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Abstract

Medical Resonance Imaging (MRI) stands as a vital non-invasive imaging tool, offering detailed visualization of soft tissue, organs, and neurological structures. While MRI is fundamental in pediatric care, unique challenges arise in this demographic. The MRI system comprises key components, including a superconductive magnet for generating the magnetic field, shimming for field homogenization, and radiofrequency (RF) fields to stimulate hydrogen nuclei for signal emission and image formation. Additional elements like RF pulses, coils for signal detection, and slice selection techniques contribute to image acquisition.

Pediatric patients present distinct challenges due to anatomical variations and developmental stages. Their smaller brain size, elevated heart rate, and limited capacity for stillness can compromise image clarity. Sedation and anesthesia are frequently employed to address these challenges, despite associated drawbacks like cost, allergic reactions, and potential long-term effects. Furthermore, the use of adult-sized RF coils can lead to discomfort and compromised image resolution in pediatric patients.

Thermoregulation issues and heightened sensitivity to noise further complicate pediatric MRI. The loud MRI gradient acoustic noise may impact hearing and development. Prolonged scan durations, lasting up to 90 minutes, exacerbate the challenge of maintaining stillness in pediatric patients, resulting in psychological risks such as fear, panic, and anxiety.

To optimize MRI for pediatric patients, various techniques and strategies have been developed. These include reducing scan time to minimize sedation requirements and enhance image quality. Optimization techniques

involve adjusting MRI parameters such as Field of View (FOV) and oversampling, employing accelerated data acquisition methods like compressed sensing and parallel imaging, and utilizing simultaneous multi-slice (SMS) imaging to capture signals from multiple areas concurrently.

Addressing the psychological challenges faced by pediatric patients during MRI procedures is paramount. Strategies involve familiarizing children with the MRI environment through simulated scanning, leveraging virtual reality technology to reduce anxiety, and implementing patient-centered communication approaches during the scan.

In summary, while pediatric MRI presents unique challenges, advancements in techniques and strategies aim to enhance patient comfort, cooperation, and imaging outcomes in this vulnerable population.

Chapter 1

Introduction

In this first chapter, we introduce the thesis objectives and provide an overview of MRI, along with its clinical applications in the pediatric department.

1.1 Thesis Objectives

"Adaptation of MRI Technology for Pediatric Imaging: Exploring Challenges and Solutions in Pediatric MRI"

Magnetic Resonance Imaging (MRI) systems (**Figure 1.1**) serve as invaluable tools for non-invasive examination of the human body's internal organs and structures. Comprising powerful magnets, radiofrequency coils, gradient coils, and sophisticated computer systems, MRI facilitates the acquisition and processing of MR signals to generate detailed images. Recognized as the cornerstone of diagnostic imaging, MRI plays a central role in primary assessment and clinical practice [1].

This thesis explores the utilization of MRI in pediatric imaging, with a focus on its applications, complications, and unique considerations. By examining various factors influencing pediatric MRI, including clinical efficacy, psychological implications, and scanning protocols, this study aims to elucidate the inherent challenges in pediatric MRI [2]. Through the identification and addressing of these challenges, the thesis seeks to explore effective solutions proposed by previous research studies to optimize the use of MRI technology in pediatric care [2].

1.2 Introduction to MRI

The invention of MRI has revolutionized medical diagnostics, offering unprecedented insights into the human body. MRI provides medical professionals with a non-invasive imaging method that visualizes soft tissues, organs, and neurological structures. It is used across a wide range of specialties including orthopedics, cardiology, and oncology [3].

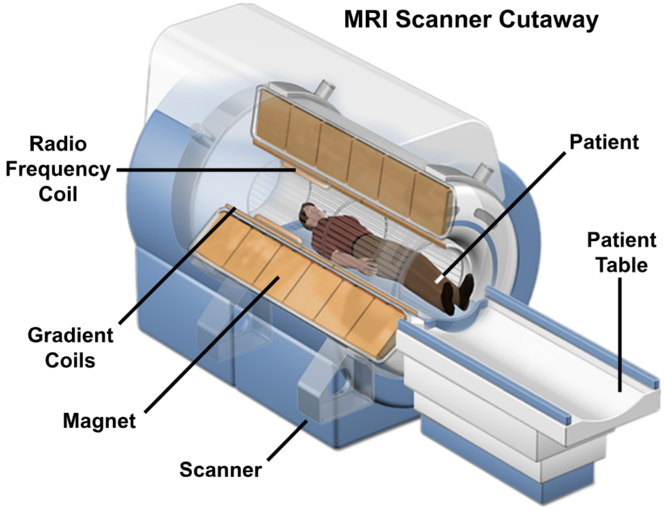

Figure 1.1: MRI machine illustrated, where the different components as Radio Frequency Coil, Gradient Coils, Magnet and Scanner are illustrated. The patient lies inside the machine during the examination on the patient table. Illustration is taken from [4] with permission.

1.2 Introduction to MRI

MRI utilizes the body's natural magnetic properties to generate detailed images from any body part, mainly by leveraging the hydrogen nucleus due to its abundance in water and fat. Inside the magnetic field of an MRI scanner, hydrogen protons in the body will align uniformly, like shown in **Figure 1.2**. By applying radiofrequency energy, these protons are deflected, causing them to resonate at specific frequencies depending on the strength of the magnetic field and the targeted area. When the protons are stimulated, they will spin out of equilibrium and resist against the magnetic field. After the radiofrequency field is turned off, the protons will return to their original state, emitting a signal which the MRI sensor will detect as energy released and make MRI images. Receiver coils enhance signal detection, and cross-sectional images are constructed based on the intensity of received signals [5]. This realignment varies based on environmental factors and molecular composition, allowing physicians to distinguish between different tissue types [3].

Gradient electric coils alter the magnetic field's strength throughout the body, allowing different body slices to resonate at different frequencies [6].

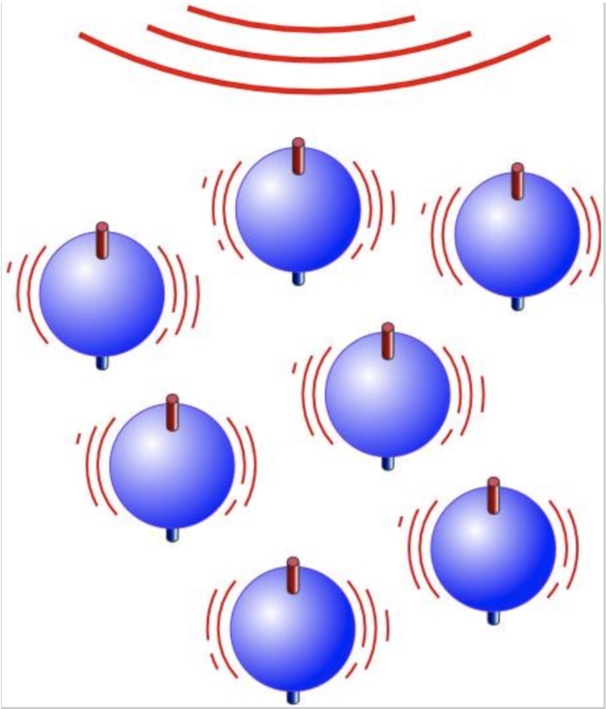

Figure 1.2: When the body is positioned within a powerful magnetic field, like an MRI scanner, the protons align their axes uniformly, generating a magnetic vector oriented along the scanner's axis. Illustration is taken from [7] with permission.

Pulse sequences with varying radiofrequency pulses highlight specific tissues or abnormalities by exploiting differences in their relaxation times, known as $T1$ and $T2$ relaxation. MR examinations consist of multiple pulse sequences, allowing for the identification of different tissues, such as fat and water [8].

MRI is highly sensitive to diseases characterized by increased water content, though discerning the exact pathology, such as distinguishing infection from tumor, may pose challenges. Expert analysis by a radiologist is essential for accurate diagnosis [9]. MRI scan time often vary from 30-90 min.

1.3 Clinical application

In the recent years, the use of MRI in pediatric medicine has been getting more attention and significance. Unlike X-rays or computed tomography (CT) scans, MRI offers a non-invasive and radiation-free method for obtaining detailed images of the internal structures of the body. Minimizing radiation exposure is crucial for pediatric patients, making MRI the preferred imaging method in the pediatric department [10].

Each year in Norway, approximately 200 children between the age of 0-18 years are diagnosed with cancer [11]. Cancer stands as the primary cause of natural demise among pediatrics in developed nations. However, early detection yields cure rates surpassing 70%. Treatment decisions for pediatric cancer patients rely on evaluating tumor type, location, and staging. Imaging protocols should be rapid, produce high-quality images with minimal radiation exposure, and provide clinically relevant information [12]. When a physician suspects that a child may have cancer, they will be promptly referred to a cancer care pathway. This cancer care pathway usually involves getting an MRI scan [11]. Such pathways entail standardized patient journeys outlining the organization of diagnostics, treatment, communication with the child and their caregivers, as well as clear delineation of responsibilities and time frames [11].

