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SAFE AND SOUND

Managing acoustic noise, gradient field applications, and static magnetic field exposure in MR – A radiography perspective

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To my beautiful wife and our wonderful children. This thesis is a testament to your unwavering faith in me. With all my love, I dedicate this work to you.

[*Remember, no one can hear you cry in k-space*]
- Collegial proverb at Örnsköldsvik's MR unit

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Abstract

Background: During magnetic resonance imaging (MRI), the interaction between the alternating currents of the gradient coil and the static magnetic field (SMF) generates vibrational forces, perceived as loud acoustic noise. The sound pressure levels (SPLs) are high enough to cause hearing damage, necessitating hearing protection for anyone in the scanner room. To address this, technological advancements have introduced acoustic noise reduction (ANR) software that can alter the gradient currents, resulting in lower vibrational forces and quieter scans. However, such alterations might decrease image quality and prolong scan times. Therefore, it is crucial to evaluate different ANR software to understand their specific utilities and limitations. Additionally, it remains unclear whether, when, and how such software is being utilized clinically, and how MR personnel manage acoustic noise overall. Furthermore, exposure to the SMF within the scanner vicinity can induce transient adverse health effects, such as vertigo, dizziness, nausea, headaches, drowsiness, and metallic taste. However, the evidence is inconclusive regarding the regularity of symptoms, and control groups are needed to account for environmental confounders. Insights into the management of acoustic noise, gradient field applications, and SMF exposure may assist in making MRI both safer and quieter, thereby improving the MR work environment, patient comfort, and the overall clinical experience.

Aim: The overall aim of this thesis was to present a radiography perspective on acoustic noise management, gradient field applications and SMF exposure in MR.

Methods: This thesis encompasses four studies. In Study I, we explored health complaints subjectively associated with SMF and acoustic noise exposure, including symptom prevalence and attribution over the last year. Data were extracted from a nationally distributed cross-sectional survey answered by MR radiographers and CT radiographers (the latter used as controls; CT, computed tomography) across Sweden. In total, data from 529 participants were included and analyzed both descriptively and analytically using logistic regression. In Study II, we conducted 15 individual semi-structured interviews with MR radiographers across Sweden, to explore how they manage acoustic noise in clinical MR settings. The interviews were analyzed thematically. Studies III and IV were both experimental studies that compared ANR software to conventional (non-ANR) imaging. Study III evaluated T2-weighted turbo spin echo (T2W TSE) during lumbar MRI at 1.5 Tesla (T)

using two different ANR software – Whisper Mode (WM) and Quiet Suite (QS). In Study IV, we evaluated T2W fast spin echo (FSE) and three-dimensional T1-weighted turbo field echo (3D T1W TFE) during brain MRI at 7 T using the ANR software SofTone. In both Studies III and IV, peak SPLs, perceived noise levels, image quality, and inter-observer agreements between radiologists were compared. In Study III we also measured switched gradient field exposure and gradient currents. Study III included 40 patients, and Study IV 28 healthy volunteers. Data were analyzed using repeated measures analysis of variance (ANOVA), Friedman's ANOVA, and Wilcoxon's signed-rank test in Study III. In Study IV, we used paired t-test and Wilcoxon's signed-rank test. Inter-observer agreement between radiologists' assessments of image quality was reported in percentage agreement for both studies, with Krippendorff's alpha also calculated in Study IV.

Results: In Study I, no significant differences in symptom prevalence were seen between the radiographers who work in MR and those in CT. However, working at ≥3 T doubled the risk of SMF-associated symptoms as compared to working at ≤1.5 T. Stress was a significant confounder of symptoms. Work-related acoustic noise was rated as more troublesome by CT than MR radiographers. Study II yielded three main themes on how MR radiographers manage acoustic noise: (I) *Navigating Occupational Noise: Risk Management and Adaptation*; (II) *Protecting the Patient and Serving the Exam*, and (III) *Establishing a Safe Healthcare Environment with Organizational Support*. Compared to conventional imaging, software-based ANR reduced the peak SPLs by 72% and 84% with WM and QS, respectively (Study III), and by 89% (T2W FSE) and 92% (3D T1W TFE) using SofTone (Study IV). In both Studies III and IV, all ANR sequences were perceived as being significantly quieter than their conventional counterparts. Furthermore, all sequences remained diagnostic, although qualitative assessment scores differed slightly for 3D T1W TFE. Switched gradient field exposure was reduced by 48% and 66% using WM and QS, respectively.

Conclusion: No significant differences in symptom prevalence were seen between MR and CT radiographers. However, working at 3 T increased the risk of SMF symptoms, and stress increased adverse health effects. Although noise was considered to be more troublesome by CT radiographers, this does not suggest that acoustic noise is not problematic in MR environments. MR radiographers demonstrate a willingness to adapt and employ measures to mitigate acoustic noise, thereby enhancing safety and comfort for both patients and personnel, all while striving to deliver diagnostic exams. However, they require

appropriate tools and support to do so, suggesting that organizations need to adopt more proactive, holistic approaches to safety initiatives. This thesis also evaluated software-based ANR for its functionality in clinical practice, and found that T2W TSE/FSE and 3D T1W TFE can maintain acceptable subjective image quality while considerably decreasing peak SPLs. This reduction in sound intensity provides both a safer, quieter, and (presumably) more comfortable scan environment.

Key words: magnetic resonance, MR safety, patient safety, occupational health, acoustic noise reduction, gradient field, static magnetic field, symptom, radiography, human factors and ergonomics.

Sammanfattning på svenska

Bakgrund: Vid magnetkameraundersökningar (MR, magnetisk resonans) skapar samspelet mellan växelströmmarna i gradientspolen och det statiska magnetfältet (SMF) vibrationskrafter som uppfattas som höga oljud. Ljudnivåerna är så pass höga att hörselskydd krävs för att undvika hörselskador under bildtagning. Modern mjukvara har utvecklats för att minska detta buller genom att ändra eller begränsa gradientströmmarna, men kan påverka bildkvaliteten negativt och förlänga scanningstiden. Genom att utvärdera olika bullerreducerande mjukvaror kan vi förstå deras specifika användningsområden och begränsningar. Dessutom är det oklart om, när och hur sådan mjukvara används kliniskt, eller hur MR-personal hanterar buller generellt. Exponering för SMF i närheten av magnetkameran kan även orsaka tillfälliga negativa hälsoeffekter som yrsel, illamående, huvudvärk, dåsighet och metallsmak. Hur ofta dessa symtom uppträder är inte helt klarlagt, och kontrollgrupper behövs för att ta hänsyn till påverkande omgivningsfaktorer. Ökad kunskap om hanteringen av buller, gradientfältsapplikationer och SMF-exponering kan bidra till att göra MR både säkrare och tystare, vilket förbättrar arbetsmiljön, patientkomforten och den övergripande kliniska upplevelsen.

Syfte: Det övergripande syftet med denna avhandling var att presentera ett radiografiskt perspektiv på hantering av buller, gradientfältsapplikationer och SMF-exponering vid MR.

Metod: Denna avhandling omfattar fyra studier. I Studie I undersökte vi förekomst av symtom och hälsobesvär som kopplats till SMF- och bullerexponering. Data hämtades från en nationellt utskickad tvärsnittsenkät besvarad av MR-röntgensjuksköterskor och CT-röntgensjuksköterskor (CT, datortomografi, användes som kontroller) runtom hela Sverige. Totalt inkluderades data från 529 deltagare och analyserades både beskrivande och med logistisk regression. I Studie II intervjuade vi 15 MR-röntgensjuksköterskor runtom Sverige för att undersöka hur de hanterar buller i kliniska MR-miljöer. Data analyserades med tematisk analys. Studie III och IV var båda experimentella och jämförde bildtagning med bullerreducerande mjukvara med konventionell (icke-bullerreducerande) MR-bildtagning. Studie III utvärderade två olika mjukvaror – Whisper Mode och Quiet Suite – under MR-ländrygg vid 1,5 Tesla (T). Studien inkluderade 40 patienter. I Studie IV utvärderades mjukvaran SofTone på två olika bildtagningssekvenser av MR-hjärna vid 7 T, och inkluderade 28 friska

frivilliga. I både Studie III och IV jämfördes ljudtrycksnivåer, upplevda bullernivåer, bildkvalitet samt överensstämmelse mellan bedömningar från röntgenläkare. I Studie III mätte vi också exponeringsnivåer från växlande gradientfält samt gradientströmmar.

Resultat: I Studie I sågs inga signifikanta skillnader i symtomförekomst mellan de röntgensjuksköterskor som arbetar inom MR och de inom CT, men stress var en tydligt påverkande faktor. Däremot dubblerades risken för SMF-symtom (yrsel, illamående, metallsmak, rörelseillusioner) vid arbete vid ≥3 T jämfört med arbete vid ≤1,5 T. Arbetsrelaterat buller skattades som mer besvärande av CT-röntgensjuksköterskor än av de vid MR. Studie II resulterade i tre huvudteman kring röntgensjuksköterskors hantering av buller i klinisk MR: (I) Navigera yrkesmässigt buller: riskhantering och anpassning; (II) Skydda patienten och genomföra undersökningen, och (III) Etablera en säker vårdmiljö med organisatoriskt stöd. Jämfört med konventionell MR-bildtagning minskade bullerreducerande mjukvaror ljudtrycksnivåerna med 72% (Whisper Mode) och 84% (Quiet Suite) i Studie III, och med 89–92% med SofTone i Studie IV. I både Studie III och IV upplevdes alla bullerreducerande sekvenser som betydligt tystare än deras konventionella motsvarigheter. Dessutom förblev alla bilder diagnostiska enligt röntgenläkarnas bedömningar. Exponeringen av växlande gradientfält minskade med 48% och 66% med Whisper Mode respektive Quiet Suite.

Slutsats: Inga signifikanta skillnader i symtomförekomst sågs mellan MR- och CT-röntgensjuksköterskor. Däremot ökade arbete vid 3 T risken för SMF-symtom, och stress ökade negativa hälsoeffekter. Även om buller ansågs vara mer besvärande av CT-personal, innebär detta inte att buller inte är problematiskt vid MR. MR-röntgensjuksköterskor visar en vilja att anpassa sig och vidta åtgärder för att minska buller, vilket ökar säkerheten och komforten för både patienter och personal, samtidigt som de strävar efter att leverera diagnostiska undersökningar. De behöver dock lämpliga verktyg och stöd för att göra detta, vilket tyder på att arbetsplatser med MR-enheter behöver anta mer proaktiva, helhetsbaserade tillvägagångssätt för säkerhetsinitiativ. Denna avhandling utvärderade också bullerreducerande mjukvaror för deras funktionalitet i klinisk praxis och fann att bildkvaliteten kan bibehållas diagnostiskt acceptabel samtidigt som bullernivåerna minskas avsevärt.

Nyckelord: magnetkamera, MRT, MR-säkerhet, patientsäkerhet, arbetsmiljöhälsa, buller, bullerreduktion, gradientfält, statiska magnetfält, symtom, radiografi, ergonomi och human factors.

Abbreviations

3D – three-dimensional
AI – artificial intelligence
ANR – acoustic noise reduction. In this thesis used in conjunction with “software-optimized ANR pulse sequences”, i.e., “quiet” pulse sequences
B_0 – main static magnetic field
CI95 – 95% confidence interval
CNR – contrast-to-noise ratio
CSF – cerebrospinal fluid
CT – computed tomography
dB – decibel
dBA – A-weighted decibel
dB/dt – a gradient field’s time rate of change
ESP – echo spacing
FDA – Food and Drug Administration
FOV – field of view
FSE – fast spin echo (synonymous with turbo spin echo)
HFE – human factors/ergonomics
ICNIRP – International Commission on Non-Ionizing Radiation Protection
ICU – intensive care unit
MR/MRI – magnetic resonance/imaging. While the two terms are often used interchangeably, MR is the umbrella term that encompasses all technologies related to magnetic resonance, whereas MRI specifically refers to magnetic resonance imaging
NRR – noise reduction rating
OR – odds ratio
PETT – *people*, *environment*, *tools*, and *tasks*; a concept for looking at sociotechnical interactions in a work system
PNS – peripheral nerve stimulation
QS – Quiet Suite
RF – radiofrequency
ROI - region of interest
SD – standard deviation
SEIPS - Systems Engineering Initiative for Patient Safety
SMF – static magnetic field
SNR – signal-to-noise ratio
SPL – sound pressure level
T – Tesla
TE – echo time
TFE – turbo field echo
TR – repetition time
TSE – turbo spin echo (synonymous with fast spin echo)
T1W – T1-weighted
T2W – T2-weighted
WM – Whisper Mode

Preface

The magnetic resonance (MR) scanner room is potentially one of the most hazardous environments in the hospital, and at the same time a working environment that MR personnel are exposed to every day. Given the multitude of safety concerns inherent to MR, selecting a specific area for a PhD project on MR safety felt close to overwhelming. However, my journey as a clinical radiographer specializing in magnetic resonance imaging (MRI) has repeatedly brought me face to face with patients expressing discomfort and complaints during their MR exams due to the loud acoustic noise. These personal experiences have not only highlighted the urgency of this issue, but awoken my academic curiosity regarding the management of acoustic noise in MRI. Throughout my undergraduate education and trainee years, the prevailing advice on dealing with acoustic noise in MRI was simple: ensure the patient wears earplugs or headphones. Yet, despite wearing hearing protection, patients still complained about the noise. This discrepancy made me question the oversimplified solution applied, and sparked my interest in exploring a more comprehensive approach to acoustic noise in MRI. Hence, after much deliberation, the foundation for this thesis became clear: to go down the rabbit hole that is acoustic noise.

As with all journeys, the trail expands as the road continues. My path down the rabbit hole eventually led me to gradient field applications and static magnetic field (SMF) exposure. While safety work includes numerous factors that may possibly interact with each other, my eyes were also opened to system perspectives. In this thesis, I hope to shed light on some of the complexities that affect both patients and personnel, and how these can possibly be managed.

Original papers

This thesis is based on the following studies, which are cited in the thesis using their Roman numerals:

I. Glans A, Wilén J, Lindgren L, Björkman-Burtscher IM, Hansson B. Health effects related to exposure of static magnetic fields and acoustic noise–comparison between MR and CT radiographers. Eur Radiol. 2022 Nov;32(11):7896-7909. doi: 10.1007/s00330-022-08843-y.

II. Glans A, Wilén J, Hansson B, Audulv Å, Lindgren L. Managing acoustic noise within MRI: A qualitative interview study among Swedish radiographers. Radiography (Lond). 2024 May;30(3):889-895. doi: 10.1016/j.radi.2024.04.002.

III. Glans A, Wilén J, Lindgren L. Maintaining Image Quality While Reducing Acoustic Noise and Switched Gradient Field Exposure During Lumbar MRI. J Magn Reson Imaging. 2021 Jul;54(1):315-325. doi: 10.1002/jmri.27527.

IV. Glans, A.[1], Wennberg. L[1], Wilén, J., Lindgren, L., Sundgren, P.C, Mårtensson, J., Markenroth Bloch, K., Hansson, B. Evaluation of software-optimized protocols for acoustic noise reduction during brain MRI at 7 Tesla. (In manuscript form).

[1]*Co-first authorship*

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Background

A radiography perspective

This thesis has its starting point in Sweden, where radiographers, also known as technologists, serve as the frontline workers in MRI. Radiographers are typically responsible for both patient care and scanner operation, although these roles vary internationally [1-3]. Given their pivotal role in ensuring safe MR examinations, this thesis adopts a perspective rooted in radiography, contextualized within MR safety.

