantages such as no sedation, no immobilization, and <2 minutes examination time. In comparison, the stMRI brain protocol also showed 100% diagnostic quality, but then 37% had to be sedated, 63% had to be immobilized, and the examination time required approximately 15 minutes. In addition, 11 sequences in 6/24 scans had to be repeated with stMRI, versus ufMRI which only had to repeat 4 sequences in 3/24 scans.

3.6 Article 7

McKinney et al. (2007) found that a DWIMRI easier can more easily identify unilateral HIE. At DWIMRI, HIE was confirmed in the subacute phase in ⅔ patients who had previously confirmed HIE from CT- and MR imaging. The third child with AHT and HIE had bilateral injuries. DWIMRI in patient 1 and 2 showed diffuse cortical infarction and severely restricted diffusion through the left cerebral white matter. In addition, T2* GRE confirmed interhemispheric and convexity subdural hematoma, and the FLAIR-sequence identified cerebral swelling.

3.7 Article 8

Beavers et al. (2015) looked at the value of a standard MRI brain protocol to detect RH. 46/77 children had RH detected by extended fundoscopic examination. Out of these 46 children with RH, 28 were identified on MRI. On the other hand, no RH was identified on MRI in the children who did not have RH on extended fundoscopic examination. Most cases of TH were seen in 2 sequences: 27/28 (96%) were seen in GRE images and 22/28 (79%) were identified in T2-weighted images. The one case that did not show RH on the GRE images was identified on the post-contrast images. Furthermore, RH was found in 11/27

(41%) of the FLAIR images, 7/27 (26%) in T1-weighted images and 5/28 (18%) in T1 weighted images after contrasting medium injection.

3.8 Article 9

Franklin et al. (2023) considered rapid sequence MRI protocol and skull radiography as an alternative to head CT in the investigation of AHT in pediatric patients. 10/12 patients with skull fracture were identified by using both skull radiography and MRI. Of the 10 skull fractures detected by the first radiologist, 9 (90%) were detected by the second radiologist. MRI identified 15/16 patients with intracranial bleeding. Scalp hematoma for simultaneous skull fracture showed 75% sensitivity by the first radiologist, versus 58% by the second radiologist.

4. Discussion

4.1 CT and MRI as imaging techniques

MRI is best suited for detecting various types of intracranial bleeding and estimating the bleedings approximate age. In contrast, MRI is not as good at visualizing acute brain edema due to the fact that the unmyelinated white matter in infants has a higher water content (Hsieh et al., 2015). Several of the studies included in this review mention advantages of using MRI as an alternative or supplement to CT. Increased utilization of MRI in investigation of AHT could lead to a reduction in the number of CT examinations, thereby minimizing exposure to its consequential ionizing radiation. The Australian Protection and Nuclear Safety Agency has assessed the risks associated with CT, and estimates that the radiation dose for a CT head examination is approximately 1,5-2,5 mSv. This corresponds to approximately up to 1,5 years of natural background radiation (Australian Radiation, Protection and Nuclear Safety Agency). Reducing CT usage would be particularly beneficial for the youngest children, who face an elevated risk of developing leukemia and brain cancer due to head CT radiation exposure (Miglioretti et al., 2013). In addition, the threshold for possible screening of intracranial bleeding will be lowered due to the eliminated radiation exposure (Flom, 2015).

4.2 Diffusion weighted imaging & susceptibility weighted imaging

In this literature review, multiple studies were examined to explore the effectiveness of different MRI sequences in identifying and diagnosing head injuries in children with confirmed or suspected AHT. All the included studies in this review can refer to positive findings when using MRI, either as a supplement or as a replacement to other neurological imaging methods. It is clearly shown in Thamburaj et al. and Zuccoli et al´s studies that susceptibility weighted MRI is very beneficial for identification of retinal hemorrhage. The sequence is both sensitive and specific, and the studies conclude that a SWI protocol can be advantageously integrated into the neuroimaging of pediatric patients being evaluated for AHT. In addition, the sequence diffusion weighted MRI show very promising results in Zimmermann et al., Biousse et al. and McKinney et al´s studies. This particularly applies during the acute phase, as cortical abnormalities will become more pronounced. This due to the cortex having high metabolic demand, making it more susceptible acutely.