The most common type of cancer, and also the deadliest form is brain tumor [13]. A brain tumor refers to any type of tumor located within the skull (cranium), encompassing growths found in the brain itself, the meninges, or the intracranial segment of the cranial nerves [14]. Each year approximately 40 children in Norway gets a tumor in the central nervous system [15].

Brain tumors are a significant cause of mortality in children, with an incidence of 6.06 per 100.000 children aged 0-19 years in the United States [16].

MRI is important for diagnosing, characterising, planning treatment, and monitoring these tumors, providing detailed anatomical, cellular and vascular information. Integrated MRI offers significant clinical benefits for staging and reevaluation pediatric cancer, providing both functional and anatomical evaluation in a single imaging session [17][2].

MRI is also employed across various domains for pediatric patients, with some of these applications outlined in **Table 1.1**.

Table 1.1: Common clinical applications of MRI.

Disease	Symptoms	Source
Brain tumor	Headache, nausea, vomiting, visual disturbance	[18]
Psychiatric diagnoses (schizophrenia)	Larger ventricles in the brain	[19]
Brain damage	Acute injuries, head trauma, car accidents	[20]
Multiple sclerosis	Neurological symptoms, visual disturbances, decreased strength	[21]
Stroke	Brain cell swelling, decreased strength, asymmetric face	[22]
Aneurysm	Little to no symptoms, can be headache	[23]
Premature aftereffects	Neurological disturbances	[24]

Chapter 2

Theory

In Chapter 2, we will briefly outline the history of MRI's invention, discuss the theory behind MRI by discussing its main components, and explore anatomical development in children.

2.1 A Brief Introduction to the History of MR

The theory behind MRI was first introduced in 1924 when Wolfgang Pauli proposed the concept of nuclear spins. Almost ten years later Otto Stern and Walther Gerlach demonstrated nuclear spin by deflecting a beam of hydrogen molecules in a magnetic field [25].

In 1937, Professor Isidor i. Rabi from Columbia University made a significant discovery. The same year Nikola Tesla found the Rotating Magnetic field [26], which began the historical overview of magnetic resonance imaging. Together, they uncovered nuclear magnetic resonance (NMR), a quantum phenomenon. NMR made it possible to see the structure of a molecule in details.

Before the 1970s, MRI was limited to chemical and physical analysis. Dr. Raymond Damadian, however, envisioned its potential for disease detection in living organisms. In 1971, he theorized that cancerous tissue, with its higher water content, could be detected using scanners emitting radio waves and measuring local hydrogen atom emissions. Damadian then initiated the construction of a full-body scanner named the Indomitable. Around summer of 1977 [26], Damadian finished the first Indomitable, yielding the first whole-body MR images.

Since their debut in the 1980s, clinical MRI systems have seen ongoing improvements. Advancements in individual components, such as data acquisition, image reconstruction, and hardware systems, have interconnected and spurred innovation across the board in MRI technology development [27].

The 1.5 Tesla MRI was launched in early 1980, and the 3T MRI was approved and on the marked in the early 2000. The most common one still is 3T, but systems higher than 3T are now available. In 2020, regulatory approval has been granted to certain MRI manufacturers for their 7T systems [27].

2.2 Major Components of MRI Systems

The MRI consists of important components: the Superconductive Magnet, Shimming, RF coils, and Gradient field [28]. In this section, we discuss the utilization of these components and their roles in MRI technology.

2.2.1 Superconductive Magnet

MRI consists of a powerful magnet that creates a magnetic field [3]. The Superconductive MRI magnet utilize a coil in a solenoid shape, crafted from wires like titanium or tin, and encased in copper. At low temperatures, the copper surrounding the coil will act as an insulator, preserving the wires zero resistance [29]. In this state, the superconductor, in this case copper, can conduct electricity without any resistance or energy loss [30]. As a result, they generate powerful and homogeneous magnetic field. This is achieved by immersing the wires in a constant flow of liquid helium at a temperature of -269.1°C. A standard MRI scanner requires 1,700 liters of liquid helium, which must be replenished regularly [31].

The main static magnetic field is refereed to the B_0 field, which is measured in Tesla (T) [32]. To achieve the desired magnetic field strength, the power supply gradually increases the current to the coil over several hours, connected on either side of a short heated segment. Once the heated segment reaches superconducting temperature, the power supply is disconnected. The closed-loop current within the coil persists for years without significant decline, ensuring a constant magnetic field presence [29]. **Figure 2.1** shows an illustration of the principle behind an MRI system with a superconductive component. Superconducting electromagnets are the preferred choice in most applications due to their high efficiency.

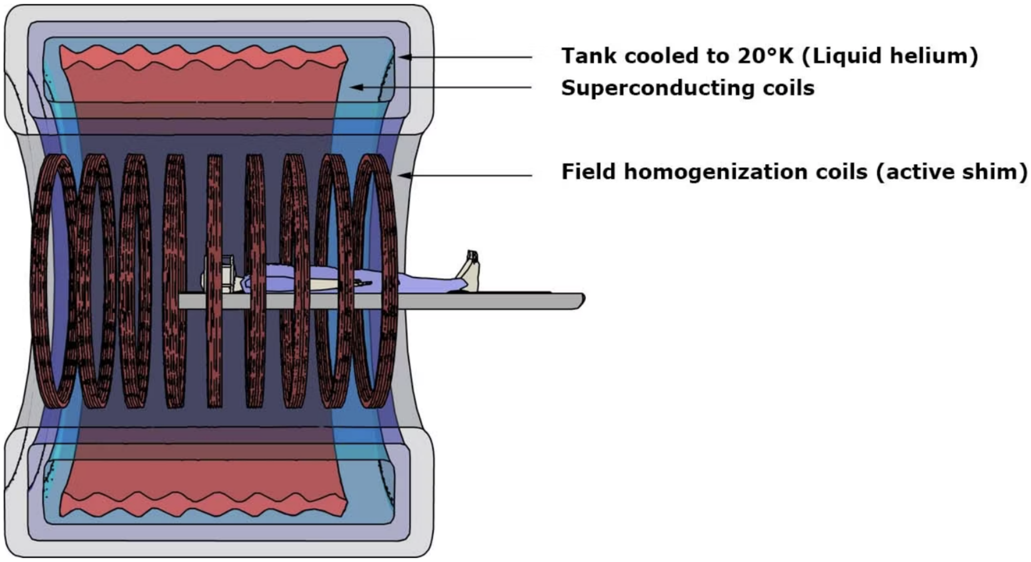

Figure 2.1: Illustration the principle behind an MRI system with a superconductive component. The coils going around the patient creating a magnetic field. On top is where the liquid helium is stored and making the coils superconductive. Illustration is taken from [33] with permission

An initial viability study [34] of an MRI system for imaging neonates in the NICU they have adapted a small 1.5T MRI system designed for orthopedic applications and originally developed and marketed as the MSK Extreme 1.5T by ONI Medical Systems (Wilmington, MA) [34]. Recently, GE purchased ONI, and the scanner is now being marketed as the OPTIMA MR430s (GE Healthcare, Waukesha, WI). Several modifications to the OPTIMA scanner were made to accommodate neonatal imaging. Specifically, the orientation and height of the magnet were changed as seen in **Figure2.2** and the patient chair was replaced with a custom-built MRI patient table. The magnet is superconducting and has a field strength of 1.5T [34].

Figure 2.2: Image of the 1.5T OPTIMA MRI system post-adjustment for neonatal imaging. Adjustments to the OPTIMA system during the sheep studies involved raising the magnet's height and aligning it horizontally.Illustration is taken from [34] with permission

Shimming

Shimming represents a critical procedure in MRI, serving as a cornerstone in the quest for optimal magnetic imaging. The goal of shimming is to achieve an optimal balance between field and imaging resolution [35].

Shimming falls under two categories: passive and active techniques. With passive shimming which employ materials with magnetic properties to passively counter distortions, and the active shimming which involve strategically positioned and energized electric coils to generate corrective magnetic fields [36].

In the pursuit of enhancing MRI images, scanners have advanced by amplifying the main signal source in MRI, known as the B_0 field. Elevating the B_0 field enhances the signal-to-noise ratio (SNR) , enabling higher spatial imaging [37]. SNR analyses the process of evaluating data, determine whether a peak should be acknowledged relies on the SNR [38]. **Figure 2.3** represents the B_0 field, which is the main static magnetic field. It is measured in Tesla [32].