Radiography is an interdisciplinary field that incorporates features of nursing, radiology, medical physics, and medicine [4-6]. As a research field, it aims to advance the development of, and insights into, the interactions between healthcare, technology, and humans, typically within the context of medical imaging and radiotherapy practice [6]. Approaching radiography as a multidisciplinary research field, underpinned by interprofessional perspectives and heuristics, naturally challenges the traditional divisions between research disciplines. This is reminiscent of how nursing debated its unique position as a research discipline a few decades ago [7]. Currently, radiography is engaged in a similar discourse about what constitutes radiography science and how it distinguishes itself from other disciplines [8].

One proposed cornerstone of radiography as a research discipline is the evaluation of technology based on its functionality for clinical practice [5]. Other central aspects encompass safety in radiation and MR, as well as occupational health and professional development [5; 8]. It is also argued that radiographers should actively partake in, and contribute to, technological development, rather than merely being its users [8]. Radiographers are typically perceived as the bridge between the patient and the technology in use; hence, by incorporating radiographers' insights and input into the process of technological advancement, these technologies could be better aligned with patient-centered practice [8]. However, while most radiography research seems focused on technical and practical knowledge, the discipline also embraces critical theory and reflective research [4].

To clarify the role of radiography in identifying clinical issues and provide insights into risk factors and possible strategies to ensure a safer MR environment, the following sections will provide a basic walkthrough of MRI physics and pinpoint some of the safety concerns associated with this technology.

Safety principles in MRI

Central to any MR safety measure is the well-being of two key groups: the patients/research participants undergoing MR procedures, and the personnel who facilitate these procedures. Their safety is ultimately the cornerstone upon which all other aspects of this field are built.

From a radiation point of view, MRI is considered a safe imaging technique [9]. MRI uses non-ionizing electromagnetic radiation, i.e., energy not high enough to cause direct cell damage, and – unlike X-rays or computed tomography (CT), for example – there is no evident association between MRI and cancer [10]. However, MRI still involves several risks for both the patient and anyone in the vicinity of the MR scanner. These risks include magnetic-object projectiles, burns, current induction and concomitant tissue stimulation, hearing injuries, and implant deflection [11; 12]. To prevent severe harm, MRI adheres to industrial standards and established guidelines, which ensure that threshold levels for e.g., energy deposition, current alteration, magnetic field strength, and acoustic noise level, are not exceeded [13-16]. Nonetheless, even below these threshold levels the risks inherent to MRI remain significant and must be approached with caution. “Safety first” is, thus, of utmost importance, and an integral part of working with MRI.

Fundamentally, producing an MR image requires three distinct types of magnetic fields: a static magnetic field (SMF), radiofrequency (RF) fields, and switched gradient fields. These fields are generated by coils placed inside the bore of the MR scanner [17], as shown in Figure 1. The properties of each field are uniquely utilized within MRI, but each also poses inherent safety risks [11; 12]. This thesis focuses on the gradient field, and the effects of static magnetic field exposure.

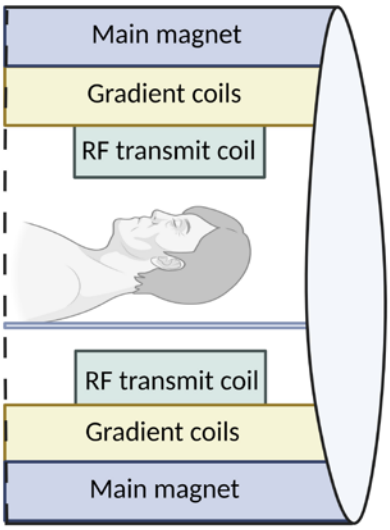

Figure 1. Basic overview of the coils used to generate each type of magnetic field used in MRI. *RF*, radiofrequency. Image created with BioRender.com

Symptoms associated with the static magnetic field (B_0)

MRI utilizes a strong SMF, known as B_0, which is always present in the MR scanner bore and extends into its vicinity. Field strength, which is expressed as magnetic flux density and measured in Tesla (T), typically ranges from 1.5 T to 3 T in clinical settings [10; 11], and is thousands of times stronger than the Earth's magnetic field. As a result, the B_0 can forcefully attract ferromagnetic objects, such as oxygen cylinders and hospital beds, and cause deflection and torque in implants. Tragically, lethal outcomes have been reported due to magnetic objects being brought into the MR room [18; 19]. The field strength of an MR system is fixed, meaning that it is crucial to follow safety routines to control what is, or can be, brought into the MR room in order to prevent harm. Naturally, stronger SMFs are associated with greater risks. However, the demand for higher-field MR systems is continuously increasing, as a higher B_0 provides an increased signal-to-noise ratio (SNR) and may enable improved image quality and diagnostic utility[20; 21].

Rapid technological advancements have made it possible for ultra-high-field MR systems (≥ 7 T) to enter the market. Notably, the first 7 T system to receive approval for clinical use from the U.S. Food and Drug Administration (FDA) occurred in 2017 [22]. At the time of this PhD project's inception (2019), Sweden only had one ultra-high-field MR system, a 7 T scanner located in Lund. Since then, Karolinska Institutet

has installed a 7 T scanner in Stockholm (2023), and the number of 7 T MR systems globally is expected to grow rapidly [20].

Unfortunately, exposure to strong SMFs can lead to short-term adverse effects, such as transient symptoms or sensory effects [12; 23]. Any physical movement within the SMF creates motion-induced time-varying magnetic fields in the body, which induce electrical currents that can stimulate sensory organs [24; 25]. Consequently, both patients and MR personnel are vulnerable to these potential adverse effects [26]. Data collected over a three-year period revealed that 81% of patients and research participants that underwent 7 T MRI reported dizziness, 40% headaches, and a third nausea [27]. Moreover, MR personnel have reported transient symptoms including vertigo, tiredness, metallic taste, headache, nystagmus, ringing sounds (tinnitus), and nausea [24; 28; 29]. Some personnel have also experienced flashing lights (known as magnetophosphenes) and difficulty concentrating [30-32]. Given current knowledge, personnel are recommended to move slowly, if possible, when near the MR bore to limit motion-induced symptoms [32; 33].

To mitigate the adverse health effects of exposure to electromagnetic fields (including both static magnetic and time-varying), occupational exposure limits are set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [34-36]. These form a basis for legislation, such as EU Directive 2013/35 [37]. While there is currently no well-established scientific evidence for the long-term effects of electromagnetic field exposure, EU Directive 2013/35 clearly acknowledges both direct and indirect biophysical effects of electric magnetic fields, and is set out to prevent these [37]. Notably, however, MR personnel are given a derogation, permitting them to exceed exposure limits if certain prerequisites are fulfilled. This is on the basis that, without this, practicing MR would not be possible. Few other environments exist, whether work-related or for the general public, where similar levels of exposure to the three types of magnetic field required in MRI – the SMF, the switched gradient field, and the RF field – take place [38]. In MRI, the exposures of these fields approach the threshold of physiological tolerance [39; 40] and are thus near the applicable limits and standards set by ICNIRP.

While many of the transient symptoms discussed above are associated with SMF exposure [41], and particularly during movement of the head, the mechanisms behind them are not entirely understood [11; 20]. One probable explanation is that the magnetic fields induce electrical fields, which affect the vestibular system and trigger vertigo [42; 43]. This is especially pronounced with stronger SMFs, such as 7 T [27; 44].

However, a limitation of previous studies [28; 41; 45] that have investigated transient symptoms in MR has been the absence of control groups to account for environmental confounders. Improving our understanding of the factors in the working environment that contribute to causing harm is an important step in addressing, and ideally preventing, adverse health effects [25].

Effects of the gradient field

The way MRI utilizes gradient fields generates loud acoustic noise, may induce stimulation of nerve and muscle cells, and can potentially cause vibrations and damage to electrically conductive implants [12; 46].

MRI uses gradient coils to create a time-varying (gradient) magnetic field. The gradient coils are mounted on cylindrical formers inside the bore of the scanner (see Figure 1). To apply a gradient, power is simply turned on until the gradient's maximum strength is reached, and is then switched off. By applying a linear gradient field that is superimposed on the main SMF (B_0), the resultant magnetic field is either subtracted or added to B_0, leading to different field strengths along the bore [10; 47; 48]. This causes magnetic field differences among hydrogen nuclei along the scanned subject's body, making it possible to spatially encode the MR signal that eventually constitutes the MR image [11; 47]. During MRI data acquisition, the gradients are switched on and off rapidly throughout the scan, alternating current polarity at a sub-millisecond rate. The rate of change of these gradient fields is denoted dB/dt (measured in Tesla per second, $T\ s^{-1}$) [46].

The induced currents created by the swiftly alternating gradient magnetic field can stimulate conductive tissues, such as nerves and muscles, and are regulated by industrial standards [15] and national legislation [49] to avoid cardiac stimuli [11]. However, peripheral nerve stimulation (PNS), in the form of e.g., uncontrolled twitching or itching in the limbs, can occur, which may cause discomfort or, worse, pain. Although PNS is not dangerous, minimizing the risk of tissue stimulation is desirable in order to increase patient comfort [11; 50; 51]. Clinical scans are typically operated in "Normal Operating Mode", which not only restricts the energy deposition (specific absorption rate, SAR), but prevents the gradient dB/dt from exceeding 80% of the mean threshold for onset of PNS. However, MR personnel may select "first level controlled operating mode" to speed up an exam, since this allows for increased SAR deposition and gradient output. However, it also permits gradient shifts up to 100% of the mean threshold for PNS [16]. As per the International Electrotechnical Commission (IEC) directive, IEC 60601-

2-23 [16], first level controlled operating mode is default when scanning at 7 T, since $B_0 > 3$ T and ≤ 8 T. Thus, 7 T scanning also increases the risk of PNS, merely by operating at first level.

Alternating gradient currents also create large vibrational (Lorentz) forces on the gradient coils, which in turn generate sound waves that are perceived as acoustic noise. These noises can be described as loud knocking, banging, tapping, and/or chirping frequencies [52; 53], that resemble a pneumatic drill or jackhammer [54], and are typically produced as a series of repetitive pulses. The sound pressure levels (SPLs) of these pulses are expressed in decibels (dB) [55]. To adjust for human hearing – which does not respond uniformly to all audible frequencies – SPLs are commonly frequency-weighted into 'A-weighted' decibels (dBA). Notably, dB is a logarithmic scale, where a 3 dB increase represents a doubling of the sound intensity [12; 56].

The SPLs that occur during MRI generally vary between 80 and 110 dBA, but some pulse sequences may reach 130 dBA [11; 57-60]. For SPLs above 85 dBA, hearing protection is essential in order to minimize the risk of temporary or permanent hearing loss [14; 53; 61]. One of the cheapest and least complex solutions is disposable hearing protection, e.g., wearing earplugs and/or headphones. However, such methods do not change the acoustics in the bore, and they impede communication between the MR radiographer and the patient [61; 62]. Some patients also feel discomfort when wearing earplugs, e.g., due to small ear canals [53]. Even with the use of hearing protection, the acoustic noise exposure during MRI at 1.5 T and 3 T can cause transient hearing threshold shifts [59; 63].

A gradient's strength and rise time are both associated with acoustic noise [47; 48]. The gradient strength (also known as *amplitude*) defines how much the magnetic field changes over distance, and is expressed in millitesla per meter ($mT\ m^{-1}$) [10]. A stronger amplitude increases the delineation between adjacent hydrogen spins, enabling a higher image resolution to be obtained [47]. The time it takes for the gradient field to change from zero to the peak amplitude is expressed by the gradient's *rise time* (expressed in microseconds, μs) [10]. The relationship between the gradient amplitude and rise time is described by the *slew rate*, shown in Figure 2. A high slew rate means a faster rise time and/or higher amplitude, i.e., a higher performance output on the gradient coils. Normally, slew rates vary from $20–200\ Tm^{-1}\ s^{-1}$ [10; 47]. High slew rates can shorten the waiting times within the sequence and enable an overall shorter scan time, but can also increase SPLs and the risk of time-varied magnetic-field effects, such as PNS [47].

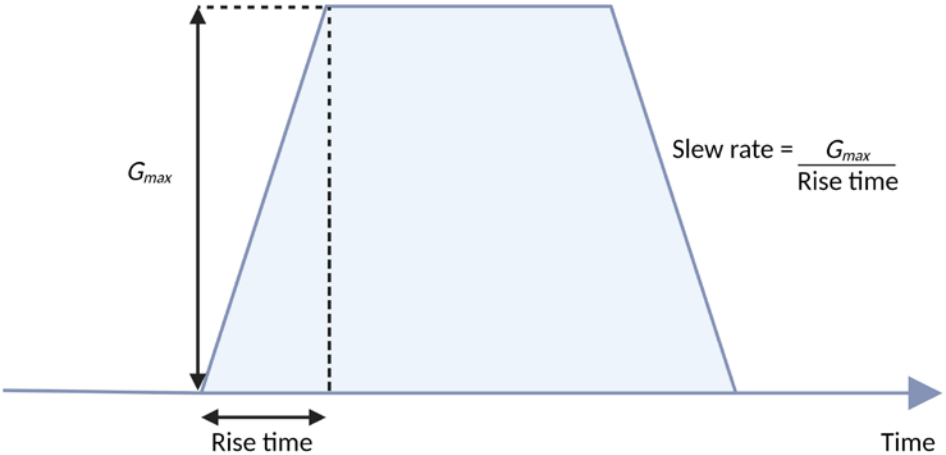

Figure 2. Schematic showing the slew rate for a conventional trapezoid-shaped gradient. G_{max} = peak gradient amplitude. Image created with BioRender.com.

The need for gradient performance varies depending on the MR pulse sequence [10]. MR systems with higher B_0 (e.g., 7 T) are typically utilized when there is a need for high spatial or temporal resolution, which generally pushes the gradient system further, and may cause higher vibration amplitudes and louder scans [64]. Furthermore, decreasing the field of view (FOV), repetition time (TR), echo time (TE), or slice thickness, or using fast imaging techniques, such as turbo or fast spin echo (TSE/FSE), echo planar imaging (EPI), or spiral k-space filling, all require a higher gradient output [52; 53; 57; 65]. Thus, high-resolution images and fast scans typically result in louder exams.

Impact and implications of acoustic noise

Even in the early days of MR, temporary threshold shifts in hearing were shown among patients not wearing earplugs during scanning in a 0.35 T system [66]. There have also been case reports of patients experiencing tinnitus and/or hearing loss after undergoing MR procedures [67; 68], even when using hearing protection [69]. Yet, despite the fact that MRI normally exceeds 85 dBA during scanning, reports of acoustic noise-related incidents in MRI are relatively sparse. The US FDA reports that 6% of MRI-related incidents are due to acoustic noise (temporary or permanent hearing loss) [70]. A three-year review of MR incidents in the United Kingdom reported that acoustic-noise complaints constitute 0.89% of incidents, and that these were primarily patient complaints regarding lack of information or improper ear-protection fitting, and not related to adverse hearing loss [9]. However, their incidence only applies

to an independent healthcare sector, and is thought to be greatly underreported.