Based on the included articles in this review, diffusion weighted imaging and susceptibility weighted imaging show promising results for identifying different AHT-lesions. DWI is a sequence useful for gaining insight into metabolic disturbances in the brain of pediatric patients. DWI is sensitive to the diffusion of water molecules, which is altered by cerebral lesions (Beaulieu et al., 1999). In acute injuries, cortical abnormalities are often seen on a DWI sequence. This susceptibility arises due to the cortex´s high metabolic demand, particularly during acute situations (McKinney et al., 2007). Cerebral ischemia in pediatric patients can be diagnosed much earlier with a DWI sequence compared to other MRI sequences, which is due to the differences in water diffusion between grey matter and white matter. The white matter of the brain in infants is very vulnerable to damage and is particularly susceptible to damage after hypoxia-ischemia that can occur in AHT (Beaulieu et al., 1999).

SWI constitutes another source of contrast in MRI by exploiting the magnetic susceptibility differences of different structures. SWI is particularly useful in trauma (Halefoglu & Yousem, 2018) and is 3-6 times more sensitive, consequently better, than conventional T2* GRE sequences in detecting hemorrhagic axonal injuries and cerebral microbleeds. Thus, this sequence has great potential to improve the diagnosis of diffuse axonal injury (DAI) (Tong et al., 2003). SWI also increases the MRI sensitivity in presenting retinal hemorrhages, particularly with a high-resolution orbital SWI sequence (Cheon & Kim, 2022). This is also supported by the results shown in this review.

4.3 Sensitivity and specificity

Out of the nine included articles, there were six articles that refer to sensitivity and specificity in their results section. Diagnostic sensitivity and specificity are technical characteristics of a test, and it indicates the ability to identify injured and healthy individuals in the groups. Diagnostic sensitivity refers to the analysis´ ability to correctly identify individuals with the condition, i.e. the probability that an injured patient will receive a true test result. Specificity is understood as the ability of an analysis to exclude healthy individuals, i.e. the probability that a healthy patient will get the true answer. Some of the articles also include positive predictive value (PPV) and negative predictive value (NPV). These values say something about how likely it is that the test result is correct, which may be more interesting to know for the individual patient. Thus, PPV is the probability that the patient is injured, given that it received a positive test result, and NPV is the probability that the patient is healthy, given that it received a negative test result (Lydersen, 2017). The results clearly show high specificity on SWI, DWI and GRE in several lesions. The outcome show a moderate level of sensitivity on SWI when identifying retinal hemorrhages. DWI also show a moderate level of sensitivity, however the article by Kralik et al. was the only article that shows sensitivity on DWI. The level of sensitivity on GRE was high when identifying intracranial hemorrhages, and moderate when identifying retinal hemorrhages.

4.4 Limitations

Obtaining a sufficient number of patients with AHT has been challenging as several of the included articles consisted of a small patient sample. In addition, only one of the articles contained control groups. If several articles had used control groups, it would be easier to clarify significant differences through statistical analysis. Inclusion and exclusion criteria were designed thoroughly, but too strict delimitations may have excluded relevant articles. In addition, with articles written in a language other than the authors´ native speech, it cannot be ruled out that some content may have been misinterpreted or misunderstood.

4.5 Recommendations for future research

The findings in this literature review build on previous research that different MRI sequences can be used with advantage in the investigation and diagnosis of AHT. However, the articles do not provide sufficient and unambiguous evidence to draw firm conclusions. To improve future research on this type of imaging technology, it would be beneficial for prospective studies to address the role and benefit of gradient echo sequences, diffusion weighted imaging and susceptibility weighted imaging. In order to increase the validity of the MRI sequences´ specificity and sensitivity, a larger patient group is needed, as well as focusing on the role of each individual sequence in specific injuries.

5. Conclusion

Based on the findings in this literature review we can conclude that there are multiple MRI sequences that can identify different lesions in the brain from AHT, and that certain sequences are more favorable to use. The common denominators are DWI, SWI and GRE. It was clear that these sequences had an advantage with identifying different lesions. Furthermore, by creating a time efficient screening protocol, it may avoid repeating scans in future examinations. Therefore it will save the amount of examination time, which further will lead to not having to use sedation or immobilization. The results also show that the MRI sequences have a high level of specificity, and a moderate level of sensitivity. Taking all factors into account, there needs to be further research on how MRI sequences can contribute to enhancing and strengthening the identification of different lesions.