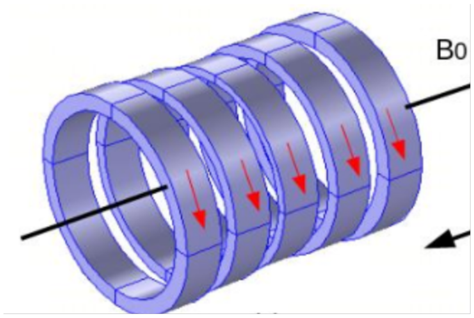

Figure 2.3: The picture represents the B_0 field, which is the main static magnetic field. It is measured in Tesla's [32]. Illustration is taken from [39] with permission.

B_0 field inhomogeneities result in artifacts like geometric distortions in Echo planar imaging (EPI) [40] and the disruption of Radioactive Frequency pulses [41]. EPI is the primary and quickest imaging sequence employed in MRI. It relies on gradient-echo techniques, which can be used to susceptibility artifacts, especially in regions with air-tissue boundaries. To summarize these artifacts, B_0 shimming is necessary to homogenize the B_0

field [42] which is the main magnetic field.

2.2.2 Radio Frequency Field

A Radio Frequency (RF) field indicates the electromagnetic field connected with RF waves. It represents a three dimensional area where electric and magnetic fields oscillate at radio frequencies [43]

Nuclear excitation alters energy states and spin orientations. On the quantum scale, a solitary proton transitions to a higher energy level (shifting from parallel to anti-parallel) [44].When RF fields are used to adjust the alignment of this magnetization, the hydrogen nuclei generate a rotating magnetic field that the scanner can detect [45].

Radio Frequency in MRI relies on the magnetization of specific atomic nuclei, commonly hydrogen, within tissue when subjected to an external magnetic field. Initially aligned with the main magnetic field, which is named B_0, this magnetization generates a net magnetization, M, in the tissue. An MRI experiment begins by transmitting an RF pulse to disrupt this magnetization, a process known as RF excitation, which transmit coils in the hardware setup [46].

In MRI scanning, the interaction with protons within the body is essential for signal generation. Protons align with the strong magnetic field of the scanner. Then the scanner emits a series of rapid radiofrequency pulses, inducing proton excitation and resonance. Upon the removal of each pulse, protons relax and realign with the magnetic field, emitting radiofrequency signals that are detected and translated into an image by the scanner [47].

Nuclear excitation and signal reception are important topics to discuss when learning about MRI. Different Magnetic fields in MRI is applied to the human body to manipulate magnetic moments of nuclei in the human tissue. This is used to produce a detectable RF signal [48].

RF Pulses and Sequence Development:

An MRI Radio Frequency pulse sequence refers to the ordered series of RF pulses and magnetic field gradients used in image generation [49].

RF pulses in MRI is extensive, and each pulse produces a unique frequency. The pulses play a vital role in MRI scans and spectroscopy experiments, enabling manipulation of spins for tasks like excitation, inversion, and refocusing. While short, constant-amplitude pulses are straightforward for non selective excitation [50].

An RF pulse consists of a magnetic field that rotates at or close to the Larmor frequency [50]. The Larmor frequency is the rate at which the proton's magnetic moment processes around the external magnetic field [51]. The pulses play a vital role in MRI scans and spectroscopy experiments, enabling manipulation of spins for tasks like excitation, inversion, and refocusing. While short, constant-amplitude pulses are straightforward for non selective excitation [50].

RF Coils

Coils, typically loops of wire, exhibit electromagnetic properties when an electrical current flows through them. In MRI, receiver coils detect the MR signal, and their design varies based on functionality and manufacturer. They play a crucial role in creating images by interacting with the magnetic field. Analogous to a digital camera, the MRI's external field serves as light, passing through a coupled-charged sensor (the coil) to translate images into digital format. This explanation highlights the cooperation between the coils and electromagnetic field in MRI imaging [52].

Volume coils in MRI serve as both transmit and receive radiofrequency coils. Additional smaller volume coils, like head coils, may be required for specific imaging, such as head or extremity examinations [32].

Head coils, often shaped like birdcages, exemplify circularly polarized coils or quadrature excitation. Circularly polarized coils enhance efficiency by adding a second set of coils perpendicular to the first, creating a rotational

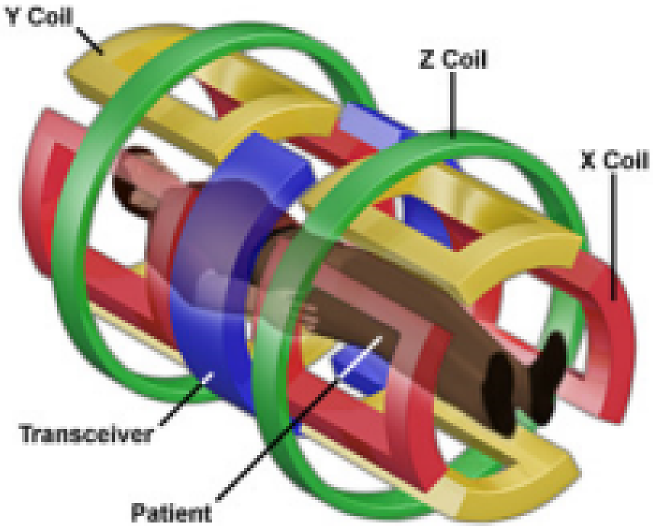

Figure 2.4: The bore on the picture has three coils surrounding the MRI. This causes a linear field, with an x-, y- and z-axis. Current is being pumped in these directions. Illustration is taken from [53] with permission.

B_0 field [32].

2.2.3 Gradient Field

Gradient coils generate magnetic fields [50] that augment the constant main magnetic field B_0. Despite the magnetic field strength increasing linearly with distance along the x-, y- or z-axis, the field's orientation remains consistently in the z-direction, aligned with the main magnetic field.

By using magnetic field gradients, one can create spatial information by making the resonance frequency of atomic nuclei position-dependent [50]. One of the most common gradient has a linear amplitude variation. These gradients, frequently in the X, Y, and Z directions as shown in **Figure 2.4**, are created by specially shaped coils and alter the magnetic field strength at different positions. The direction of a gradient to the static magnetic field component remains along the z-axis [50].

Slice Selection

In MRI, slice selection involves choosing spins within a specific plane across the object, to make an image of a body part. This process is accomplished by implementing a one-dimensional, linear magnetic field gradient while applying the RF pulse [54].

Spatial encoding involves selecting a slice plane, which is why it is a important topic to mention in this section. To achieve this, we apply a magnetic field gradient known as the Slice Selection Gradient (GSS), perpendicular to the intended slice plane. When combined with the Main Signal Source, B_0, this induces a resonance frequency variation in the protons, proportionate to GSS [55].

Spatial encoding in MRI also involves reducing the three-dimensional information of an object, like the human head, to a two-dimensional problem by selecting a thin slice. This selection is achieved through the combination of an RF pulse and a magnetic field gradient, where the gradient in the z-direction creates a linear magnetic field distribution along the z-axis. The RF pulse excites a selective range of frequencies and, consequently, spatial positions within the chosen slice [50].

The slice thickness depends on both the magnetic field gradient strength and the RF pulse bandwidth [50]. The spatial position of the slice is determined by adjusting the transmitter frequency of the RF pulse. On **Figure 2.5** the process can be extended to select multiple slices in a time-efficient manner through interleaved acquisition. However, the potential interference between adjacent slices necessitates careful consideration, often leading to an interleaved acquisition order. Its important to note that identical 90 degree and 180 degree RF pulses may have different frequency profiles, impacting the thickness and shape of selected slices in quantitative volumetric MRI measurements.