Considering the sparsity of reported noise complaints in relation to the obvious issue that acoustic noise constitutes in MRI, McRobbie [12] states that the general consensus seems to be to simply accept that MRI is loud. However, MR-generated noise is a known source of discomfort and anxiety [54; 71]; approximately 1–15 % of all patients undergoing an MR exam are either too claustrophobic to go through with the exam or require sedative drugs to do so [72]. In addition, distress can increase involuntary patient movement and, thus, cause motion artifacts and reduced image quality [73-75]. Anxiety during MRI can also lead to reluctance to attend future exams, and worsen the patient's associations with the quality of care [76]. Dewey et al. [72] found a correlation between acoustic noise reduction and a reduction in exams being terminated due to claustrophobia. Furthermore, although literature regarding the impact of acoustic noise on MR personnel is limited, Wilén and de Vocht [28] reported noise as a significant factor that contributed to increased perceived workload among MR radiographers (referred to as "MRI nurses" in their publication). Thus, we should not be complacent regarding acoustic noise in MRI.

Acoustic noise reduction (ANR)

While earplugs and/or headphones may offer sufficient noise attenuation to minimize the risk of hearing damage, they require proper fit and compliant patients to do so. Poorly fitted hearing protection may lose up to half its noise reduction rating (NRR), since the noise-attenuation values derived in laboratory testing, which establish a device's NRR, are significantly higher than those obtained in real-world use [77; 78]. While simultaneously wearing both earplugs and headphones may minimize the risk of each being poorly fitted, in practice a second hearing-protection device only adds up to 5 dB of attenuation to the first (presumably superior) device [16]. Given the potential shortcomings of hearing-protection devices, a more straightforward and proactive way to manage noise is to address it at its source: the MR system itself.

There are two primary strategies for limiting sound propagation within an MR system: hardware modifications, and software optimizations [53; 74; 79-83]. Hardware modifications aim to reduce mechanical forces and the currents induced in the metallic structures (eddy currents), thereby decreasing vibrations and sound pressure waves. Examples include embedding gradient coils in a vacuum chamber, gradient shielding,

dampening mechanical components, and novel gradient design [53; 80-82; 84-86]. However, these modifications are often complex and expensive, and can sometimes reduce gradient efficiency [81; 84]. Moreover, such implementation lies outside the control of clinical MR personnel.

Software optimizations, which can be controlled by MR personnel, involve utilizing various options to alter the gradient waveform. Advancements in software-based acoustic noise reduction (ANR) have gained significant traction in the last decade, with all major MR vendors offering commercially available options. These optimizations generally aim to modify the gradient current waveform by smoothing steep current alterations, thereby reducing the mechanical output of the coil [80; 87] and avoiding gradient resonant frequencies [10]. One of the simplest ways to achieve this is by restricting the maximum gradient amplitude and slew rate. However, this results in a reduced performance rate for the gradients, and imposes limitations on parameters such as TE and TR. Such adjustments may potentially extend scan times or limit the number of available image slices, and concerns have also been raised regarding possible compromises in image quality [65]. Therefore, these methods often require extensive optimization by MR personnel [61; 65].

Studies that have evaluated the effect of software-based ANR on image quality have yielded somewhat inconclusive results when compared to conventional imaging. Several studies have demonstrated mildly affected or unaffected image quality between ANR and conventional imaging, whereas others have shown worse image quality or decreased diagnostic utility. Findings vary across different ANR techniques, MR systems, pulse sequences, weightings, and anatomical regions [73; 75; 79; 81; 88-92]. Previous studies have primarily focused on brain imaging [58; 65; 73; 74; 80; 89; 92-94], although a few have studied abdominal imaging [88; 91].

Different vendors use different names for this gradient-restricting approach, e.g., “Whisper Mode” and “SofTone” [95; 96]. A more recent commercial innovation is the Quiet Suite (QS) algorithm, which optimizes gradient trajectories to minimize gradient activity. This algorithm specifically targets gradients that do not interfere with radiofrequency signals or readout activity, allowing for the removal of unnecessary gradient activity while preserving the net effect on magnetization. This approach optimizes the gradient waveform, regardless of timing constraints [74; 81; 94]. However, the QS algorithm is not available for all types of pulse sequence, whereas that vendor’s traditional Whisper Mode technique can be applied to most sequences.

Conversely, the literature is limited regarding Whisper Mode and comparable techniques, such as SofTone. To help MR personnel make informed decisions, it is of interest to evaluate and compare these techniques with respect to image quality and SPLs.

Lastly, but importantly, altering the gradient waveform can not only facilitate acoustic noise reduction, but decrease the time derivative of the switched magnetic gradient field. This, in turn, reduces the induced current, which in clinical imaging easily reaches levels at which there is a risk of patients experiencing PNS [50; 96]. Given 63% of study participants reported PNS sensations to some degree while undergoing 7 T MR [27], protocols designed to reduce acoustic noise (e.g., SofTone) are particularly interesting to evaluate in ultra-high-field MR.

Rationale

Given medical imaging depends on technology, and technological development is rapidly advancing, there is an unequivocal need to ensure that professional knowledge and understanding remain up to date [5; 97]. Insights regarding the management of acoustic noise, gradient field applications, and SMF exposure may guide and assist in making MR safer and quieter, thereby improving the work environment and patient comfort, along with the overall clinical experience.

As both patients and personnel are exposed to strong magnetic fields and loud acoustic noise, it is crucial to consider both groups in safety research that assesses and addresses risks. Although several transient symptoms linked to SMF exposure have been established experimentally, the results remain inconclusive regarding the regularity of symptoms. Additionally, the influence of occupational noise in MR is unknown. We need to identify which workers are at risk of adverse effects [98], which is why there is a need to compare symptoms to control groups.

CT personnel are proposed as a particularly suitable control group for studies related to MR work, given their similar work tasks and organization but absence of strong SMFs and potentially hearing-damaging noise levels. Including CT personnel may help to adjust for the “natural occupational background” [28] that personnel within the same organization are exposed to daily.

Understanding how MR personnel manage acoustic noise can help us to better recognize clinical challenges. Their insights could be crucial in guiding the development of noise-reduction strategies and the future application of these. Despite significant advancements in software-based ANR in the last decade, it remains unclear if, when, and how such software is utilized clinically. Given the commercially available options, it is also essential to compare different ANR techniques to understand their specific utilities and limitations. Additionally, it is uncertain whether ANR effectiveness varies with MR systems of different field strengths. As ultra-high-field systems become more clinically adopted, optimizing and evaluating available ANR technology could, hopefully, facilitate the accessibility of 7 T MRI.

Aim

The overall aim of this thesis was to present a radiography perspective on acoustic noise management, gradient field applications and SMF exposure in MR.

The specific aims were:

- To explore the prevalence of health complaints subjectively associated with SMF and acoustic noise exposure among MR personnel in Sweden, using CT personnel as a control group. Additionally, to explore the attribution of symptoms in relation to these modalities and whether personnel use strategies to mitigate adverse health effects (Study I).

- To explore how MR radiographers manage acoustic noise in clinical MR settings (Study II).

- To evaluate SPLs, image quality, switched gradient field exposure, and perceived noise levels for two different ANR techniques – Quiet Suite (QS) and Whisper Mode (WM) – and to compare these with conventional T2-weighted turbo spin echo (T2W TSE) of the lumbar spine (Study III).

- To evaluate image quality, SPLs, and perceived noise levels when using the ANR technique SofTone for T2-weighted fast spin echo (T2W FSE) and three-dimensional T1-weighted turbo field echo (3D T1W TFE), and to compare these to conventional imaging during 7 T brain MRI (Study IV).

Materials and Methods

Methodological underpinnings

This thesis embraces a diverse array of methods and is, at its core, underpinned by pragmatism [99-102]. Pragmatism recognizes the existence of multiple realities and philosophies, on the basis that the primary focus in research should be the problem being studied and the research questions posed; here, truth is considered to be what works at the time [102]. All four studies in this thesis focused on understanding and/or exploring practical problems related to acoustic noise in MRI. The research questions that we posed necessitated different methodological approaches, including both quantitative and qualitative designs, in order to answer them appropriately. This diversity of methods allowed us to view problems from various perspectives, enabling a broader comprehension that contributes towards the overall aim [101].

In terms of qualitative research, my methodological approach has been guided by interpretive description [7; 103]. Interpretive description shares a constructivist and naturalistic orientation [104; 105], asserting that research should stem from "real-world" problems and/or aims to apply for, e.g., clinical settings. While qualitative research should be grounded in established theories, it is not strictly bound to a specific theoretical perspective. Instead, you are encouraged to draw inspiration from the necessary theoretical frameworks in order to generate knowledge that are relevant to the applied practice context [7]. As such, I acknowledge that the knowledge I generate here is socially constructed and contextualized for the time being – that today's truths may differ tomorrow [7; 105]. In this context, my epistemological stance embraces constructivist thinking and the belief that knowledge is co-created by the researchers and research participants [104; 105]. As the researcher, your insights and field experiences are highly relevant to uncover applied science. Thus, subjectivity is not necessarily seen as a methodological weakness in interpretive description; however, it requires you to exercise reflexivity towards your own preconceptions and experiences, in order to inductively interpret different views on the research topic and constrain bias [103; 104].

A Human Factors/Ergonomics framework

Adopting a systems perspective on safety aspects can improve our understanding of interactions between humans (in this thesis patients and personnel) and technology (MRI). Human factors/ergonomics (HFE) is a recognized discipline that embraces this viewpoint [106]. By design, HFE aims to *reduce error*, *increase productivity*, and *enhance safety and comfort* during interactions between humans and the systems they work with [107]. The Systems Engineering Initiative for Patient Safety (SEIPS) model is a HFE concept that was specifically devised to study and improve health-related outcomes, including safety aspects, within healthcare [108; 109].

One of the core HFE principles of the SEIPS model is *systems orientation*: in short, safety outcomes need to be viewed from a holistic perspective, rather than attributing faults to individuals. Although individuals play a central role in safety, they are considered to be embedded components that interact within a sociotechnical system [108]. A 'system' can be a physical device (e.g., an MR scanner) or a larger environmental context, such as a work site or organization [110]. The SEIPS 101 model [109], which is more simplified and practice-oriented than its predecessors (SEIPS 1.0 [111], 2.0 [108], and 3.0 [112]), posits that every work system, at its most basic level, comprises *People*, *Environments*, *Tools*, and *Tasks* (PETT), along with interactions between these components. Environments can be further categorized as physical, socio-organizational, and external.

One way to apply PETT is to scan your data for these four components – i.e., to conduct a PETT scan [109]. As a concept, PETT can be utilized to identify barriers or facilitators within each component, and to pinpoint factors that require attention [109]. Identifying these factors can help to explain work processes, and/or serve as a basis for planning interventions and evaluating work outcomes.

To frame the findings of the four studies presented in this thesis, I have embraced the SEIPS 101 model [109], and conducted a PETT scan of each study. A SEIPS 101 schematic is presented in the 'Results' section (Figure 9), and the concept is further delved into in the 'Discussion' section.

Design and setting

This thesis encompasses four studies. Three of these (I, III, and IV) used quantitative methods, while Study II adopted an inductive qualitative design [113]. An overview of the four studies is presented in Table 1.

All studies were conducted in Sweden, where healthcare services are provided by both the public and private sectors; however, the ultimate responsibility for healthcare is shared among 21 regional councils and local or municipal governments [114; 115]. In 2018, approximately 550,000 MR exams were performed in Sweden, corresponding to 54 MR exams per 1,000 inhabitants. This marked a 104% increase in MR exams compared to 2005, and speaks to a trend of MR being increasingly utilized [116].

Studies I and II were intended to have a national setting through the inclusion of participants from across Sweden, whereas Studies III and IV were prospective, single-center studies that compared software-optimized ANR sequences to their conventional counterparts. Study III was conducted at a county hospital in northern Sweden, and Study IV at a university hospital in southern Sweden.

Studies I and IV were collaborative efforts between Umeå University and Lund University. In Study I, we looked at cross-sectional survey data from a previously collected questionnaire; part of this data was previously published and analyzed in relation to MR incidents elsewhere [117].

Study IV is part of a larger research project in collaboration with Lund University, which aims to improve our understanding of software-based ANR at ultra-high-field (7 T) MRI. This project includes prospective data on induced PNS, muscle activity, and other stress responses in the sympathetic nervous system. However, the evaluation of non-auditory aspects in this project falls outside the scope of this thesis, and will be reported in future publications.

Table 1. Overview of the studies.

Study	Design	Participants	Analysis	Status
I	Cross-sectional survey study	529	Logistic regression Chi-square test Descriptive statistics	Published 2022-06-08
II	Exploratory interview study	15	Thematic analysis (Braun & Clarke)	Published 2024-04-01
III	Prospective within-subject study	40	Repeated measures ANOVA Friedman's ANOVA Wilcoxon's signed-rank test Inter-observer percentage agreement	Published 2021-01-09
IV	Prospective within-subject study	28	Paired t-test Wilcoxon's signed-rank test Krippendorff's alpha Inter-observer percentage agreement	In manuscript form

Data collection and participants

Study I

To explore health complaints, we extracted data from a cross-sectional national survey with 202 items that was sent electronically to the 92 hospitals that were known to have MR units in Sweden. Although we primarily targeted radiographers, all personnel working to any degree with MRI and/or CT scanning were considered to be eligible for participation. In Sweden, it is not unheard of for biomedical scientists, assistant nurses, registered nurses, and physicists in radiology

departments to perform MR scans on a regular basis. Data were collected between September 2015 and April 2016, during which time three survey reminders were sent to increase the response rate.

Three stratifications were conducted to create an overview of the data. First, we included all eligible participants, and used their number of weekly MR working hours as an independent variable to predict symptom prevalence. Second, we categorized participants into three separate groups: *MR personnel*, *CT personnel*, and *mixed* (both MR and CT) *personnel*. To meet group inclusion, we added an *a-priori* cut-off value of 20 work hours/week (h/w), i.e., ≥ 50% of full-time work in Sweden, within the imaging modalities. Personnel who worked ≥ 20 h/w with MR and did not work with CT at all were categorized into the MR group. Personnel who worked ≥ 20 h/w with CT and not with MR at all were categorized into the CT group. The mixed group consisted of participants who worked with both CT and MR for at least 20 h/w combined. Third, we subcategorized all MR users from *MR personnel* and *mixed personnel* into those whose work included MR systems > 1.5 T, and those who worked exclusively with ≤ 1.5 T.

Our survey was answered by 546 participants from 86 hospitals (nine of which were private). After we excluded incomplete submissions and participants who did not work with MR, CT, nor human scanning, 529 participants were eligible; of these, 345 worked with MR and 392 with CT. These 529 participants constituted our first stratum. By adding the cut-off value of 20 work h/w within the imaging modalities, 342 participants remained for group inclusion, and constituted our second stratum. Of these, 121 participants worked ≥ 50% with MR but not CT (78% female; mean age ± SD: 52 ± 8.9 years, range 30–66); 75 participants worked ≥ 50% with CT but not MR (84% female; mean age ± SD: 43 ± 13 years, range 23–65); and 146 participants worked ≥ 50% with both MR and CT combined (71% female; mean age ± SD: 42 ± 12 years, range 24–65). All participants were radiographers except for two biomedical scientists, one registered nurse, and one physicist. In total, 267 (121 + 146) MR personnel were included in the last (third) stratum, based on division of regular work into SMFs ≤ 1.5 T, and > 1.5 T. The strata are presented as a flowchart in Figure 3.