References

Australian Radiation Protection and Nuclear Safety Agency. CT scans for children. *Australian Commission on Safety and Quality in Health Care*. https://www.safetyandquality.gov.au/sites/default/files/migrated/CT-scans-for-children-information-for-referrers.pdf

Beaulieu, C., D´Arceuil, H., Hedehus, M., Crespigny, A., Kastrup, A. & Moseley, M. E. (1999). Diffusion-weighted magnetic resonance imaging: Theory and potential applications to child neurology. *Seminars in Pediatric Neurology, 6(2)*, (87-100). https://doi.org/10.1016/S1071-9091(99)80035-7

Beavers, A. J., Stagner, A. M., Allbery, S. M., Lyden, E. R., Hejkal, T. W. & Haney, S. B. (2015). MR detection of retinal hemorrhages: correlation with graded ophthalmologic exam. *Pediatric Radiology, 45*, (1363-1371). https://doi.org/10.1007/s00247-015-3312-1

Biousse, V., Suh, D. Y., Newman, N. J., Davis, P. C., Mapstone, T. & Lambert, S. R. (2002). Diffusion-weighted magnetic resonance imaging in shaken baby syndrome. *American Journal of Ophthalmology, 133(2)*, (249-255). https://doi.org/10.1016/S0002-9394(01)01366-6

Chavhan, G. B. (2016). Appropriate selection of MRI sequences for common scenarios in clinical practice. *Pediatric Radiology, 46*, (740-747). https://doi.org/10.1007/s00247-016-3556-4

Cheon, J. & Kim, J. H. (2022). Imaging of Abusive Head Trauma: A Radiologists´ Perspective. *National Library of Medicine, 65(3),* (397-407).

Flom, L., Fromkin, J., Panigrahy, A., Tyler-Kabara, E. & Berger, R. P. (2015). Development of a screening MRI for infants at risk for abusive head trauma. *Pediatric Radiology, 46,* (519-526). https://doi.org/10.1007/s00247-015-3500-z

Franklin, D., Tiwari, C., Zamora, C., Barnett, R., Woolard, A., Hung, S., Berkoff, M. & Quinsey, C. (2023). Combined rapid sequence MRI protocol and skull radiography as an alternative to head CT in the evaluation of abusive head trauma in children: a pilot study. *Neurosurgical Review, 46(175)*. https://doi.org/10.1007/s10143-023-02084-3

Gonzalez, D., Mirabal, A. B. & McCall, J. D. (2023). Child abuse and Neglect. *National Library of Medicine.* https://www.ncbi.nlm.nih.gov/books/NBK459146/

Halefoglu, A. M. & Yousem, D. M. (2018). Susceptibility weighted imaging: Clinical applications and future directions. *World Journal of Radiology, 10(4)*, (30-45). https://doi.org/10.4329%2Fwjr.v10.i4.30

Hsieh, K. L., Zimmermann, R. A., Kao, H. W. & Chen, C.Y. (2015). Revisiting Neuroimaging of Abusive Head Trauma in Infants and Young Children. *American Journal of Roentgenology, 204(5)*. https://doi.org/10.2214/AJR.14.13228

Hung, K. (2020). Pediatric abusive head trauma. *Biomedical Journal, 43(3)*, (240-250). https://doi.org/10.1016/j.bj.2020.03.008

Jackson, E. F., Ginsberg, L. E., Schomer, D. F. & Leeds, N. E. (1997). A review of MRI pulse sequences and techniques in neuroimaging. *Surgical Neurology, 47(2)*, (185-199). https://doi.org/10.1016/S0090-3019(96)00375-8

Johnson, A. B. & Burns, B. (2023). Hemorrhage. *National Library of Medicine.* https://www.ncbi.nlm.nih.gov/books/NBK542273/

Joyce, T., Gossman, W. & Huecker, M. R. (2024). Pediatric Abusive Head Trauma. *National Library of Medicine*. https://pubmed.ncbi.nlm.nih.gov/29763011/

Kanukollu, V. M. & Ahmad, S. S. (2023). Retinal Hemorrhage. *National Library of Medicine*. https://www.ncbi.nlm.nih.gov/books/NBK560777/