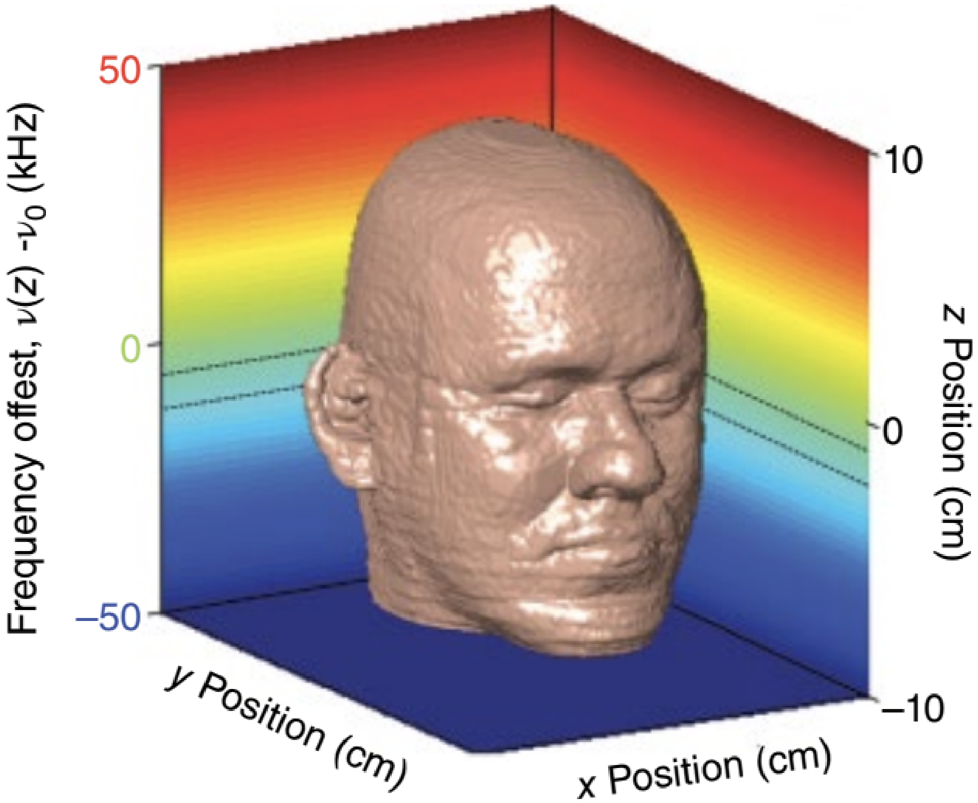

Figure 2.5: The principle of slice selection in MRI involves applying a magnetic field gradient along one of the Cartesian axes, creating a linear relationship between the Larmor Frequency and spatial position. When spins are excited using a frequency-selective RF pulse in the presence of this gradient, the resulting frequency corresponds to a specific spatial slice. Both the thickness and position of the slice depend on the magnetic field gradient strength, with the slice thickness influenced by the RF pulse bandwidth and the slice position determined by the RF pulse offset. Illustration is taken from [50] with permission.

2.3 Anatomical Development in Children

Some anatomical organs undergo significant development during the first years of life and are markedly different in neonates, young children and adults. Among these organs are the brain, lungs, and heart [56].

Infants generally refer to children from birth to around one year old. Neonatal specifically refers to the first four weeks of a child's life after birth. Adults denote individuals who have reached adulthood, typically from around 18 years and above, where the body has undergone full development and growth [57].

2.3.1 Brain Development

Physiologically and anatomically, neonates and infants differ significantly from adults, particularly in terms of head size and brain development. Initially, the head is disproportionately large compared to the body but gradually assumes adult proportions over several years. Rapid growth occurs in the first few years of life, with about half of postnatal brain growth happening in the first year or two [58][59].

The ratio of head to body length is nearly double in infants compared to adults, reflecting gestational changes. The weight of the head also impacts movement and susceptibility to falls or impacts. Additionally, the skull undergoes significant changes as fontanels and sutures close at different times, with the anterior fontanel typically closing by 12-18 months of age [60].

During the first year after birth, head circumference undergoes significant increase, primarily driven by the rapid growth of the entire brain. The correlation between brain size and skull size is noteworthy and can be illustrated as percentages: around 70% of adult brain weight is reached by 18 months, 80% by 3 years, 90% by 5-8 years, and approximately 95% by the age of 10. In adults, the average brain weight is 1350 grams [57].

Volumetric studies typically reveal that while there's minimal alteration in total brain volume between ages 4 and 18, there are concurrent relative

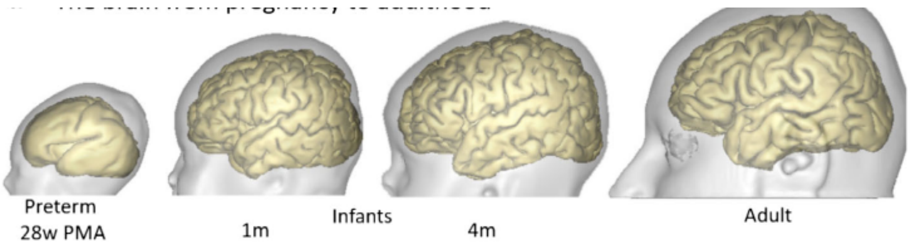

Figure 2.6: Brain development from 28 weeks post menstrual age to adult. As seen in the illustration, the skull and brain of an infant is smaller than an adult. The main challenge is that obtaining high quality and accurate images can be more difficult.Illustration is taken from [61] with permission

increments in white matter volume extending into adulthood, alongside relative declines in grey matter volume [62].

The human cerebral cortex consists of densely packed neurons arranged in a deeply folded sheet, with thickness ranging from 1 to 4.5 *mm* [63]. Cortical thickness, representing the thickness of the cerebral cortex, develops dynamically with a heterogeneous pattern, posing a measurement challenge due to spatial resolution limitations. Longitudinal data analysis characterizes cortical thickness evolution from 1-24 months, revealing region-specific developmental patterns. By age 2, cortical thickness reaches 97% of adult values, while surface area is two-thirds complete. Interpretation of MRI thickness changes is complex, influenced by synaptic pruning and micro structural alterations. Quality control procedures are crucial due to age-related variations in movement artifacts. In older children, the apparent thickness of the cortical areas decreases by the age of three [64].

This information elucidates that images appear differently in children and adults on an MRI scan.

2.3.2 Lung and Cardiac Development

The heart and lungs originate from distinct layers within the embryo, necessitating communication between them for proper organ development. Chemical signals can be released from and traverse between these layers, triggering cellular processes in different regions [65].

During fetal development, neonatal life, infancy, and early childhood, significant changes occur in the cardiovascular and respiratory systems. Consequently, the physiological functioning of the respiratory and cardiovascular systems differs markedly between young children, particularly neonates and infants, and older children and adults. These distinctions render young children more susceptible to critical events related to anesthesia and may even lead to cardiac arrest [65].

Lung Development

Neonates, particularly premature ones, have fewer alveoli, which continue to develop until adolescence, increasing lung surface area for gas exchange. However, during neonatal and early infancy stages, alveoli lack inter alveolar communications and are at risk of collapse, leading to potential atelectasis [66].

In young children, intercostal muscles are underdeveloped, and ribs are horizontally aligned, limiting thoracic expansion during inspiration. As a result, neonates rely heavily on diaphragmatic descent for inspiration, leading to rapid, shallow breathing and early diaphragmatic fatigue, which can result in respiratory failure [66].

Infants have low total lung capacity (TLC) and functional residual capacity (FRC), with a higher closing volume due to compliant thoracic walls and poorly compliant lung tissue [67]. They compensate by adjusting respiratory mechanics to maintain small airway potency, but general anesthesia can blunt these mechanisms, leading to reduced FRC and increased pulmonary shunt fraction [67]. Combined with high metabolic oxygen demand, this can cause a rapid drop in arterial oxygen tension during anesthesia induction [68].

These physiological differences may pose challenges for pediatric patients during an MRI examination.

Cardiac Development

Young children, including neonates and infants, exhibit distinct cardiovascular physiology compared to fully grown adults [69].

In neonates, the cardiovascular anatomy and physiology undergo rapid changes in the first few days to several weeks following birth, eventually reaching adult levels later in infancy. During this period, there are alterations in circulatory pathways, gradual maturation of the myocardium, and shifts in autonomic control of the heart.
These developmental changes result in reduced cardiac reserves and cardiac output in young children, which are dependent on heart rate. Additionally, they have limited tolerance for decreased myocardial contractility and alterations in systemic vascular resistance or blood volume during anesthesia [70].

The prevalent parasympathetic influence on the heart often leads to bradycardia and its adverse effects in neonates and infants when exposed to various harmful and autonomic stimuli.
Neonates are particularly susceptible to hypoxia due to elevated levels of fetal hemoglobin (HbF), resulting in diminished oxygen delivery at the tissue level despite having higher overall hemoglobin levels [71]. Overall, these significant developmental differences make neonates and infants more vulnerable to cardiovascular challenges compared to older children and adults [68].

Chapter 3

Challenges in Pediatric MRI

In this chapter we are going to discuss the challenges with a standard MRI in the pediatric department. These challenges include anatomic differences, sedation, heating, acoustic noise, scan time and the psychological aspects.

3.1 Challenges Associated with Brain and Chest Anatomy

When it comes to performing MRI scans of children at different stages in their life, the brain and chest development they are undergoing can lead to challenges, particularly in terms of image quality and execution.