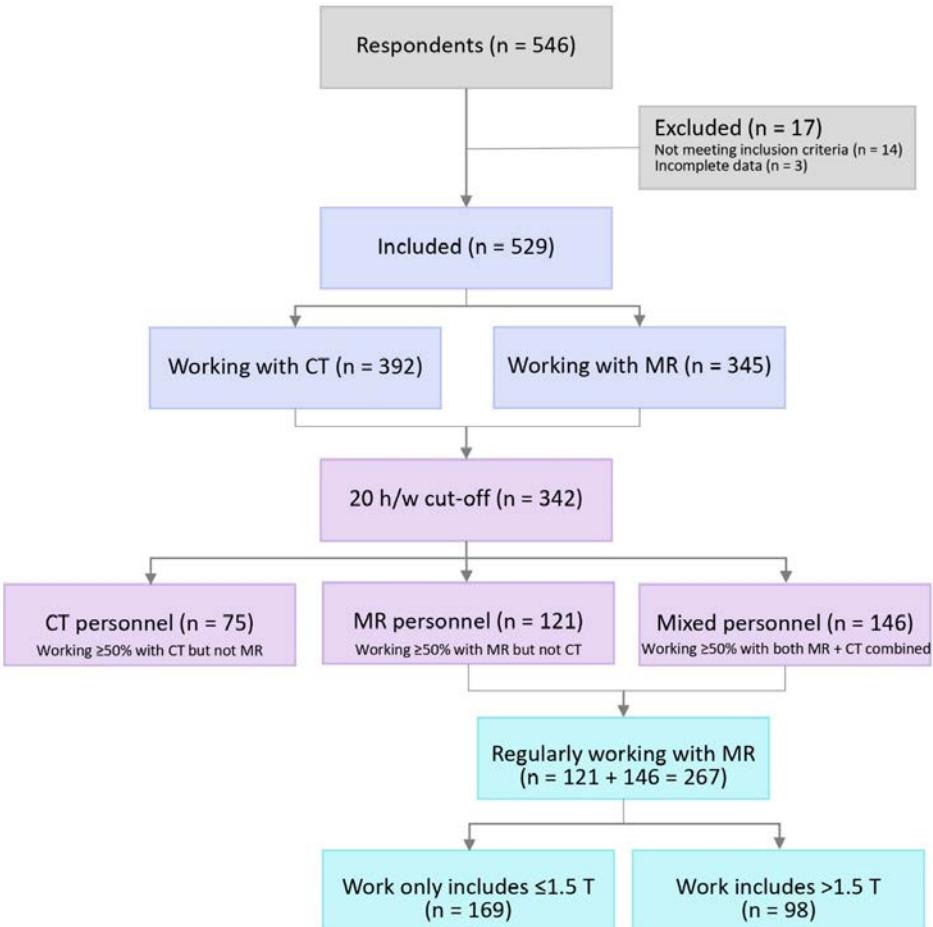

Figure 3. Flowchart of the steps taken to stratify the participants into data groups for separate testing. Blue, Stratum I; pink, Stratum II; turquoise, Stratum III. *T*, Tesla.

Study II

We conducted 15 semi-structured individual interviews. Eligible study participants were radiographers in Sweden working clinically at an MR department with at least one year of MR experience. To enable nationwide participation, all interviews were performed and video-recorded via Zoom (Zoom Video Communications, Inc., San Jose, CA, USA). The interviews were conducted between October 2022 and April 2023.

Using convenient sampling, three participants were recruited via advertisement on the social-media pages of the national radiographer

professional association and trade union, and the remaining participants were recruited by reaching out to MR units and contacts in our professional networks via email and/or telephone. We purposively included radiographers from different hospitals with varying experiences and roles, to account for local and cultural aspects and gain sufficient information power [118].

In total, 15 MR radiographers (nine women and six men, aged 30–60, with a median age of 42 years) from 15 public hospitals were included. The hospitals ranged from larger university hospitals to smaller county hospitals, and from northern to southern Sweden. The participants worked either with only 1.5 T MR systems, or with a mixture of 1.5 T and 3 T systems. They had worked as radiographers for between 4.5 and 37 years (median: 16 years), and their MR experience ranged between 2.5 and 29 years (median: 10 years). The interviews lasted between 23 and 69 minutes (median: 36 minutes). I performed all interviews. Before starting the interviews, each participant was informed about my professional background as an MR radiographer, to facilitate the participants using technical terms and MR jargon if they wanted to.

Study III

We conducted a prospective, single-center study, using a consecutive sampling of adult patients (≥ 18 years old) who had been clinically referred to the study center for lumbar MRI. The exclusion criteria were contraindication for MRI (e.g. non-MR-compatible implants), pregnancy, emergency referral, spatial and temporal disorientation, and the need for a sedative during the exam. After eligible participant selection and prior to their exam, each invited participant underwent a pure-tone air-conduction sound hearing-sensibility test. To enable the collection of data regarding the participants' noise-level ratings, we chose to exclude anyone with a hearing level that exceeded 80 dB in the better ear, i.e., had bilateral profound hearing loss. We decided to include 40 participants, based on comparison of studies with similar designs [73; 74; 119]. Of the 44 invited participants, four declined to participate. Thus, 40 participants were included in the study (27 female and 13 male; age range 21–83; mean ± SD: 51.5 ± 18.2 years).

The participants were scanned using a 1.5 T MAGNETOM Avanto Fit MR scanner (Siemens Healthcare, Erlangen, Germany). All exams were conducted between March and April 2020. Each participant was scanned feet-first in a supine position, utilizing the patient table integrated 32-channel spine coil along with a 30-channel body matrix coil placed over the abdomen.

Participants were scanned with three sagittal T2W TSE sequences in a randomized order: T2W TSE alone (conventional), T2W TSE with QS, and T2W TSE with WM. The participants were blinded to the specific sequence order.

With the exceptions of gradient mode and echo spacing (ESP), we attempted to keep the same image parameters for all three sequences (see Table 2). Compared to the conventional and WM sequences, QS allows for manual ESP adjustment. Therefore, we increased the ESP by 20% in the QS sequence to potentially achieve further SPL reduction.

Table 2. Image parameters for the T2W TSE protocols.

	Sequence		
Image parameter	T2W TSE Conv.	T2W TSE QS	T2W TSE WM
Slice thickness (mm)	3.0	3.0	3.0
Slice gap (mm)	0.3	0.3	0.3
Acquisition matrix (mm^2)	336 x 448	336 x 448	336 x 448
Field of view (mm^2)	350 x 350	350 x 350	350 x 350
Slice orientation	Sagittal	Sagittal	Sagittal
Slices	22	22	22
NSA	2	2	2
Acceleration factor (GRAPPA)	2	2	2
Echo train length	14	14	14
Scan time (min:sec)	03:11	03:11	03:11
Bandwidth (Hz/pxl)	180	180	180
TR/TE (ms)	4210/88	4210/88	4210/88
Gradient mode	High	High	Whisper
Echo spacing (ms)	9.9	11.9	10.8

TSE, turbo spin echo; *Conv.*, conventional; *QS*, Quiet Suite; *WM*, Whisper Mode; *Hz/pxl*, Hertz/pixel; *NSA*, number of signals averaged; *TR*, repetition time; *TE*, echo time; *GRAPPA*, generalized autocalibrating partial parallel acquisition.

Study IV

In this prospective, single-center study, we evaluated software-optimized (SofTone) ANR sequences during brain MRI conducted using a 7 T system (Achieva, Philips, Best, the Netherlands). Scanning was performed in first level controlled operating mode, limiting the specific absorption rate (SAR) to 4 W/kg for whole-body or 3.2 W/kg for the head. Each participant was examined head-first in a supine position,

using a 2 transmit (Tx)/32 receive (Rx) head coil (Nova Medical, Wilmington, MA, USA).

Our evaluation focused on T2W FSE and 3D T1W TFE, both of which commonly used for morphological brain imaging at the study center. For each of these, we conducted one conventional scan and one SofTone-optimized scan. During optimization, we tried to ensure that both image contrast and scanning time were as close as possible to the original (i.e., conventional) sequences. The SofTone sequences required a minor increase in the minimum allowed TE and ESP, for which we applied the shortest possible settings, and an increased receiver bandwidth. These changes resulted in a slight reduction in the signal-to-noise ratio (SNR). All other parameters were kept the same between the conventional and SofTone pairs (see Table 3).

Table 3. Image parameters for the T2W FSE and 3D T1W TFE protocols.

	Sequence			
Image parameter	T2 FSE Conv.	T2 FSE SofTone	3D T1 TFE Conv.	3D T1 TFE SofTone
Slice thickness (mm)	1.0	1.0	0.7	0.7
Matrix (mm^2)	440 x 366	440 x 366	304 x 343	304 x 343
Field of view (mm^2)	220 x 190	220 x 190	240 x 210	240 x 210
Acquired voxel size (mm^3)	0.50 x 0.52 x 1.0	0.50 x 0.52 x 1.0	0.70 x 0.71 x 0.70	0.70 x 0.71 x 0.70
Reconstructed voxel size (mm^3)	0.29 x 0.29 x 1.0	0.29 x 0.29 x 1.0	0.36 x 0.36 x 0.35	0.36 x 0.36 x 0.35
Slice orientation	Transversal	Transversal	Sagittal	Sagittal
Slices	48	48	543	543
NSA	2	2	1	1
Acceleration factor (SENSE)	1.7	1.7	1.4 x 1.4	1.4 x 1.4
Turbo factor	9	9	250	250
Scan time (min:sec)	08:26	08:26	08:40	08:40
SofTone factor	–	3	–	4
Bandwidth (Hz/pxl)	125.9	142.6	252.5	336.6
TR/TE (ms)	5060/60	5060/69	8.0/2.7	8.0/3.8
Inversion time (ms)	–	–	1200	1200
Flip angle (°)	90	90	7	7
Echo spacing (ms)	12.0	13.8	–	–
Shot duration/interval (ms)	–	–	2210/3500	2210/3500

FSE, fast spin echo; *TFE*, turbo field echo; *Conv.*, conventional; *Hz/pxl*, Hertz/pixel; *NSA*, number of signals averaged; *TR*, repetition time; *TE*, echo time; *SENSE*, SENSitivity Encoding (used in both phase x slice directions in 3D imaging).

Regarding study recruitment, the exclusion criteria were non-MRI-compatible implants, being < 18 years old, pregnancy, and not meeting the clinic's MRI safety criteria. Participants were also required to have functional hearing so as to be able to evaluate perceived noise levels. To reach a power > 80% (alpha = 0.05), 28 healthy volunteers were included in the study. Among these, 20 identified as women and eight as men (age range 18–56; mean ± SD: 33 ± 11 years).

Assessments

Study I

The included survey items were based on similar validated questionnaires concerning the impact of the work environment on health, such as the widely used MM questionnaires [120] (a part of the Swedish "Örebro Model" [121]), and The Occupational Stress Questionnaire [122]. Specifically, participants were asked to rate the prevalence of symptoms that are subjectively associated with exposure to SMFs and acoustic noise: vertigo/dizziness, nausea, metallic taste, illusion of movement, ringing sensation or sound (tinnitus), headache, forgetfulness, unusual drowsiness or tiredness, difficulty concentrating, and difficulty sleeping. We asked for symptom prevalence in general in the last year, without taking their work with MR or CT into account. Prevalence ranged on a five-point Likert scale from '*never*' to '*more than four times a week*'. They were also asked about whether symptoms occurred or intensified when in the MR and/or CT scanner room, and if so, where in the room and what type of movements, if any, were related to these symptoms/intensification. These items have previously been adapted to and tested in the MRI setting in a published pilot study among MR radiographers (referred to as "MRI nurses" in that publication) [28]. In addition to demographic data, the participants were also asked about work-environmental noise, self-rated hearing function, and whether they used any strategies to mitigate adverse health effects in their work.

To assess symptom prevalence, each variable was *a-priori* dichotomized into *never/seldom* (< 1 time/week) or *often* (≥ 1 time(s)/week), as previously done by Wilén & de Vocht [28]. The symptoms were also categorized into three groups in relation to: *SMF* (vertigo/dizziness, illusion of movement, metallic taste, and nausea), *general work environment* (difficulty concentrating, difficulty sleeping, forgetfulness, headache, and unusual drowsiness or tiredness), and *acoustic noise* (ringing sensations or sound/tinnitus). The variable "are you experiencing acoustic noise in your work in general as troublesome?"

was dichotomized into *little* ("not at all" or "somewhat") or *a great deal*. Additionally, the following variables were dichotomized: sex (male/female), established hearing loss (yes/no), and self-rated hearing function (normal/impaired).

Study II

An interview guide was used that included open-ended questions about experiences and management of acoustic noise in MRI. The participants were also informed that probing questions could occur to follow up on uncertainties or confirm understandings. We conducted a pilot interview with one radiographer to test the interview guide. Based on this, the guide's structure was minimally adjusted but the original questions were retained, and the pilot interview was included in the study. After covering background and demographic details, each interview began with the following: "Tell me how you feel about noise in your work with MRI." Examples of additional prompts/questions were: "Tell me about a time when you thought extra about hearing protection/noise reduction in your work" and "What strategies/aids/methods does your unit use to address noise levels in your work with MRI?" Towards the end of each interview, the participants were asked "What is the most important thing that I, as a radiographer, should consider regarding MRI noise according to you?" in an effort to summarize their thoughts.

Studies III and IV

Acoustic noise measurements

Peak SPLs (in dBA) were assessed using an MRI-compatible sound level meter (OptiSLM 100; Optoacoustics Ltd., Mazor, Israel), with the microphone (OPTIMIC™ 1155) placed on the right ear of the participant's headphones for Study III, and on the jugular notch for Study IV (since headphones did not fit into the head coil in that MR system).

Differences in averaged peak SPLs, ΔL, between the conventional imaging sequences (A) and the ANR software sequences (B) were calculated as

$$\Delta L = A - B.$$

Since decibel is a logarithmic scale, we converted dB to Pascal (Pa) to enable linear comparison (%) of sound pressure differences, ΔSP, using

$$\Delta SP = 10^{\Delta L/20}.$$

The Borg CR10 scale® was used to evaluate how the participants perceived the noise levels during the pulse sequences. This is a categorical ratio scale that ranges from 0 to 10 (allowing the use of decimals), and is validated for assessing perceptions and feelings [123]. The scale takes into account the participant's previous experiences, as an anchor for reference of the perception. In this context, 0 signified complete silence, and 10 the loudest sound the participant had ever experienced. If they perceived the sound level to exceed 10, they could use > 11 as a new absolute maximum [123] (see Figure 4). The scale was shown and explained in the preparation area before the exam started, and was visible in the scanner during the exams. Immediately following each sequence, we asked the participants over the speaker system to verbally rate how they had experienced the noise level.

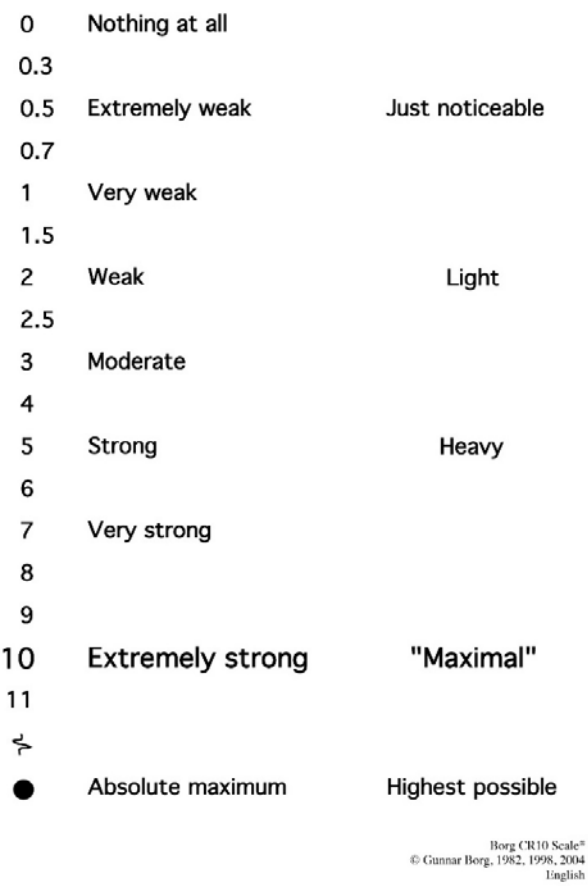

Figure 4. The Borg CR10® Scale . The scale with correct instructions can be obtained from Borg Perception, see www.borgperception.se. Since we attributed loudness, "Strong" was supplemented by exchanging the word "Heavy" for "Loud", as described in The Borg CR Scales® folder [124].