Kralik, S. F., Yasrebi, M., Supakul, N., Lin, C., Netter, L. G., Hicks, R. A., Hibbard, R.A., Ackerman, L. L., Harris, M. L. & Ho, C. Y. (2017). Diagnostic Performance of Ultrafast Brain MRI for Evaluation of Abusive Head Trauma. *American Journal of Neuroradiology, 38(4)*, (807-813). https://doi.org/10.3174/ajnr.A5093

Luc, M., Pawlowski, M., Rymaszewska, J. & Kantorska-Janiec, M. (2021). Diffuse axonal injury - an interdisciplinary problem. *Psychiatria Polska, 55(1)*, (171-180). https://doi.org/10.12740/PP/OnlineFirst/112404

Lydersen, S. (2017). Hva er sannsynligheten for riktig resultat av en diagnostisk test? *Tidsskriftet*. https://tidsskriftet.no/2017/10/medisin-og-tall/hva-er-sannsynligheten-riktig-resultat-av-en-diagnostisk-test

McKinney, A. M., Thompson, L. R., Truwit, C. L., Velders, S., Karagulle, A. & Kiragu, A. (2007). Unilateral hypixic-ischemic injury in young children from abusive head trauma, lacking craniocervical vascular dissection or cord injury. *Pediatric Radiology, 38*, (164-174). https://doi.org/10.1007/s00247-007-0673-0

Miglioretti, D., Johnson, E., Williams, A., Greenlee, R. T., Weinmann, S., Solberg, L. I., Feigelson, H. S., Roblin, D., Flynn, M. J., Vanneman, N. & Smith-Bindman, R. (2013). The use of computed tomography in pediatrics and the associated radiation exposure and estimated cancer risk. *JAMA Pediatrics, 167(8)*, (700-707). https://doi.org/10.1001/jamapediatrics.2013.311

Nehring, S. M., Tadi, P. & Tenny, S. (2023). Cerebral Edema. *National Library of Medicine.* https://www.ncbi.nlm.nih.gov/books/NBK537272/

Oates, A. J., Sidpra, J. & Mankad, K. (2021). Parenchymal brain injuries in abusive head trauma. *Pediatric Radiology, 51*, (898-910). https://doi.org/10.1007/s00247-021-04981-5

Pierre, L. & Kondamudi, N. P. (2023). Subdural Hematoma. *National Library of Medicine*. https://www.ncbi.nlm.nih.gov/books/NBK532970/

Ransom, G. H., Mann, F. A., Vavilala, M. S., Haruff, R. & Rivara, F. P. (2003). Cerebral infarct in head injury: relationship to child abuse. *Child Abuse & Neglect, 27(4)*, (381-392). https://doi.org/10.1016/S0145-2134(03)00025-5

Thamburaj, K., Soni, A., Frasier, L. D., Tun, K. N., Weber, S. R & Dias, M. S. (2018). Susceptibility-weighted imaging of retinal hemorrhages in abusive head trauma. P*ediatric Radiology, 49*, (210-216). https://doi.org/10.1007/s00247-018-4292-8

Tong, K. A., Ashwal, S., Holshouser, B. A., Shutter, L. A., Herigault, G., Haacke, E. M. & Kido, D. K. (2003). Hemorrhagic shearing lesions in children and adolescents with posttraumatic diffuse axonal injury: improved detection and initial results. *Radiological Society of North America, 227(2),* (332-9). https://doi.org/10.1148/radiol.2272020176

World Health Organization. (2022). Child maltreatment. *World Health Organization*. https://www.who.int/news-room/fact-sheets/detail/child-maltreatment

Zimmermann, R. A., Bilaniuk, L. T. & Farina, L. (2007). Non-accidental brain trauma in infants: diffusion imaging, contributions to understanding the injury process. *Journal of Neuroradiology, 34(2)*, (109-114). https://doi.org/10.1016/j.neurad.2007.01.124

Zuccoli, G., Panigrahy, A., Haldipur, A., Willaman, D., Squires, J., Wolford, J., Sylvester, C., Mitchell, Lope, L. A., Nischal, K. K. & Berger, R. P. (2013). Susceptibility weighted imaging depicts retinal hemorrhages in abusive head trauma. *Neuroradiology, 55,*

(889-893).
https://doi.org/10.1007/s00234-013-1180-7

NTNU
Norwegian University of
Science and Technology