3.1.1 Brain

Pediatric brain MRI poses significant challenges due to the rapid changes in structure, metabolism, and function in the developing brain. These challenges vary depending on the age of the patient. The pediatric brain are different structurally and chemically from the adult brain, evolving rapidly during growth and development. Obtaining clear images is difficult, particularly in premature neonates and fetuses, due to their small brain sizes and high water content [72]. As the brain grows before birth, it forms grooves on its surface called sulci [73]. These grooves develop quickly from early pregnancy to birth, which can make it tricky to interpret images of the brain. Additionally, myelination—the coating of axons with myelin alters the MRI signal characteristics, affecting image contrast and segmentation. Myelin, composed of fats and proteins, acts as insulation around nerve fibers, enhancing electrical conductivity and signal transmission [74]. Motion artifacts from the neonate's head movement further hinder image quality. These challenges underscore the need for specialized techniques and protocols to effectively perform pediatric MRI [75].

MR images of infant brains typically exhibit reduced tissue contrast (especially around 6 months of age), substantial intensity variations within tissues, and dynamic, regionally diverse changes, which differ from adult brain MR images. Consequently, existing computational tools primarily tailored for adult brains are not suitable for processing infant brain MR images [75].

3.1.2 Chest

Pediatric chest MRI presents notable hurdles, especially in achieving clear images of the lungs and airways [76].

Challenges arise from prolonged scan times, the naturally low proton density of lung tissue, and issues with patient motion. Normal lung tissue typically generates low signal, while abnormalities often manifest as increased signal, complicating diagnosis [76]. Challenges arise in pediatric MRI due to patient motion and respiration. Children aged 3 months to 6 years often cannot cooperate or hold their breath, necessitating deep sedation or general anesthesia for successful imaging [77].

Successful MRI scans hinge on patient cooperation, yet children may struggle with prolonged breath-holding and remaining still during quiet breathing. Younger children pose an added challenge due to their faster heart and breathing rates, which can cause blurring in images. Therefore, correct and precise patient preparation and specialized techniques are essential to overcome these obstacles and ensure optimal pediatric chest MRI results [76].

3.2 Sedation and Anesthesia

This section will be a discussion on the use of anaesthesia and sedation for children when undergoing an MRI examination. Sedation is a prescribed medication that depresses the central nervous system, resulting in decreased awareness and responsiveness to external stimuli, inducing a relaxed state. General anesthesia is a carefully managed and reversible state of unconsciousness [78].

3.2.1 Sedation and anesthesia on children

The use of sedation and general anesthesia has increased in pediatric MRI [79], contributing to the significant growth in MRI utilization among children [78]. Initially, moderate sedation is considered, but if the child is uncooperative, deeper sedation may be necessary. This deeper sedation often involves combinations of medications such as midazolam, fentanyl, and ketamine. However, caution must be exercised due to the risk of complications such as laryngospasm and hypoxia, even with careful administration [80]. Additionally, recovery from deeper sedation is often prolonged, and the use of reversal agents such as naloxone and flumazenil may be required [81].

Anesthesia, preferred by anesthetists, is considered safer during procedures compared to sedation. Despite being perceived as expensive by endoscopes due to the need for specialized personnel, the use of short-acting agents like propofol [81] and sevoflurane can reduce costs by shortening recovery times. Sevoflurane has been effectively administered to neonates and infants, with the maximum vaporizer setting reaching 4 vol for MRI imaging [82].

Anesthesia also avoids the financial burden associated with sedation failure. Additionally, anesthesia reduces colonic tone, potentially making deep sedation safer during procedures like colonoscopy where bowel distension can cause pain and serve as an indicator of colonic perforation [83].

A recent study by Vanderby et al. (2010)[84] indicates that the expenses for additional time and human resources required for sedation or anesthesia during pediatric MRI procedures are 3.24 and 9.56 times greater, respectively, compared to studies involving awake pediatric populations.

In a study by Hertzog et al.(2019) [85] allergic reactions to sedation were tested. The study aimed to determine the incidence and characteristics of allergic and anaphylactic during pediatric procedural sedation outside the operating room using data from the Pediatric Research Consortium (PSRC). Out of 227,833 cases in the database, 54 allergic reactions occurred, with 6 cases consistent with anaphylaxis. The study identified a significant association between allergic reactions and the use of midazolam, ketamine, methohexital, and morphine. No fatalities were reported. This is considered a short-term risk.

Sedation and general anesthesia are generally considered safe, particularly in institutions with established sedation services, but there is still a notable risk of mild to moderate adverse events during administration [79]. Additionally, there are concerns about potential long-term effects on neurodevelopmental outcomes following anesthetic exposure, highlighted by recent preclinical and retrospective clinical data [86]. However, extended or repeated exposure to anesthesia may yield some unfavorable effects [87]. The influence of general anesthesia on various developmental domains varies across different age groups.

Serious side effects and allergic reactions from anesthesia are uncommon. Following sedation or general anesthesia, patients may experience mild and brief side effects such as nausea, vomiting, dizziness, headache, sore throat, blood pressure changes, or pain, which are typically treatable. In some cases, children may not achieve sufficient sedation, necessitating rescheduling with general anesthesia. While more severe complications are rare, they are more likely in patients with complex medical conditions [88].

3.3 Coil Size

Pediatric MRI is performed with coils designed and built for adults and therefore will not fit the small body of a pediatric patient [89]. These coils are heavy, inflexible, and can cause discomfort and poor image quality in awake children. Additionally, the wide variation in patient sizes can result in poorly fitting commercially available coils and less than ideal coil choices

[90]. Coils designed to effectively interface with the patients anatomy play a big role in getting the wanted data and image [90].

The size of the head and brain of pediatric patients are relatively smaller compared to adults. Smaller brain structures require higher spatial resolution, which entails a decrease in sensitivity due to the smaller voxel size. Voxel size is a 3D analog of a pixel and plays a big role in the image quality [91].

The compact size of an infant's head, coupled with the brain's proximity to the surface, makes close-fitting arrays of multiple small elements ideal for imaging young children [92].

These excessively large arrays also compromise image quality. This is due to the inadequate anatomical fit, which increases the distance between the receiving elements and the targeted anatomy, resulting in diminished coil sensitivity [93].

To show the difference in size a visual representation of Head-Spine coils especially designed for an adult patient in **Figure 3.1A** versus a pediatric patient in **Figure 3.1B** are presented. This illustrates the significant disparity in coil size designed for pediatric versus adult use.

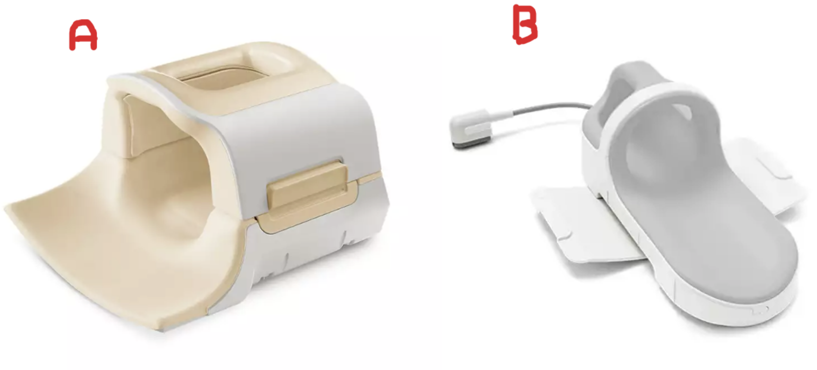

Figure 3.1: **A**:Head-Spine coil designed for an average adult. **B**: Head-Spine coil design for a pediatric patient weighting up to 10 kilograms. llustration is taken from [94] with permission.

Philips [94] designed a pediatric neurospine coils for pediatric neuro and spine imaging. It is optimized for neonates and designed for pediatric patients weighing up to 10 kilograms. An illustration of the coil are shown in **Figure 3.1 B**.

Research done at Stanford university is making MRI better for children [95]. They have developed innovative solutions collaborating with engineers from UC-Berkeley, and designed new methods for creating highly and flexible MRI receiving coils specifically tailored for children's bodies. Standard coils are larger than necessary for children, and create bad image quality due to increased noise. Child-sized receiver coils improve image clarity and reduce scan times. These smaller coils also significantly enhance the performance of PET-MR hybrid imaging technology. It is used as Packard Children's Hospital, and are being developed for commercial use [95].

3.4 Heating and SAR Levels

Specific Absorption Rate (SAR) poses a greater concern for pediatric patients than adults undergoing an MRI examination, due to differences in anatomical size and tissue composition [96]. SAR is the amount of RF energy absorbed per unit of time by the body(W/kg), which means SAR quantifies the risk of heating in the patient's tissue resulting from the application of RF energy to generate the MR signal [97].