Image quality

Image quality was assessed both quantitatively and qualitatively in Study III, and only qualitatively in Study IV. For quantitative analysis, signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were calculated. For this, digital regions of interest (ROIs) were manually placed on a selected midplane slice visualizing the spinal canal for each patient, at the same position for all three sequences. Specifically, one ROI was placed on each of the following areas: intervertebral disc, cerebrospinal fluid (CSF), vertebra, conus medullaris, and background air. If participant movement occurred between the three sequences to be compared, ROI placements were manually adjusted. This ensured that the same anatomical region was covered, enabling reproducibility [89; 91].

Relative SNR and CNR were calculated as

$$\mathrm{SNR}_{\mathrm{TissueA}} = \frac{Signal_{TissueA}}{SD_{Background}}$$

$$\mathrm{CNR}_{\mathrm{TissueA\text{-}TissueB}} = \frac{Signal_{TissueA} - Signal_{TissueB}}{SD_{Background}}$$

where *signal* is the mean signal in the ROI of the given tissue, denoted A or B, and *SD* is the standard deviation of the noise in the background air in the image [74; 81; 91].

For the qualitative assessments, three radiologists per study (totaling six) independently evaluated the images on separate workstations. To minimize bias, all sequences were coded and renamed, and the image order was randomized for each subject. In Study III, the radiologists graded the presence and extent of artifacts, the overall image quality, and the ability to distinguish anatomical structures in the spinal canal, soft tissues, and skeleton from adjacent tissues, on an ordinal scale of 1–4 (Table 4). They also selected the sequence or sequences that offered the best overall image quality.

Table 4. Radiologists' qualitative image assessments for Study III

Image assessment	Scoring system
1. Image artifacts	1, Unreadable 2, Major artifacts interfering with image interpretation 3, Minor artifacs slightly interfering with image interpretation 4, No artifacts interfering with image interpretation
2. Overall image quality	1, Poor; 2, Moderate; 3, Adequate; 4, Excellent
3. Ability to depict structures in:	
a) spinal canal	1, Inadequate; 2, Moderate; 3, Good; 4, Excellent
b) soft tissues	1, Inadequate; 2, Moderate; 3, Good; 4, Excellent
c) skeleton from adjacent tissues	1, Inadequate; 2, Moderate; 3, Good; 4, Excellent
4. Best overall image quality	Mark which sequence(s) have the best overall quality (multiple choices possible)

In Study IV, we employed an ordinal scale similar to the one used in Study III, also ranging from 1–4, but modified the items in order to focus on brain morphology, taking inspiration from another publication that evaluated image quality based on similar criteria [125]. The items were discussed with the radiologists before finalizing the definitions and terminology. The presence and distribution of artifacts were assessed as: unreadable (1), major artifacts (2), minor artifacts (3) or no artifacts (4). Where an artifact was perceived to interfere with image interpretation, we asked the radiologists to specify the type of artifact on a separate item. They also assessed the general image quality, the ability to differentiate between white and grey matter, and the ability to differentiate CSF from surrounding soft tissues, using the gradings "poor" (1), "fair" (2), "good" (3), or "excellent" (4). Table 5 provides an overview of the scoring system.

Switched gradient magnetic field exposure

In Study III, we measured the switched gradient magnetic field during scanning of the three T2W TSE sequences on a water phantom. We used a Narda ELT B-Field probe (3 cm^2; Narda Safety Test Solutions, Pfullingen, Germany) with three orthogonal induction coils, combined with a Narda ELT-400 exposure-level tester (Narda Safety Test Solutions) in B-field measuring mode (320 µT, High, 1 Hz). The 2010 ICNIRP [35] evaluation mode was used as a proxy of the time derivative of the magnetic field (% general public, High, 1 Hz, std). We also measured the current feeding the gradient coils, using a PicoScope 5444B (Pico Technology, Cambridgeshire, UK).

Table 5. Radiologists' qualitative image assessments for Study IV

Image assessment	Scoring system
1. Image artifacts	1, Unreadable; non-diagnostic examination due to artifacts. 2, Major artifacts interfering image interpretation. 3, Minor artifacs slightly interfering image interpretation. 4, No artifacts interfering image interpretation.
2. General image quality	1, Poor: poor image quality, impossible to diagnostically interpret images. Non-diagnostic; re-scanning needed. 2, Fair: suboptimal anatomical delineation but offers diagnostic anatomical definition; sufficient image quality with diagnostic limitations. 3, Good: well delineated anatomical structures with good internal anatomy preservation; standard examination without diagnostic limitations. 4, Excellent: very well delineated and contrasted anatomy between structures and excellent internal anatomy preservation; no diagnostic limitations.
3. Ability to differentiate between white and grey matter	1, Poor; indistinct anatomical delineation and disturbed internal structure; non-diagnostic. 2, Fair; suboptimal anatomical delineation but offers diagnostic anatomical definition; diagnostic limitations. 3, Good; well delineated anatomical structures between white and grey matter with good internal anatomy preservation; standard examination without diagnostic limitations. 4, Excellent; very well delineated and contrasted anatomy between white and grey matter, and excellent internal anatomy preservation; no diagnostic limitations.
4. Ability to differentiate CSF from surrounding soft tissues	1, Poor; indistinct anatomical delineation and disturbed internal structure; non-diagnostic. 2, Fair; suboptimal anatomical delineation but offers diagnostic anatomical definition; diagnostic limitations. 3, Good; well delineated anatomical structures between CSF and surrounding soft tissues with good internal anatomy preservation; standard examination without diagnostic limitations. 4, Excellent; very well delineated and contrasted anatomy between CSF and surrounding soft tissues, excellent internal anatomy preservation; no diagnostic limitations.

Data analysis

Quantitative data in Studies I, III, and IV were analyzed using SPSS versions 26 and 27 (IBM Corp., Armonk, NY). In all tests, a p-value of ≤ 0.05 was considered statistically significant.

During the process of writing this thesis, I performed PETT scans on all four studies to identify the central system factors and their interactions [109]. These factors were then structured into a SEIPS 101 model. This illustrates the key components of SEIPS, and was used to collate and integrate data from all the studies. The results are explored in detail in the 'Discussion' section.

Study I

We used descriptive statistics to survey symptom prevalence and display participant characteristics. We accounted for missing data by calculating proportions (%) based on the number of responses for each symptom (adjusting the total *n* of each symptom). When appropriate, we used Chi-square tests to compare categorical data between the three groups.

Logistic regression was used to test the association between MR work exposure (h/w) and symptom prevalence for all 529 eligible participants (Stratum I). We also tested the association between symptom prevalence and *MR*, *CT*, and *mixed* personnel (Stratum II). Symptoms were tested both individually and within the three symptom groups as dependent variables in separate logistic regression models. Lastly, *MR* and *mixed* personnel (Stratum III) were analyzed in order to evaluate whether SMF strength affected the prevalence of the three symptom groups. In all logistic regression models, the adjustment variables were age, sex, and stress level. Each independent variable was initially tested using univariate logistic regression. Any variable with a p-value < 0.2 was included in a multivariate regression model to adjust for confounders [126; 127]. Missing data in any of the logistic regression variables were excluded from that model. All variables were also tested for multiplicative interaction. Outcomes were described in 95% confidence intervals (CI95) and odds ratios (OR), where values > 1 denote the increased risk factored.

Study II

For this qualitative study, we used Braun and Clarke's thematic analysis [128] to analyze data inductively. Thematic analysis searches data for themes, i.e., shared conceptual ideas or meaningful patterns that are relevant to the research questions [129]. Thematic analysis is a relatively straightforward and user-friendly method that acknowledges the researcher's subjectivity as a primary tool, granted a reflexive and conscious understanding of how the researcher's role is imperative to the generated knowledge [129]. To stay focused on the clinical context, we approached our analysis from a descriptive interpretation mindset [7], pragmatically searching for meaning and concepts that could offer real-world applicability. As such, our analysis focused on the practical implications of participants' noise management in their clinical experience of different work and healthcare environments.

The analysis process was iterative, with our team repeatedly examining the data over a six-month period. Throughout this time, we engaged in continuous reflection and collaborative discussions. The six phases of thematic analysis can be summarized as follows:

We began by familiarizing ourselves with the data, where I first manually transcribed all interviews verbatim using MAXQDA (v. 22.7.0; VERBI Software, Berlin). I and two of the other authors (LL and JW) read and re-read all of the transcripts. Initial impressions of the data were shared in a joint discussion session. We then labeled data extracts into codes, and all authors started to discuss potential themes. To refine our focus

and provide a more targeted analysis, we concentrated on the management aspects of acoustic noise. Theme names were refined and data extracts were carefully chosen to exemplify the themes. Our findings were compared to related literature to further discuss implications.

Study III

Data on SPLs, SNR and CNR values, and Borg CR10® scores were analyzed using repeated measures analysis of variance (ANOVA). We controlled these data with Mauchly's test of sphericity. Where the sphericity criterion was not met, a non-parametric Friedman's ANOVA was used. First, all statistical tests compared the three sequences together. Then, if a test was statistically significant, we applied a *post-hoc* Bonferroni correction for pairwise comparisons among the three sequences. This allowed us to pinpoint which specific sequences differed.

We analyzed qualitative assessments using Friedman's ANOVA; comparing the scores for the three T2W TSE scores by each radiologist separately. Inter-observer agreement between the radiologists for each sequence's score in each assessment category was calculated using descriptive agreement percentages. We used Wilcoxon signed-rank test with a Bonferroni-adjusted alpha level of .017 (0.05/3) for non-parametric paired comparisons.

Study IV

To determine the sample size, we performed an *a-priori* power calculation. Assuming a 63% prevalence of PNS during conventional scanning [27], G*Power (v. 3.1.9.4) suggested that 28 participants would achieve a power > 80% (alpha = 0.05, two-tailed). Based on the SPL differences between ANR and conventional scanning observed in Study III, 28 participants would yield a power > 99% (alpha = 0.05, two-tailed).

We analyzed peak SPLs and Borg CR10® scores using a paired t-test, provided the data were normally distributed. Given our study's relatively small sample size, the normality of the distribution was tested using the Wilks-Shapiro test [130]. Where the data did not adhere to a normal distribution, a non-parametric Wilcoxon signed-rank test was used instead. We analyzed qualitative assessments of image quality by also using the Wilcoxon signed-rank test, where each assessment item between both sequence pairs was tested for each reader individually.

Similar to Study III, we tested inter-observer agreement by conducting three pairwise comparisons between each reader using percent agreement. We also tested reliability by calculating Krippendorff's alpha (α), using 10,000 bootstrap samples, to weight the observed values and to account for chance [131]. The value of α, which ranges between 0.000 (absence of reliability) and ± 1.000 (perfect reliability), was used to indicate agreement between the readers. A negative Krippendorff's alpha value indicated systematic disagreement among the readers.

Ethical considerations

All studies were conducted in accordance with the ethical standards outlined in the World Medical Association Declaration of Helsinki [132]. Each study received approval from an ethics review board prior to commencement.

Study I (DNR 2014/867) was unique in that the ethics committee waived the requirement for written informed consent. However, participation was still voluntary, with a decision to participate in the survey being considered to be consent. Given the anonymous nature of the data collected through the web-based questionnaire, it was not possible for participants to withdraw from the study after submission, as the data could not be traced back to any individual.

Ethical review for Studies II–IV was applied for from 2019 onwards, and all were approved by the Swedish Ethical Review Authority. Participation in these studies was voluntary and based on informed consent. The participants had the right to withdraw their participation at any time, without needing to state a reason in doing so. We made sure to respect and protect our participants' safety and privacy in order to minimize harm. While data for Study I were anonymous, data for Studies II–IV were pseudonymized. The code keys linking to any personal details were kept in password-protected documents that were only accessible to the research group.

The audio and video files pertaining to Study II (DNR 2022-05555-01) were deleted after the interviews had been transcribed in order to uphold participant privacy. We recognize that any interview situation can potentially place a participant in a vulnerable position. However, we concluded that the topic of acoustic noise management is unlikely to be overly personal or sensitive, and that the risk of emotional distress was minimal. Nevertheless, we were prepared for the possibility that a participant might require comfort or counselling during or after the

interview. In such cases, our strategy was to engage in a discussion with the participant and, if necessary, refer them to a professional counsellor.

In Studies III (DNR 2019-06321) and IV (DNR 2022-05816-01), where research participants underwent MRI exams, we adhered to the clinic's standard routines for personal safety. To protect their hearing, participants were required to use hearing protection during the scans. While headphones were used in Study III, the head coil used in Study IV could not fit headphones, and so the participants were required to wear earplugs and a sound-attenuating impression paste applied in their auricles.

All MR exams conducted on human participants in our studies were diagnostically interpreted by a radiologist to ensure no incidental pathologies were overlooked or unreported. Any findings were reported to the appropriate parties for further follow-up: the referring physician in the case of Study III, and the proper care entity for Study IV.

Study IV was the only study where we offered compensation to study participants. In contrast to the other studies, Study IV recruited healthy volunteers and required up to 90 minutes of their time. Because of this, each participant received two cinema tickets as a token of our gratitude for their involvement.

Results

Subjective symptoms from MR work (Study I)

The number of MR working hours per week (n = 529 participants; Stratum I) had no significant association with symptom prevalence among the SMF, general work environment, or acoustic noise symptom groups (all $p > 0.05$). Instead, stress was revealed as a significant confounder to all symptom variables individually (all $p < 0.05$), except for metallic taste ($p = 0.18$). Stress also confounded the three larger symptom groups (SMF, $p < 0.001$; general work environment, $p < 0.001$; and acoustic noise, $p < 0.001$). Additionally, for each year of age, the odds of experiencing ringing sensations or sound (tinnitus) one or more times a week increased by 3% (OR: 1.03; CI95: 1.00–1.06, $p = 0.04$).

Reported symptom prevalence (n = 342 participants; Stratum II) did not differ significantly between the MR, CT, and mixed groups, as shown in Table 6 (all $p > 0.05$). The CT group were 2.6 times more likely than the MR group to experience acoustic noise at work in general as troublesome to "a great deal" (OR: 2.61; CI95: 1.27–5.36, $p < 0.01$). However, no differences were found for self-rated hearing function ($p = 0.54$) nor established hearing loss ($p = 0.79$) between CT, MR, and mixed personnel.

Among the participants in the MR and mixed groups (n = 267; Stratum III), however, those working with ≥ 3 T were twice as likely to experience SMF symptoms ≥ 1 time(s)/week as those who worked only with ≤ 1.5 T (see Table 7; OR: 2.03; CI95: 1.05–3.93, $p = 0.04$).