In addition to being smaller in size, infants and children have higher tissue water content compared to adults. This difference may impact the dielectric and thermal properties relevant for them, as current data are primarily based on adult measurements [96].

Temperature increases in children due to RF energy application are influenced by their immature physiological systems and morphological disparities compared to adults, alongside uncertainties in tissue thermal properties. Unlike adults, children have lower sweating rates per gland, affecting their thermoregulation [98][99]. Pediatric patients exhibit greater cutaneous vasodilation and skin blood flow relative to adults, enhancing their ability for dry heat loss [100]. Despite having a higher ratio of total blood volume to body mass, children have smaller absolute blood volumes, which increases the potential for their blood temperature to rise during RF exposure, especially in smaller children [101].

In a study by Malik et al.(2022) [101] of SAR rate [102] in neonates undergoing MRI procedures at 1.5T and 3T using a RF transmit coil model and Voxel models. The RF transmit coil model was a generic birdcage transmit coil, mostly used in 1.5T and 3T MRI systems. The coil, designed with a circular band-pass structure consisting of 16 rungs and measuring 0.6m in diameter with a 0.4m end-to-end spacing, was enclosed within a cylindrical metal shield. This shield, 1.0m in length and 1mm thick, had an internal diameter of 0.678m. Tuned to either 128MHz (3T) or 64MHz (1.5T) and operated in quadrature, the coil's metallic components were assumed to have the conductivity of copper($5.997 * 107m^{-1}$).

Voxel models representing neonates at term equivalent age (40 weeks gestational age) were derived from an existing model of a deceased eight-week-old female infant weighing 4.2 kg and measuring 57 cm in length. The voxel models were reduced in size by 10% in all dimensions to simulate a neonate, named "Baby A," weighing 3.02 kg and measuring 51.3 cm in length [96].

The SAR predictions for a magnetic flux density of 1 μT, with a duty cycle of 100%, and under realistic operating conditions where found in this study. In the heart-centered baby model, where the infant is fully exposed to RF fields, partial body SAR and whole body SAR are equivalent. However, in the head-centered baby model (with 83% exposure), partial body SAR slightly exceeded whole body SAR at 0.4 W kg1. Minimal discrepancies were observed in SAR predictions for heart-centered models, even with the introduction of a TPN feed line or a conductive medium between the heels, resulting in changes of less than 5% in the quoted SAR values. The heart-centered case displayed a larger whole-body averaged SAR, while the head-centered case exhibited greater head-averaged SAR, consistent with their respective positions [101].

3.5 Gradient Acoustic Noise

The presence of gradient acoustic noise in MRI poses significant challenges to both patients, but especially pediatric patients which is more sensitive to sound[103]. The operation of gradient coils within MRI scanners involves the generation of large Lorentz forces due to the rapid switching of electrical currents amidst the static magnetic field B_0. These forces induce vibrations in the coil conductors, emitting acoustic pressure waves and sound radiation into the surrounding environment [104]. The resulting acoustic noise pattern varies depending on the specific gradient form utilized in each pulse sequence. The sound pressure levels (SPL) produced by these gradient coils can often exceed safety limits established by organizations like the National Institute of Occupational Safety and Health, typically set at 85 dB [105].

Exposure to such elevated noise levels can lead to patient discomfort, anxiety, and in some cases, temporary hearing loss, necessitating the provision of hearing protection for patients and operators alike [106]. Acoustic noise presents a significant concern in neonatal MRI, as it has the potential to induce autonomic instability in both full-term and preterm neonates [107]. Elevated sound pressure levels are believed to negatively impact the growth and neurological development of both term and preterm infants, through both direct and indirect pathways [108]. Heightened SPLs have been known to cause undesirable effects such as spectral line shape distortions, anti symmetrical side bands, and signal loss. The human sensitivity to sound initiates at 0 dB, with discomfort or pain often experienced beyond 120–140 dB. Typical conversation levels fall between 50–60 dBA. During clinical 1.5-T MRI exams, sound pressure levels typically range from 81–117 dB [109][106]. Background noise levels surpassing 60 dB impede infants' ability to differentiate between voices, language, music, and other meaningful environmental sounds amid background noise [106].

Still there are no regulatory guidelines for the sound pressure level for neonates, although it can have a big impact on their hearing and development [110]. Passive hearing protection is commonly integrated into neonatal noise reduction protocols, primarily aimed at promoting sound sleep. Foam earplugs and soft-shell earmuffs are the prevailing passive noise reduction devices used during neonatal MRI exams. Due to the unavailability of infant-sized earplugs, adult earplugs are frequently used instead [111].

3.6 Scan Time and Subject Cooperation

The scan time of an MRI examination varies from 15-90 minutes, depending on the number of images needed and the size of the area intended for imaging [112]. Given the significant impact of the area intended for imaging on scan time, shorter scan times in pediatric cases due to their smaller body size should be achievable.

The duration of scanning in any pulse sequence is determined by three key factors: the repetition time (TR), the number of excitation's for phase-encoding (NEX), and the number of signals averaged (NSA) [113]. Repetition Time is the amount of time between successive pulse sequences applied to the same slice [114], while NEX and NSA are measurement parameters used to show how many times each set of data is collected. They're mainly used to boost the SNR [115].

The TR affects the image contrast. Long TR functional imaging experiments offer several advantages: they yield raw images with maximum SNR, enable collection from numerous slice locations, and reduce the size of acquired data sets, streamlining storage and handling. Conversely, shorter TR acquisitions (around 1000 ms) enhance discrimination between activated and non-activated brain tissue regions compared to long TR acquisitions [116].

A successful MRI exam depend entirely on the child‘s cooperation. To achieve good images, it is important for them to remain completely still. For the long scan time this can be very hard. Children find it difficult to remain still during a 45-minute MRI scan due to different reasons [117]. Children's natural energy levels and shorter attention spans make it challenging to stay still for an extended period. Also the enclosed space of the MRI machine can induce feelings of claustrophobia and anxiety, particularly for young children who may not fully comprehend the procedure. The loud noises produced by the MRI machine can be frightening and overwhelming, exacerbating their discomfort and prompting them to fidget or move. Physical discomfort or sensory sensitivities, such as discomfort from the hard MRI table or sensitivity to certain sensations, can further contribute to restlessness. Overall, a combination of factors, including high energy levels, anxiety, discomfort, and sensory issues, makes it challenging for children to maintain stillness throughout the duration of an MRI scan [118].

3.7 The Psychological Aspects

Despite that MRI is a noninvasive and painless nature, it is frequently linked to patient stress and anxiety. This can impact their overall experience and potentially lead to negative outcomes [119].

A few studies have examined children's fear and discomfort during research MRI, but clinical MRI experiences generally indicate low levels of discomfort, with over 98% of children reporting no or minimal discomfort [120].

MRI environments pose psychological risks to patients, including transient feat and panic than can lead to prematurely terminated scans. Long-term effects, such as changes in claustrophobic feelings, have been observed during MRI scans. There are more data on psychological risks from adult patients, than pediatrics. Risks for children are less explored, except for a few studies, and may differ due to their limited understanding of the environment and reduced ability to communicate during the scan [121].

In a study by Malisza et al.(2010) [121] , seven children aged 2 to 7 participated. They studied the simulating MRI environment to gauge their fear levels. Thirty-seven children completed the process. Although there was not a significant correlation between age and completion success, older children (6-7 years) were more likely to complete all steps compared to the younger ones. Specifically, 67% of older children completed all steps compared to 26% of younger ones. These findings suggests that failure rates of at least 50% should be considered in study designs involving young children (2-7 years), alongside factors like motion and other experimental variables.

The study aimed willingness and comfort levels as dependent actions. Willingness was determined by the children's progression through an eight-step series mirroring typical patients behavior during MRI scans. Comfort level was measured using a 5-point self-report scale, ranging from no fear/anxiety to strong dislike or fear. The participants indicated their comfort level by pointing to a corresponding face on a printed card from 1 which is very good to 5 which is the highest discomfort [121].

Chapter 4

Current and Future Solutions

In this chapter, we will discuss some of the problems we mentioned in Chapter 3 on how scan time in MRI can be optimized, by optimizing MRI scan parameters and accelerating data acquisition. Additionally, we will get into the rising significance of psychological factors, which play a vital role in minimizing the need for sedation and anesthesia.

4.1 Reducing Scan Time

In this section, we will explore various methods to shorten the scan time. By reducing the scan time, we can decrease the need for sedation, enhance children's ability to remain still, and ultimately improve image quality [122].

MRI scans are crucial for diagnoses, but their lengthy duration and costs limit accessibility. Shortening scan times would lower expenses and increase the number of available MRI exams, broadening diagnostic capabilities [123].