When exploring symptom occurrence and attribution in relation to being in the MR or CT room, vertigo was reported to occur "sometimes" by 49% of the MR group, with movement close to the MR gantry as the most common trigger. In comparison, 16% of the CT group reported vertigo "sometimes" inside the CT room, most commonly when making sudden movements. Furthermore, MR personnel reported nausea, the illusion of movement, and metallic taste, mostly occurring when close to, or leaning towards, the MR gantry. Difficulty concentrating was reported to occur "sometimes" by 25% of CT personnel and 14% by MR personnel. Among the mixed personnel, 15% reported sometimes having difficulty concentrating at MR, and 11% at CT. However, no significant differences in prevalence of general work environment symptoms were found between the MR, CT, and mixed groups (all $p > 0.05$) (Table 6).

Table 6. Symptom prevalence in general (n = 342), and logistic regressions.

Symptom groups	Prevalence	CT (n = 75)	MR (n = 121)	Mixed (n = 146)	p-value (crude/adjusted)
Static magnetic field					
Vertigo/dizziness, n (%)	*Never - seldom*	69 (95%)	108 (92%)	129 (92%)	0.74/0.62
	≥ 1 time(s)/week	4 (5.5%)	10 (8.5%)	11 (7.9%)	
Nausea, n (%)	*Never - seldom*	70 (96%)	113 (95%)	133 (95%)	0.95/0.96
	≥ 1 time(s)/week	3 (4.1%)	6 (5.0%)	7 (5.0%)	
Metallic taste, n (%)	*Never - seldom*	72 (100%)	116 (98%)	139 (99%)	0.78/0.95
	≥ 1 time(s)/week	0 (0%)	2 (1.7%)	1 (0.7%)	
Illusion of movement, n (%)	*Never - seldom*	72 (99%)	116 (97%)	131 (95%)	0.33/0.09
	≥1 time(s)/week	1 (1.4%)	3 (2.5%)	7 (5.1%)	
General work environment					
Difficulty sleeping, n (%)	*Never - seldom*	57 (78%)	98 (82%)	111 (80%)	0.77/0.53
	≥ 1 time(s)/week	16 (22%)	21 (18%)	27 (20%)	
Fatigue/drowsiness, n (%)	*Never - seldom*	64 (88%)	104 (87%)	108 (78%)	0.11/0.08
	≥ 1 time(s)/week	9 (12%)	16 (13%)	30 (22%)	
Difficulty concentrating, n (%)	*Never - seldom*	65 (89%)	101 (84%)	121 (87%)	0.61/0.34
	≥ 1 time(s)/week	8 (11%)	19 (16%)	18 (13%)	
Amnesia/forgetfulness, n (%)	*Never - seldom*	69 (95%)	112 (93%)	126 (91%)	0.66/0.43
	≥ 1 time(s)/week	4 (5.5%)	8 (6.7%)	12 (8.7%)	
Headache, n (%)	*Never - seldom*	63 (86%)	105 (89%)	122 (88%)	0.85/0.91
	≥ 1 time(s)/week	10 (14%)	13 (11%)	16 (12%)	
Acoustic noise					
Tinnitus/ringing sound, n (%)	*Never - seldom*	65 (89%)	113 (94%)	127 (91%)	0.42/0.23
	≥ 1 time(s)/week	8 (11%)	7 (5.8%)	13 (9.3%)	

Prevalence data are presented in counts and proportions (%). Missing data are accounted for by calculating % based on the number of responses for each symptom. We used logistic regression to test whether any symptom prevalence was associated with any specific personnel group (crude), and adjusted the models for age, sex, and stress level (adjusted).

Table 7. SMF strength association with symptom groups (n = 267).

Strata 3: Static magnetic field strength Work only involves ≤1.5 T (n = 169); Work involves ≥3 T (n = 98)		
Experiencing static magnetic field symptoms ≥1 time(s) a week		
Variable	OR (95% CI)	p-value
Work involves 3 T	2.03 (1.05 – 3.93)	**0.04**
Stress		**0.01**
Only a little	2.31 (0.78 – 6.85)	0.13
To some extent	2.37 (0.81 – 6.97)	0.12
Rather much	2.07 (0.64 – 6.76)	0.23
Very much	11.9 (3.04 – 46.3)	**<0.01**
Experiencing general work environment symptoms ≥1 time(s) a week		
Variable	OR (95% CI)	p-value
Work involves 3 T	0.90 (0.52 – 1.56)	0.70
Stress		**<0.01**
Only a little	1.97 (0.86 – 4.49)	0.11
To some extent	5.70 (2.60 – 12.5)	**<0.01**
Rather much	12.0 (5.03 – 28.7)	**<0.01**
Very much	13.3 (3.80 – 46.4)	**<0.01**
Experiencing acoustic noise symptoms ≥1 time(s) a week		
Variable	OR (95% CI)	p-value
Work involves 3 T	1.24 (0.54 – 2.85)	0.62
Age	1.04 (1.00 – 1.08)	0.05
Stress		0.11
Only a little	3.92 (0.80 – 19.4)	0.09
To some extent	3.00 (0.60 – 15.1)	0.18
Rather much	7.53 (1.57 – 36.3)	**0.01**
Very much	2.61 (0.22 – 31.2)	0.45

To compare each symptom group's prevalence to SMF strength, we divided all MR-working participants (both MR and mixed, n = 267) into those whose work only involved ≤ 1.5 T (n = 169), and those whose work involved ≥ 3 T (n = 98), and tested with logistic regression adjusted for sex, age, and stress (ascending order). "Work only involves ≤ 1.5 T" and the "not at all" stress level were chosen as the reference categories. To simplify each model, we excluded all variables with a p-value > 0.2. *OR*, odds ratio; *CI*, confidence interval.

With regard to the use of strategies to mitigate adverse symptoms during work, 54% and 45% of MR and CT personnel, respectively, reported no use of strategies. However, more personnel in the MR group and mixed group reported consciously slowing their movements in the MR scanner room (4.8–7.4%) and avoiding working in proximity to the scanner gantry (16–18%) than personnel in the CT group (0–2.7%). Regarding the use of hearing protection, 66–68% of the MR group and mixed group reported always using it in the MR room during scanning. In contrast,

69–84% of the mixed group and CT group reported they never used hearing protection in the CT room during scanning.

Acoustic noise management (Study II)

The radiographers discussed noise from multiple perspectives, shifting focus between the personnel and their working environment, the patients and the examination, and various technological and organizational aspects. They acknowledged their responsibility to manage a noisy environment and mitigate its adverse effects, and reflected on the impact of noise on themselves and on patients, as well as its potential effect on examination outcomes. Furthermore, they described their interactions with, and dependence on, the technology, workspace, and larger organization in their noise management.

Our analysis yielded three themes that relate to how MR radiographers manage acoustic noise: (I) *Navigating Occupational Noise: Risk Management and Adaptation*; (II) *Protecting the Patient and Serving the Exam*; and (III) *Establishing a Safe Healthcare Environment with Organizational Support*. A thematic map is presented in Figure 5.

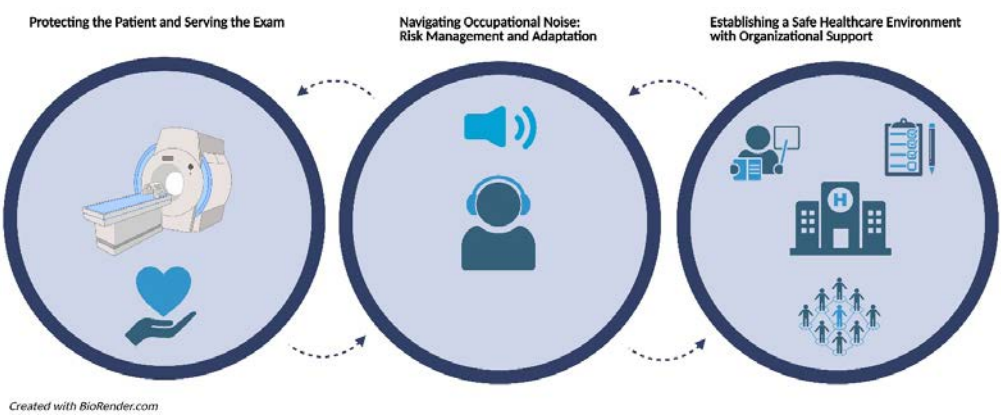

Figure 5. The finalized thematic map of our analysis. The arrows represent feedback loops and forms of interaction.

Navigating occupational noise: risk management and adaptation

Every radiographer described dealing with noise in their MR work; however, differences in how each radiographer perceived the impact of this noise influenced how actively each managed it. For some, noise was a disruptive element in their workspace, particularly in less soundproofed control rooms, leading to adverse effects such as headaches, fatigue, and difficulty concentrating. This exposure could extend into their personal lives by, for example, making them less tolerant of loud noises at home.

Some radiographers viewed noise as an inherent part of their job and managed it by simply accepting it as a given. Cultural norms and adaptation seemed to influence this perspective, with experienced staff expected to handle scanner noise better than newcomers. Conversely, there were concerns among some radiographers about potential hearing loss due to their MR careers. One participant even recounted an incident in which a colleague standing in the active scanner room without hearing protection experienced acute tinnitus.

The radiographers described specific strategies for their own hearing safety. They generally avoided staying in the MR room during scans unless necessary; when present, they typically wore headphones. In less soundproofed control rooms, scheduling of consecutive loud exams was carefully managed, and some staff wore ear protection in the control room to mitigate scanner-noise leakage. Some ensured they took breaks away from the MR section, or even requested working with a different imaging modality the following day to give their ears a rest.

While the participants stressed the importance of soundproofing between the scanner and control room, those in highly soundproofed control rooms occasionally found it challenging to discern when a pulse sequence had ended due to the absence of audible MR noise. To ensure the smooth progression of the exam, they had adapted by remaining alert and refraining from multitasking during scanning. This presented an unexpected challenge: a quiet work environment is preferred, yet the scanner noise is a reassuring indicator of the scanner operating.

Protecting the patient and serving the exam

Acoustic noise was seen as a possible hindrance to patients' well-being and, at times, disrupted their ability to successfully complete exams. Several radiographers identified noise as a primary source of discomfort and common cause of complaints among patients. A few had also encountered patients who developed acute tinnitus following their MRI. Despite these challenges, the participants perceived that most patients accepted the noise as a necessary part of the examination process; some can even sleep through the examination. However, some patient groups were perceived as more noise-sensitive than others, such as children, psychiatric or traumatized patients, sedated patients, and those with tinnitus, impaired hearing, or migraines. Recognizing these patients allowed radiographers to adapt their strategies accordingly.

To protect the patient and increase the likelihood of a successful exam, the radiographers employed strategies to minimize noise exposure. As a basic measure, they always used earplugs or headphones, often combining the two. However, they tailored their approach to the specific needs of each patient, using a range of noise reduction strategies. These included replacing conventional pulse sequences with software-optimized ANR sequences, securing headphones with foam, and informing patients about the importance of hearing protection. Notably, the radiographers found it nearly impossible to communicate with patients during scanning due to the noise. Instead, information was given in advance or during scan breaks. All strategies mentioned by the participants are listed in Table 8.

Table 8. Tool matrix of strategies that the radiographers (n = 15) described using to mitigate acoustic noise during MRI.

Strategy	Applicability	Limitations
Earplugs	Always (exceptions made: feet-first exams, ≤3 T systems)	Small ear canals; poor fit requires customization
Headphones	Almost always	Poor fit on small heads; limited soundproofing; coil size
Software-optimized ANR sequences	Most modern scanners have these options	Not available for every weighting and sequence type; requires training and knowledge to implement successfully; can compromise image quality and prolong scan time
Two-component impression putty; silicone mold putty	Children first and foremost; viable alternative for adults if the head coil is too small to fit headphones	Time-consuming to prepare two-component putty
Pillows or foam to minimize gap between ears and headphones	Head coil; small heads; children; noise-sensitive patients	More an immobilizing than noise-dampening effect?
Active noise cancellation	Unique option for functional MRI (fMRI) in this specific study	Very seldom use, requires dedicated software and hardware
Soft-shelled earmuffs	Small children (infants and toddlers)	Poor fit on larger ears; poor fit requires customization; limited soundproofing
Playing music or films to mask the MR noise	Almost always (video more rare: system-dependent)	Creates another type of noise for some patients; does not reduce physical SPLs; “poor” sound quality
Choosing a quieter MR scanner	Noise-sensitive patients; sedated patients; children; feed-and-wrap procedures	Requires access to multiple scanners
Applying the quietest pulse sequences first	Noise-sensitive or anxious patients; sedated patients; children	Depends on how the protocol is planned and executed; are previous scans needed as reference?
Speeding up sequences to reduce noise exposure time	Anxious patients; children	Applicability depends on weighting; might need faster gradients which, inherently, may cause louder volume
Patient information	Always	Does not reduce the physical SPL

Establishing a safe healthcare environment with organizational support

The participants stressed the importance of a safety culture and proactive approaches to improving safety standards. They expressed that the efforts of work organizations are central to ensuring that acoustic noise can be managed.

Some radiographers criticized their workplaces for a lack of commitment to ensuring a bearable environment as regards noise. Despite noise measurements carried out by some workplaces as part of risk assessments ruling out hearing-damaging levels, these workplaces seemed to disregard the cognitive load that noise imposes. Some participants felt that their concerns were not given due consideration by management, who did not address the annoyance and fatigue that resulted from daily exposure to noise. Wearing hearing protection was felt to be an insufficient solution since it worsens communication and can be physically uncomfortable. However, a few participants described complacency from both themselves and their radiographer colleagues with regard to reporting work-environment issues, thereby somewhat attributing a lack of organizational support to themselves.

Many felt that productivity and working through waiting lists were higher priorities than quality assurance and efforts to continuously improve. All of the radiographers were positive about increasing efforts to reduce acoustic noise, but seldom had the time, and were rarely given the opportunity by management, to do so. Some felt unsupported in their efforts to optimize ANR sequences, while others were not given the training opportunities to acquire the necessary skills. ANR implementation was seen as time-consuming and an impediment to exam production, particularly in the case of sites with scanners from multiple manufacturers. Some workplaces had approached the issue by scheduling sequence optimization for outside of office hours. Some of the participants described feeling a lack of support from their local working group, perceiving their radiologist colleagues to be indifferent to the importance of improved hearing safety and patient comfort.

A few participants described having had positive experiences involving development initiatives in their workplaces; here, collaboration between radiographers, radiologists, physicists, and engineers had led to ANR sequences and other clinical implementations. However, the fact that such changes often needed to be initiated by radiographers was noted by the participants, who also described the fact that many radiographers lack the knowledge or authority to pursue these changes without assistance from other professions as a challenge. Some saw radiologists

as facilitators and some as barriers in these scenarios: in some workplaces they gladly assisted in the process of evaluating a new method, e.g., with image-quality consultations, but in others they were felt to be disengaged or unable to consult on MR safety strategies due to lack of knowledge. One participant described that their radiologist colleagues would become upset if ANR sequences were used for adult patients, as these software were only meant for pediatric patients in their hospital.

Some participants felt limited by the few noise-reduction efforts that their workplaces had put in place. Not all clinics have formal safety guidelines for acoustic noise, but the participants valued such policies for the guidance that they provide. Existing policies were often sparse, however, and generally described as merely recommending earplugs and headphones. The participants felt that additional noise-reduction devices and aids are needed in order to better manage acoustic noise: sound level meters to facilitate real-time monitoring during scanning, improved microphones and intercom systems to improve communication between patients and MR personnel, extra headphone padding, and larger head coils to accommodate thicker headphones. The participants also described wanting more options as regards ANR software from MR manufacturers, as well as increased collaboration and overall support. Finally, the participants repeatedly noted the importance of education regarding noise reduction, both at the undergraduate level and in the context of clinical work.