4.1.1 Optimize MRI Scan Parameters

To minimize the duration of the scan, optimizing various parameters such as the Field of View (FOV) and expediting data acquisition can be implemented.

FOV and Oversampling

The Field of View (FOV) phase approach captures a distinct scanned area in the phase encoding directions, implying data collection with fewer measurement lines and consequently, shorter scan times.

Changing the FOV, phase, and phase oversampling can have a big impact on the scan time. The MRI's FOV specifies the exact part of the patient's body that will be included in the image. All Cartesian imaging sequences are constrained by the quantity of phase encoding lines needed to encompass a specific FOV at a given image resolution [124]. Due to the smaller size of pediatric patients, the required FOV may not need to be as large as that for adult patients [124].

A study conducted at the Department of Radiology from Erbil teaching hospital, Erbil, Iraq(2018) [123] worked with changing the FOV, phase and phase oversampling. Initially, the scan took 3.47 minutes with a 230mm FOV, 90% FOV phase, and 0% phase oversampling. However, with a updated protocol with FOV of 217 mm, 93.98% phase and oversampling of 13.96% the scan time can be reduced to 2.18 minutes [123].

4.1.2 Accelerate Data Acquisition

Accelerating data acquisition techniques in MRI are gaining traction for their ability to shorten scan times while preserving diagnostic quality for pediatric patients.

Compressed Sensing Reconstruction

Compressed sensing [125], an advanced method to speed up MRI scans, reconstructs images from partially filled data in a random manner. This reconstruction process involves turning raw MRI data into visual representations that doctors use to understand what's happening inside the body [126].

Instead of full sampling, compress sensing methods employ sparse sampling to reduce scanning time. Sparse sampling enables faster data acquisition significantly compared to traditional methods [127].

Compressed sensing has proven beneficial for pediatric neuroimaging, with applications including head and neck angiography, among other established uses in neuro MRI [128][93].

Meister et al.(2022) [129], found that implementing compressed sensing for pediatric brain tumor imaging resulted in markedly shorter examination duration, decreased SAR, and improved image quality. Another study by Shankar et al.(2019) [130] demonstrated that compressed sensing MR spectroscopic imaging decreased scan duration by 80%.

Parallel Imaging

Parallel imaging is a method used for accelerating the collection of MRI data, opening up new possibilities in MRI applications to generate the image and reduce scan time [131].

This technique involves capturing a smaller amount of data using an array of receiver coils, which helps in faster data collection. However, this reduced data collection can lead to aliased images due to under-sampling. To counteract this, reconstruction methods are used to create clear images without artifacts. The clinical advantages of parallel imaging include quicker image acquisition, which helps in reducing issues related to patient motion. Shortening imaging times in MRI is linked to the acceleration factor. This factor compares the amount of data collected in fully sampled images to that in faster, accelerated acquisitions [132].

Parallel imaging refers to a set of MRI techniques that help eliminate aliasing artifacts that occur when MRI scans don't sample enough data points in certain directions during image acquisition [133]. In parallel imaging mode, each receiver element measures and processes the signal from the nearest tissue portion to it [134]. Since each receiver has its unique position and sensitivity, parallel imaging capitalizes on spatial signal localization to speed up scanning while maintaining image quality and minimizing artifacts [135].

All reconstruction methods offer comparable image quality and time efficiency. They are commonly utilized in clinical settings to reconstruct images from under-sampled data obtained via parallel imaging techniques [135].

SMS Imaging

Simultaneous Multi Slice (SMS) imaging [136], works by using a special radiofrequency pulse to excite protons in different areas all at once during a single scanning sequence. This implies gathering signals from these areas in a single go, expediting the imaging process [136].

To ensure clear images, it's necessary to implement additional steps to address the overlap between different areas undergoing scanning. Typically, a combination of coil encoding (similar to parallel imaging) along with either radiofrequency pulse encoding or gradient encoding is employed to address this issue [137]. These techniques help move the overlapped parts of the image in a specific direction [138]. The time required for imaging using SMS decreases as multiple images of different sections are taken simultaneously [139][140].

A lot of researchers have successfully made the imaging time go down with SMS. For instance, Longo et al.(2017) [141] showed that by combining parallel imaging and SMS together, the time needed for a lumbar spine MRI was significantly cut down. The new method only took 5 minutes and 28 seconds, while the standard one took 16 minutes and 30 seconds. And, importantly, the quality of the images didn't suffer [141]. An example from this study is shown in **Figure 4.1**.

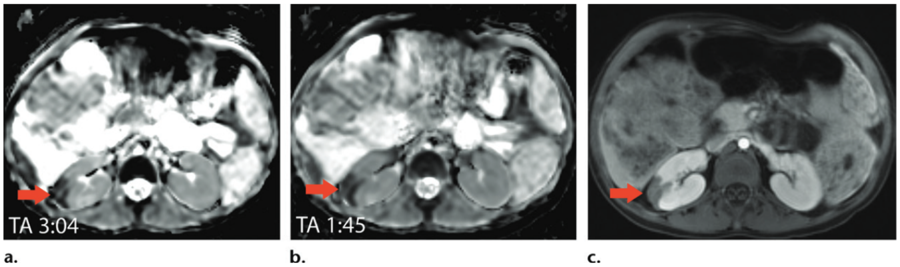

Figure 4.1: Reduced acquisition time without image degradation was achieves using SMS imaging in a 5 year-old girl with tuberous sclerosis. **Figure a and b**: Axial DWI apparent diffusion coefficient maps of the abdomen, acquired without SMS. **Figure a**: SMS with an acceleration factor of two. **Figure b**: shows similar image quality but reduced acquisition time (TA) in the SMS image. A hypointense lesion in the rights kidney (arrow) in **Figure c** An axial contrast-enhanced T1-weighted MR image of the abdomen demonstrates heterogeneous mild enhancement in this lesion (arrow). Illustration is taken from [84] with permission

4.2 Solutions for Psychological Aspects of Children MRI

Coping with the psychological challenges inherent in pediatric MRI procedures requires innovative solutions to ensure patient comfort and cooperation. Children often experience challenges during the examination process. This section explores strategies to alleviate anxiety and enhance pediatric patient experience during MRI scans [142].

4.2.1 Preparation Method and Examination Room

For specific younger children, familiarizing them with the MRI environment through simulated scanning can prove advantageous [143]. Simulated scanning aims to alleviate anxiety during actual scanning sessions. Complete with realistic lights and sounds mirroring those of a real MRI scan , it proves particularly beneficial for individuals with high anxiety or claustrophobia. [144].

For specific demographics, particularly younger children, familiarizing them with the MRI environment through simulated scanning can be beneficial. Research conducted by Rosenberg et al.(1997) [145] showed that children who underwent simulation before scanning reported reduced distress levels and exhibited lower heart rates compared to those who did not undergo simulation. Simulators can vary greatly in design, with some incorporating "child-friendly" facades for both real and mock scanners to enhance comfort and diminish the clinical atmosphere of the environment. An illustration of a child-friendly MRI simulator is provided in **Figure 4.2**. The inclusion of stars is intended to induce a sense of calmness and relaxation in the child, thereby mitigating negative feelings [72].

Figure 4.2: The figure shows a child-friendly simulator. Over the past decade, Vasanawala and his team (2018) [146] have dedicated themselves to crafting tailored MRI solutions for pediatric patients. Their efforts encompass the design of equipment specifically sized for children, alongside enhancements in MRI signal processing software. This innovation not only accelerates examination times but also diminishes risks associated with MRI procedures for children. Additionally, the tailored approach ensures a more comfortable experience for pediatric patients undergoing MRI scans. Illustration is taken from [146] with permission.

For children experiencing claustrophobia or anxiety, discussing options like sedation with their pediatrician is essential. Those who have been recently ill may consider rescheduling their MRI, for an optimal experience. Moreover, in the case of younger children, pediatricians may explore the availability of a child life specialist to facilitate maintaining calm and stillness during the examination without resorting to sedation [147]. MRI training and preparation prior the scans can serve as viable alternatives to sedation for pediatric MRI exams. Fries et al.(2020) [148], investigated non-sedation approaches for pediatric MRI exams, focusing on children diagnosed with brain tumors. The study evaluates the effectiveness of an MRI training program and its impact on patient well-being. Among the 87 patients who participated the training, 81% successfully underwent MRI without the need for sedation. This marked a significant increase compared to children who did not undergo the training. Notably, neuropsychological factors such as memory and attention played a role in determining the success of the scans [148].

Memory can significantly shape attention. Merely encountering a picture or a set of shapes before can guide where visual attention is focused, thereby boosting perceptual sensitivity. Compelling evidence suggests that hippocampal memory can direct attention. The hippocampal memory system swiftly encodes episodic memories, which are adaptable and abound in contextual intricacies [148].