Software-optimized ANR (Studies III and IV)

Software-optimized ANR significantly reduced the SPLs for both the 1.5 T and 7 T systems.

At 1.5 T (Study III), the peak SPLs were 89.9 ± 1.4, 74.3 ± 2.4, and 78.8 ± 1.6 dBA (mean ± standard deviation, SD) for the conventional, QS, and WM sequences, respectively (Wilks' Lambda = .021, $F(2, 38) = 868.181$, $p < 0.05$). There was a mean difference of 15.6 dBA ($p < 0.05$) between the conventional and QS sequence, corresponding to an 84% reduction in sound pressure with QS. There was a mean difference of 11.1 dBA ($p < 0.05$) between conventional and WM, which corresponds to a 72% reduction in sound pressure with WM. Between WM and QS, the mean difference was 4.5 dBA ($p < 0.05$), where QS reduced the sound pressure by 40%.

The participants perceived QS to be the quietest, and conventional the loudest, sequence ($p < 0.05$). The Borg CR10® scores for the

participants' perceived noise levels for the conventional, QS, and WM sequences were 5.7 ± 0.2, 3.9 ± 0.2, and 4.6 ± 0.2, respectively (Wilks' Lambda = 0.312, $F(2, 38) = 41.988$, $p < 0.05$). The scores differed significantly in all of the paired tests: between conventional and QS (mean difference: -1.8, $p < 0.05$), between conventional and WM (mean difference: -1.1, $p < 0.05$), and between WM and QS (mean difference: -0.7, $p < 0.05$).

There were no significant differences for any of the assessed image-quality categories between conventional, QS, and WM among the three radiologists' scoring (all $p > 0.05$). However, QS showed significantly improved SNR and CNR ($p < 0.05$). The inter-observer percentage agreement were all ≥ 75% for the scoring of overall image quality, artifacts, and best overall sequence(s). Example images showing the three sequences with the same patient to illustrate the differences in image quality are shown in Figure 6.

Compared to conventional scanning, the QS and WM sequences reduced the averaged standard switched gradient field exposure by 66% and 48%, respectively. Additionally, the peak gradient magnetic field strength was 39% lower using QS, and 25% lower using WM, as compared to the conventional sequence.

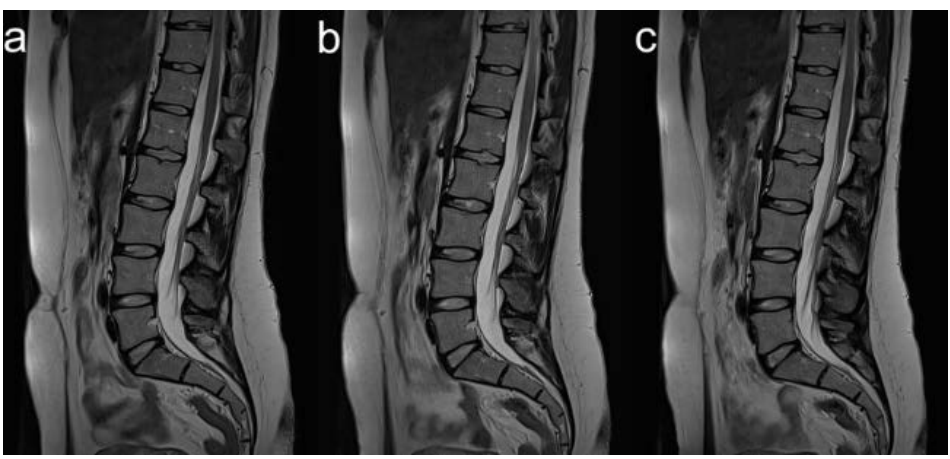

Figure 6. Example images from a patient referred for back-pain screening (Study III). All images were rated as "excellent" (mean score: 4) with no interfering artifacts (mean score: 4). (a): conventional, 90.8 dBA; (b): Quiet Suite, 73.9 dBA, and (c): Whisper Mode, 80.8 dBA.

For the 7 T MR system (Study IV), significant differences were observed in the peak SPLs between SofTone and conventional scanning during both T2W FSE and 3D T1W TFE ($p < 0.001$ for both). The peak SPL was

116.3 ± 1.8 dBA (mean ± SD) during T2W FSE conventional scanning, and 97.0 ± 2.1 dBA during T2W FSE SofTone ($p < 0.001$). This represents a mean difference of 19.3 dBA, which corresponds to an 89% reduction in sound pressure using SofTone. For 3D T1W TFE, the mean SPL was 123.7 ± 1.2 dBA for conventional scanning and 101.5 ± 1.2 dBA for SofTone scanning ($p < 0.001$). This difference of 22.2 dBA corresponds to a 92% reduction in sound pressure.

Both SofTone sequences were perceived as significantly quieter than their conventional counterparts. On average, participants perceived the conventional T2W FSE sequence as close to “strong/loud” (4.5 ± 1.7) on the Borg CR10® scale. By comparison, T2W FSE SofTone was rated as close to “moderate” (3.1 ± 1.1), $p < 0.001$. For the 3D T1W TFE sequence, conventional was rated between “strong” and “very strong” (5.7 ± 2.0), and SofTone between “moderate” and “strong” (3.9 ± 1.7), $p < 0.001$.

Unfortunately, the images of two participants exhibited motion artifacts that noticeably degraded the image quality of at least one sequence among the same-weighted conventional and SofTone pairs. To ensure a consistent basis for evaluating image quality, these two participants were excluded from all image-quality tests, resulting in $n = 26$ for those evaluations.

For T2W FSE, no significant differences were observed in terms of general image quality, nor the ability to differentiate white matter from grey matter and CSF from adjacent soft tissue (all $p > 0.05$; Table 9). Reader 2 noted a slight reduction in interfering artifacts with SofTone (3.04 ± 0.45) compared to the conventional sequence (2.88 ± 0.43), $p < 0.05$, while Readers 1 and 3 did not report any significant differences ($p > 0.05$).

The qualitative assessments for 3D T1W TFE showed a slightly higher subjective variance (see Table 10). Reader 1 rated the general image quality of SofTone (3.08 ± 0.63) lower than that of conventional scanning (3.65 ± 0.56), $p < 0.01$. However, no significant differences were observed by Readers 2 and 3 in general image quality ($p > 0.05$). Additionally, no differences were noted in terms of artifacts and the ability to differentiate CSF from soft tissues by any reader (all $p > 0.05$). Interestingly, both Readers 2 and 3 found that the differentiation between white and grey matter was significantly worse in SofTone compared to conventional scanning (both $p < 0.05$), while Reader 1 did not observe this difference ($p > 0.05$).

Examples showing the achieved image quality are shown in Figure 7.

Table 9. Image-quality assessments for T2W FSE (n = 26)

	Sequence		
Reader 1	T2 FSE Conventional	T2 FSE SofTone	**p-value**
Artifacts	3.12 ± 0.43	3.12 ± 0.52	1.00
General image quality	3.42 ± 0.58	3.35 ± 0.63	0.64
White matter from grey matter	3.50 ± 0.58	3.50 ± 0.65	0.98
CSF from soft tissues	3.96 ± 0.20	3.96 ± 0.20	1.00
Reader 2			
Artifacts	2.88 ± 0.43	3.04 ± 0.45	**<0.05**
General image quality	2.92 ± 0.69	3.00 ± 0.49	0.59
White matter from grey matter	3.50 ± 0.58	3.35 ± 0.63	0.32
CSF from soft tissues	3.85 ± 0.46	3.88 ± 0.33	0.74
Reader 3			
Artifacts	2.77 ± 0.43	2.73 ± 0.45	0.74
General image quality	2.69 ± 0.55	2.58 ± 0.50	0.37
White matter from grey matter	2.69 ± 0.55	2.54 ± 0.51	0.21
CSF from soft tissues	2.92 ± 0.27	2.92 ± 0.27	1.00

The distribution of image-assessment scores (range: 1.00 – 4.00, i.e., "poor" – "excellent") is shown with mean ± standard deviation.

Table 10. Image-quality assessments for 3D T1W TFE (n = 26)

	Sequence		
Reader 1	T1 TFE Conventional	T1 TFE SofTone	**p-value**
Artifacts	2.92 ± 0.39	2.77 ± 0.43	0.16
General image quality	3.65 ± 0.56	3.08 ± 0.63	**<0.01**
White matter from grey matter	3.85 ± 0.37	3.62 ± 0.57	0.06
CSF from soft tissues	4.00 ± 0.00	3.96 ± 0.20	0.32
Reader 2			
Artifacts	3.00 ± 0.28	2.88 ± 0.43	0.18
General image quality	3.04 ± 0.34	2.85 ± 0.54	0.13
White matter from grey matter	3.54 ± 0.58	3.19 ± 0.63	**0.02**
CSF from soft tissues	3.77 ± 0.43	3.50 ± 0.51	0.05
Reader 3			
Artifacts	2.88 ± 0.33	2.69 ± 0.55	0.13
General image quality	2.73 ± 0.45	2.50 ± 0.51	0.08
White matter from grey matter	2.81 ± 0.40	2.27 ± 0.45	**<0.001**
CSF from soft tissues	3.00 ± 0.00	2.88 ± 0.33	0.08

The distribution of image-assessment scores (range: 1.00 – 4.00, i.e., "poor" – "excellent") is shown with mean ± standard deviation.

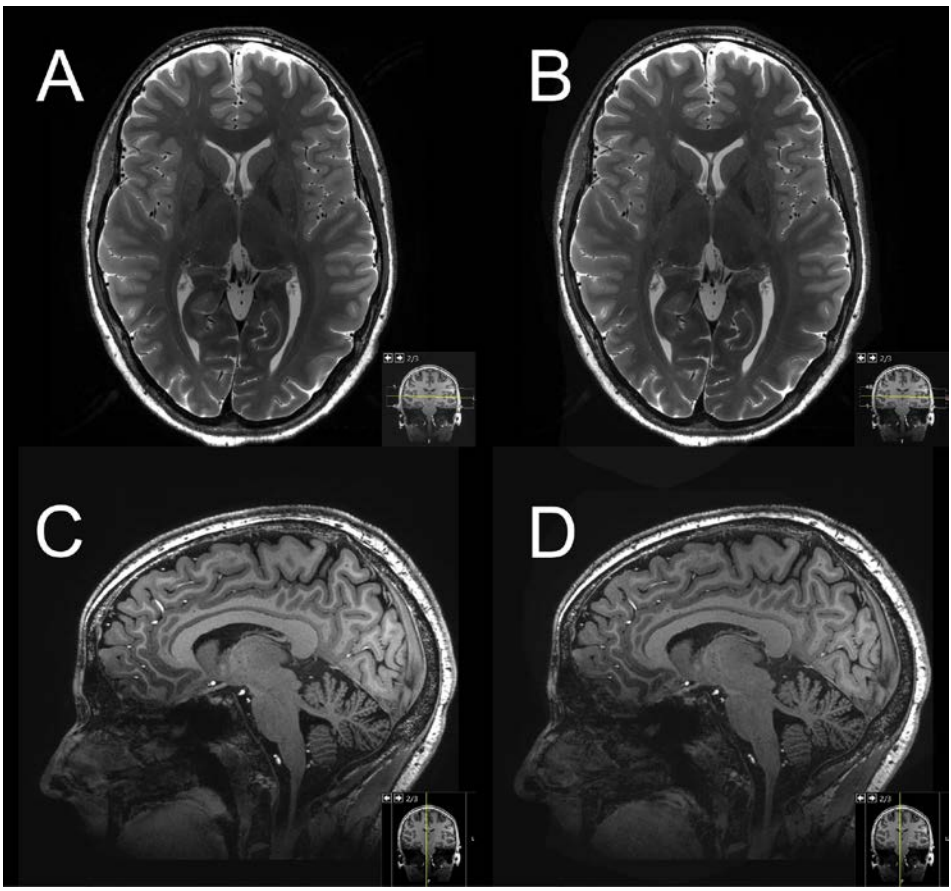

Figure 7. Images produced using T2W FSE and 3D T1W TFE of a healthy volunteer. A, T2W FSE Conventional, 116.1 dBA (peak SPL in A-weighted decibels); B, T2W FSE SofTone, 97.4 dBA; C, 3D T1W TFE Conventional, 123.5 dBA; D 3D T1W TFE SofTone, 101.2 dBA. The three radiologists rated the general image quality of all of these images as either "3, good" or "4, excellent".

The inter-observer agreement and reliability scores are shown in Table 11. No agreement between the three readers exceeded 77%. The highest Krippendorff's α was -0.3753, which corresponds to a fair systematic disagreement in assessment.

Table 11. Reliability and agreement between the readers (n = 26)

	Sequence			
Image assessment	T2 FSE Conventional	T2 FSE SofTone	T1 TFE Conventional	T1 TFE SofTone
Artifacts	α = 0.3084 76% (20/26; 18/26; 21/26)	α = 0.2719 64% (16/26; 16/26; 18/26)	α = -0.0268 77% (20/26; 19/26; 21/26)	α = 0.2745 71% (17/26; 19/26; 19/26)
General image quality	α = 0.2604 53% (15/26; 8/26; 18/26)	α = 0.0453 46% (12/26; 8/26; 15/26)	α = 0.0027 40% (8/26; 4/26; 18/26)	α = 0.2093 49% (10/26; 10/26; 18/26)
White matter from grey matter	α = 0.1473 40% (19/26; 7/26; 5/26)	α = -0.1223 33% (10/26; 7/26; 8/26)	α = -0.1477 32% (15/26; 2/26; 8/26)	α = -0.1515 29% (16/26; 3/26; 3/26)
CSF from soft tissues	α = -0.2446 33% (23/26; 0/26; 2/26)	α = -0.3753 32% (22/26; 1/26; 2/26)	α = -0.3601 33% (20/26; 0/26; 6/26)	α = -0.3086 31% (12/26; 1/26; 11/26)

The inter-observer agreement between qualitative assessments made by the three radiologists: Reader 1 (R1), Reader 2 (R2), and Reader 3 (R3). Data shown in top row, Krippendorff's alpha (α); in middle row, percentage agreement (%); in bottom row, total number of agreements out of a maximum n = 26 between R1/R2; R1/R3; R2/R3. *CSF*, cerebrospinal fluid.

Work system interactions (Studies I-IV)

The PETT scan of each study revealed numerous work systems that form interactions between people, environments, tools, and tasks; these were considered in relation to the PETT framework.

The *people* that were identified as central to Studies I–IV included patients and research participants, radiographers (technologists), radiologists, and physicists. The involvement of referring physicians is secondary within the MR environment specifically, although they play a crucial role in MR more broadly, given their communication with both patients and MR personnel. Other individuals, such as anesthesiology personnel, cleaning personnel, researchers, assistant nurses, medical engineers, and patient companions, were also identified. However, due to their less frequent involvement in daily scanning routines and/or exposure management, these roles were not considered to be equally "relevant" in the clinical context of acoustic noise and SMF exposure. Figure 8, inspired by the SEIPS 101 model [109], presents a "people map" that depicts how *people* interact with and relate to one another in a typical Swedish clinical MR context.

The central work *tasks* include operating the scanner, quality assurance, optimizing sequences (ANR software), attending to and caring for the patient or research participant, producing diagnostic exams, and overall ensuring safe practice within the MR unit.

While Studies III and IV focused on ANR software, other *tools* that form interactions with personnel and patients were primarily mentioned in Study II, and are presented in the tool matrix in Table 8 (p. 40). Additionally, medication for the onset or prevention of symptoms was identified as an available tool in Study I.