The study concludes that MRI training holds promise as an alternative to sedation, however, it underscores the importance of tailored interventions and interdisciplinary collaboration to address individual psychological needs [148].

Numerous studies explore different preparation methods for MRI exams, aiming to enhance the overall scanning experience, especially for children. One such approach, ANMTE [143] (Appropriate Number of children, appropriate Learning Methods, appropriate adaptive Training, and appropriate Encouragement), involves training groups of four children simultaneously.

This novel method was assessed in a study involving 150 children aged 3-6 who underwent MRI at the Army Medical Center from 2019 to 2023. Excluding conditions like cerebral palsy, mental disability, head trauma, and postoperative evaluation, participants were divided into three groups:

routine preparation, sedative, and ANMTE. Results from 150 participants across different preparation methods demonstrate ANMTEs success rate of 88%, comparable to sedation, and superior to routine preparation. Additionally, ANMTE ensures image quality and efficiency without the need for sedatives, making it a promising approach for pediatric MRI [143].

4.2.2 Virtual Reality

Virtual Reality (VR) technology aims in calming nerves and alleviating anxiety. The MRI scan's loud, oppressive, and intimidating atmosphere can be overwhelming, particularly for younger patients. Movement caused by discomfort or distress during the scan can adversely affect image quality [149]. Philips has invented a new VR technology (**Figure 4.3**) , to make the MRI experience safer for the children. The equipment is for reducing noise, and relaxing the body without sedation or anesthesia.

Figure 4.3: Philips have developed a VR in-bore experience for MRI patients. Patients customize their experience by choosing a video theme. The video is projected onto the wall and can be viewed from inside the bore using a conveniently adjustable mirror. With accompanying sound delivered through comfortable headphones, the experience becomes fully immersive. Illustration taken from [150] with permission.

Using VR during MRI has emerged as a potential solution for pediatric MRI, with the aim of reducing anxiety during MRI exams. In a study by Liszio and Masuch (2017) [151], a playful VR application designed for children aged 8 to 15 years old was introduced. This study aimed to alleviate anxiety and avoid the need for sedation. Their approach involves using a realistic virtual MRI scanner to familiarize children with the MRI experience using VR. They adopted a child-centered design process, which included expert interviews and iterative development. The research article concentrates on group testing to refine prototypes of the VR application [152].

In another VR study, by Ashmore et al.(2018) [153] they developed an app and supporting materials with panoramic 360-degree videos of the MRI journey. Evaluation through a clinical audit involving 23 patients aged 4 to 12 years, along with feedback from 10 staff members, showed high ratings for enjoyment, helpfulness, and ease of use. Patients reported feeling more positive about their MRI experience, while staff believed the resource could help avoid awake MRI procedures under general anesthesia, with successful outcomes observed in most cases [153].

In the discussion part of the article it is written about how feedback from experienced practitioners on a VR tool designed to prepare pediatric patients for MRI exams was positive. With this indicating its potential benefits in clinical practice [154]. Despite limited prior use of VR, participants perceived the tool as realistic and useful for patient preparation. They suggested improvements, such as adjusting the scan table speed and introducing avatars to enhance realism. While some participants experienced cybersickness symptoms, overall usability ratings were high. Participants highlighted the importance of patient preparation and practitioner-patient relationships, suggesting VR could enhance both. Additionally, they noted potential benefits for operational efficiency and staff training. Although concerns over cost and clinical efficacy exist, the increasing affordability and familiarity with VR technology may mitigate these barriers [152].

4.2.3 Communication during MRI scan

A Patient-Centered Care (PCC) approach emphasizes collaboration between patients, healthcare professionals, and the system to design care journeys that align with the patients goals, values, and constraints. PCC ensures that patients preferences drive care decisions, promoting meaningful outcomes through shared decision making and goal setting [155].

A PCC, includes structure foundational elements, such as healthcare system, resources, and organizational characteristics. Process involves patient-provider interaction during care delivery. Outcomes demonstrate the value of PCC, focusing on interactions among the healthcare system, providers, and patients [156].

A research article by Castro et al.(2023) [157] aims to investigate the impact of PCC on anesthesia use during MRI exams in children aged 4 to 10 years.

Thirty children underwent PCC and simulated the MRI exam using a toy, while another 30 received standard information and simulated the exam. Anesthesia use was compared with a control group of 30 children who received only routine information. Anxiety was assessed through self-reporting and heart rate monitoring, while satisfaction was evaluated through various questions. Group comparisons and regression analyses were conducted [157].

In the PCC + simulation group, only 7% of children required sedation, compared to 47% in the simulation group and 70% in the control group. Anxiety reduction was significantly greater in the PCC + simulation group with higher satisfaction levels. Decreased anxiety was associated with reduced anesthesia use [157].

PCC combined with simulation was more effective in reducing children's anxiety, increasing satisfaction, and minimizing anesthesia use during MRI exams compared to simulation alone and routine practices [157].

4.2.4 Pediatric MRI Using Sedation and Anesthesia

For optimal sedation and anesthesia in children undergoing MRI, the anesthesia team must understand MRI-specific safety concerns and the need for high-quality images. Continuous improvements, including the exploration of new drugs, are essential for enhancing quality and cost-effectiveness in pediatric sedation and anesthesia [82].

In a study by Håkansson et al.(2024) [158] of 27 consecutive standard brain examinations, there were used sedation and anesthesia involving 15 children undergoing sedation, and 12 undergoing anesthesia. The study involved, children aged between six months and five years, and they underwent MRI examinations. Motion artifacts typically are a concern in children under the age of 6. Sedation or anesthesia was commonly used to mitigate these artifacts. However, regardless of the method uses, all examinations yielded useful image quality. While all examinations were related as very good or excellent by radiologists, fewer motion artifacts were observed with sedation compared to anesthesia, which aligns with previous resource indicating improved image quality with sedation in over 70% of cases. Notably, in this study, a 100% success rate was achieved, contrasting with reported fail rates due to staff inexperience [**?**].

The cost difference between sedation and anesthesia is significant, primarily due to the additional expenses associated with anesthesia staff. Sedation, administered by radiographers, proved to be significantly less expensive, even with the need for an extra radiographer on site. Administering sedation extends the scope of practice for radiographers, necessitating new knowledge and skills, such as intranasal administration. This training, overseen by anesthesia specialists, led to shorter examination times, reduced hospital stays for children, and decreased examination costs compared to general anesthesia [**?**].

Unlike anesthesia, which requires fasting and poses risks of hypoglycemia and discomfort, sedation allows normal eating and drinking before the procedure. Sedation mimics natural sleep, maintains a clear airway, and is minimally invasive, with only minor reported side effects. However, careful consideration of patient history is crucial to avoid complications. While intranasal sedation may take longer to take effect compared to intravenous administration, it minimizes anxiety and eliminates the need for peripheral venous catheters, which can be distressing for children. Anesthesia offers faster onset and shorter half-life but entails higher costs and risks [**?**].

Sedation, particularly intranasal sedation administered by radiographers, provides image quality comparable to anesthesia while offering economic benefits, faster examinations, and increased safety for children [**?**].

Sedative and anesthesia drugs commonly used in children's MRI scans, lack approval from regulatory agencies like the Ministry and Drug safety(MFDS) for specific age groups. This doesn't mean these drugs cannot be used but rather indicates a lack of research by pharmaceutical companies for approval. Off-label use of such drugs in pediatric sedation has increased, prompting legislative changes to improve drug labeling for safer sedation in children [82].

Chapter 5

Conclusion

In this thesis our focus is to explore challenges and solutions for pediatric MRI. In conclusion, the research of MRI technology in pediatric imaging has opportunities within this specialized field. As outlined in this thesis, MRI is the main diagnostic imaging, with its invaluable insights into the health and well-being of pediatric patients. However, the application of MRI in pediatric settings presents challenges that require careful consideration and innovative solutions.

Throughout this study, we have gotten into the various factors influencing pediatric MRI, including clinical efficacy, psychological implications, and scanning protocols. By examining these complexities, we have gained a deeper understanding of the challenges that clinicians and researchers face in ensuring the optimal use of MRI technology for pediatric patients.

Moving forward, it is important that addressing these challenges is to enhance the efficacy and accessibility of pediatric MRI. Whether it be through advancements in imaging techniques, improvements in patient comfort, experience, new developments in VR, or the development of tailored protocols for pediatric populations, there is a clear need for ongoing innovation and collaboration within the field.

As we continue, it is our hope that the information from this research will inspire Scientists, Researchers and Engineers to make positive changes the

MRI pediatric apartment. By getting deeper into the understanding of the challenges and solutions in pediatric MRI, we can move towards a future where every child receives the best care and diagnosis.

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