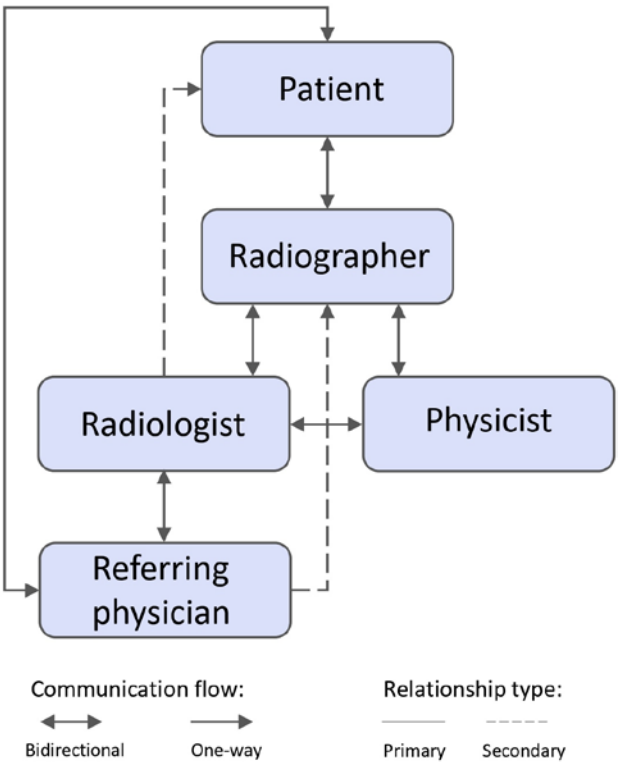

Figure 8. A "people map" schematic of the people typically involved in a clinical MRI exam in Sweden. The arrows indicate the typical communication flow, and whether the line is unbroken or dashed indicates the typical relationship between people.

Lastly, *environments* encompass physical, socio-organizational, and external systems. Central to Study I was the scanner room and the control room; however, socio-organizational aspects, e.g., stress, were also involved. In Studies III and IV, the use of ANR software directly impacted the physical environment around the MR system, i.e., the scanner room and, depending on soundproofing, control room. While Study II explored managing the physical environment in terms of acoustic noise, it also touched on the socio-organizational environments, such as work organization, interprofessional teams, and safety culture. For external environments, legislative, financial, and political means (e.g., departmental investment and budgetary priorities) were discussed.

A SEIPS 101 model [109] showing work processes and potential work outcomes is presented in Figure 9. The role of the system factors and the work processes they form are further discussed and contextualized in the 'Discussion' section below.

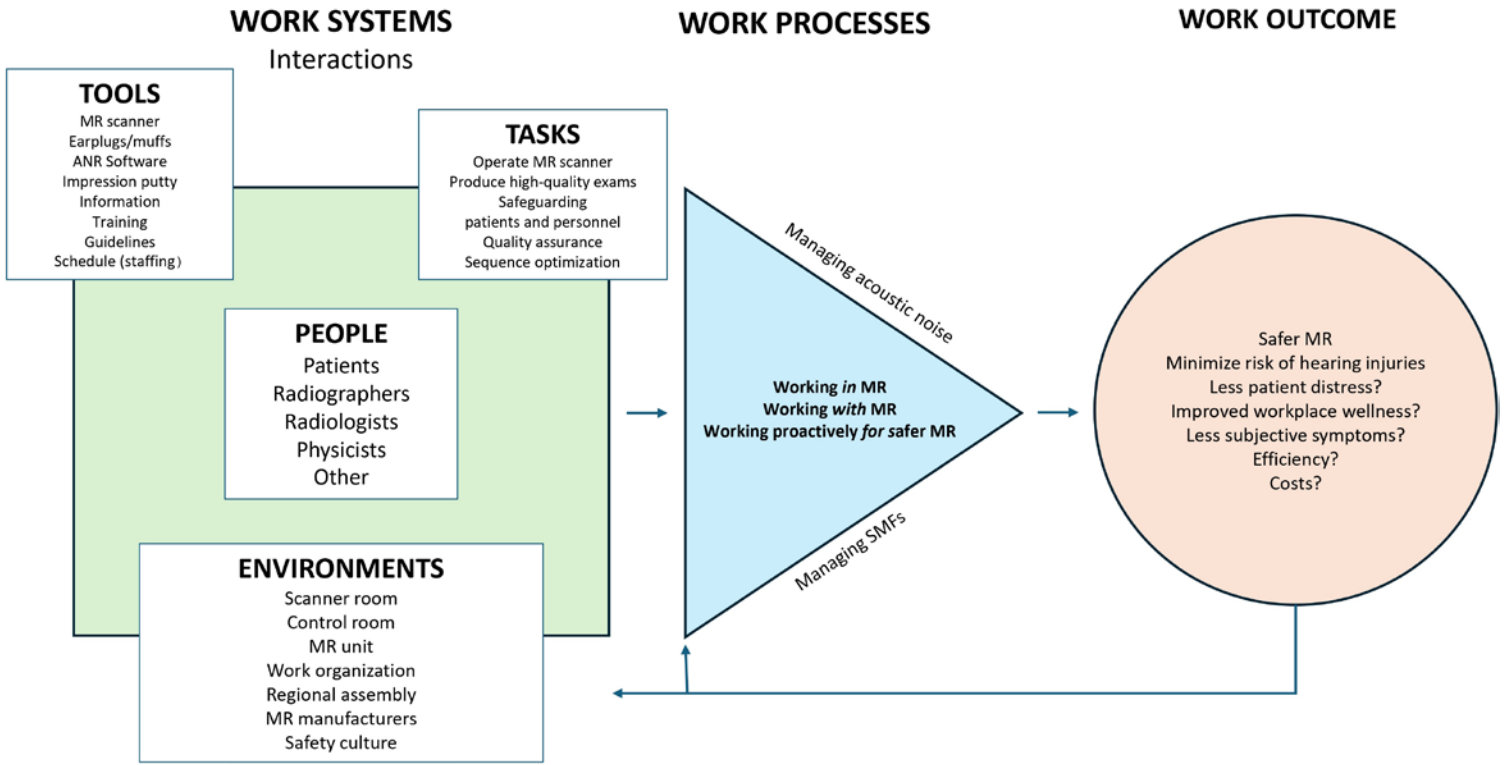

Figure 9. Schematic diagram of the work systems, work processes, and potential work outcomes identified in Studies I–IV, based on the SEIPS 101 model [109]. *SEIPS*, Systems Engineering Initiative for Patient Safety; *SMFs*, static magnetic fields.

Discussion

This thesis has investigated acoustic noise and SMF exposure as potentially problematic features of MR. It has offered insights into managing and mitigating the impact of acoustic noise on exams, encompassing both patient and personnel safety. ANR software has emerged as a promising tool for effectively reducing acoustic noise and switched gradient field exposure, while maintaining diagnostic image quality.

To weave the findings from our four studies into a cohesive narrative, this chapter is structured using the SEIPS 101 model as a framework [109]. Discussing our findings in relation to People, Environments, Tools, and Tasks (PETT) contextualizes the interactions that form crucial work processes. Given the vast potential interactions between PETT components, I have chosen to discuss the findings under three distinct work processes: Working *in* MR, Working *with* MR, and Working Proactively *for* Safer MR (see Figure 9). While this outline accents a personnel perspective, it also has a patient focus, recognizing that both are integral to MR.

Working *in* MR

Working in MR presents environmental challenges. Studies I and II showed that occupational exposure to SMFs and acoustic noise may cause adverse health effects among MR radiographers.

Contrary to our hypothesis, there were no significant differences between MR and CT radiographers as regards the prevalence of reported adverse symptoms subjectively associated with exposure to SMFs and acoustic noise. However, SMF symptoms (dizziness, nausea, illusion of movement, and metallic taste) were significantly more prevalent among MR radiographers who worked with 3 T systems than those working exclusively with ≤ 1.5 T systems.

Our findings partially support previous literature [24; 28; 41; 45; 133-135]; however, we found no significant correlation between SMF symptoms and the number of weekly MR working hours. This contrasts with de Vocht et al. [41], who observed a positive correlation between weekly MR working hours and increased reporting of SMF symptoms; however, their data could not associate subjective symptoms with

magnetic-field exposure or magnetic-field strength (1.5 T and 3 T). In comparison, Schaap et al. [24] identified a positive correlation between increased SMF symptoms and increased field strength in closed-bore MR systems. Unlike their study, however, our sample had an almost complete absence of 7 T personnel.

Furthermore, although it was not statistically significant, we observed a trend of increased occurrence and attribution of SMF symptoms among MR personnel compared to CT personnel. These symptoms were primarily reported when participants were working near the scanner bore and during movement, i.e. during exposure to strong SMFs and motion-induced time-varying magnetic fields. Notably, the so-called "healthy worker effect" [136] cannot be ruled out as a bias among MR personnel in our study, since the strong magnetic fields make it problematic for certain personnel to enter the scanning room, e.g., people with active implants, or those who experience severe symptoms in general. Regardless, given the increased demand for stronger-field MR systems and an overall increase in MRI exams, it is plausible that we will see a higher prevalence of these symptoms in the future [26; 137; 138].

The data on the effects of acoustic noise from Studies I and II appear to be contradictory at first glance. Study I did not identify any significant differences in reported symptom prevalence due to acoustic noise between MR and CT personnel. Although ringing sounds/tinnitus has been reported during SMF exposure [24; 134; 139], we chose to look at tinnitus separately from all other symptoms because it also can be triggered by acoustic noise [140]. Notably, some CT personnel reported tinnitus when inside the CT room, and CT personnel revealed a greater risk of them experiencing acoustic noise in their work environment as troublesome. In the literature, understanding of the risks that CT personnel are exposed to in their working environments is, with the exception of ionizing radiation, unfortunately quite limited, but there appears to be a trend of increasing burnout and stress among CT radiographers due to their workload [141]. While we lack data on SPLs and on noise characteristics that were perceived as troublesome, we hypothesize from clinical experience that fans and X-ray tube rotations contribute to noise nuisance. It is also plausible that noise is aggravated by increased patient and personnel turnover during CT shifts. Nevertheless, our comparison to CT does not negate the fact that acoustic noise also can be problematic in MR environments.

In Study II, our interviews revealed that some MR radiographers perceive MR-generated acoustic noise as a persistent nuisance, leading to symptoms such as annoyance, irritability, and headaches. This was particularly expressed by participants who work in loud control rooms, voicing concerns about cognitive symptoms and strain. Similar adverse health effects of occupational noise, including annoyance, fatigue, difficulty concentrating, and tension headaches, have been reported in other studies in settings such as obstetrics, intensive care units (ICUs), and operating rooms [142-145]. Notably, one radiographer in Study II described witnessing a colleague experiencing acute tinnitus from being in the scanner room without hearing protection. Interestingly, some of the radiographers speculated as to whether their self-estimated hearing degradation could be attributed to their long careers in MR. As our studies did not explore causality, we cannot explain the potential causes of their experienced hearing degradation. However, despite no observed differences in hearing loss or self-rated hearing function between MR and CT radiographers, Study I found a significant association between increased age and a higher risk of subjectively reported tinnitus. This finding is consistent with the literature [142; 146; 147], where age is clearly a risk factor for hearing loss, including tinnitus. Still, the speculation regarding hearing loss being caused by a career in MR presents an intriguing research question for future studies, which would ideally make use of longitudinal data to track potential changes over time

Importantly, a key finding of Study I was the influence of stress on subjectively reported symptoms, irrespective of the imaging modality. This finding potentially indicates a negative interaction with the physical environment, the socio-organizational environment, or both. Stress has also been identified as an important contributing factor to the health effects reported by MR personnel in other studies [41; 135]. The greatest stressors among Finnish radiographers were working shifts, working in larger departments, and/or having 6–15 years of work experience [148]. Conversely, a previous Swedish study [28] did not find that stress impacts the symptom prevalence in general among MR personnel, but reported environmental acoustic noise, including from the MR scanner, as a factor that exacerbates workload. That study, however, did not include a control group, and had a limited number of participants (n = 59). As Study I did not explore organizational structures or work culture, nor evaluate environmental stressors, we cannot establish any causality or identify specific stress-related measures for decreasing symptom occurrence.

It is worth considering another possible interpretation of our finding: that many radiographers experience negative stress during work. While stress may have confounded the symptoms reported by the radiographers, it is plausible that the relationship is bidirectional. For instance, it is well established that acoustic noise can induce stress [142; 149]. Furthermore, exposure to both acoustic noise and SMFs has been linked to cognitive impairment, such as reduced concentration, memory, attention, and sleep quality [142; 150; 151] – all of which are possible symptoms of work-related stress [152; 153]. To break this potentially vicious circle, MR departments should consider ensuring comprehensive oversight of the work environment and, ideally, addressing any identified issues.

Ultimately, our divergent findings across Studies I and II suggest that the adverse effects of working in MR cannot solely be explained by exposure to SMFs and acoustic noise. Stress appears to be an important confounder. Our findings might also indicate a significant variability in individual responses to acoustic noise. Such indication aligns with established research showing differences in noise tolerance, with some individuals being more sensitive than others [142; 154]. These observations suggest the need for a deeper investigation of the technical aspects of working with MR, including tools and strategies to manage and mitigate the impact of acoustic noise in MR environments, which are discussed in the following section.

Working *with* MR

A fundamental aspect of working with MR involves task management, which includes operating the scanner, ensuring quality assurance, optimizing sequences, attending to and caring for the patient or research participant, and producing diagnostic exams. The people that primarily interacted within this work process were patients and research participants, radiographers, radiologists, and physicists. Furthermore, working with MR entails managing and adapting to both the physical and socio-organizational environment. This necessitates using tools and strategies to mitigate potential barriers in the MR environment, thereby facilitating an environment that both promotes patient-centered care and supports employee wellness.

Although our survey did not specifically ask about the MR radiographers' awareness of SMF exposure, their reported use of mitigation strategies (e.g., moving slowly near the MR scanner) implies at least some level of

consciousness of the adverse effects associated with strong SMF exposure. These strategies could indicate an adaptation to a challenging work environment. This theory of adaptation is supported by the work of Zanotti et al. [45; 155], who found that new MR personnel reported more symptoms during their first two months of working with the modality, but the prevalence of these symptoms declined over time. While Zanotti et al. could not explain the reason for this, it is likely that with experience, radiographers may develop strategies, either consciously or subconsciously, to manage and mitigate potential adverse symptoms. Given that the average work experience with MR was quite high among our Study I cohort (14 years), it is plausible that those radiographers have had ample time to adapt, whether they are aware of these adaptations or not.

In Study II, the participants experienced acoustic noise as a problematic feature of MRI, resulting in various challenges to manage. Noise was considered to be disruptive, discomforting, and a possible hindrance to patients undergoing MRI. These experiences align with previous literature, linking MR noise to anxiety [54; 156], discomfort [53], reduced exam success rate [61; 157], increased workload [28], disrupted communication [62], and hearing impairment [53; 158]. To circumvent the potential challenges that acoustic noise presents, an essential aspect of "working with MR" is patient care. All of the MR radiographers in Study II employed multiple strategies to reduce the noise exposure for patients, including providing information to prepare them for loud scans. This was done not only to protect the patients but also to improve conditions for compliance, thereby increasing the likelihood of successful scans. Notifying patients before particularly loud sequences has been reported helpful in other research too [27].

While hearing protection is deemed mandatory in MR [11; 12; 26], the options are extensive. The IEC 60601-2-33 standard [16] recommends the use of passive hearing-protection devices, i.e., earplugs and headphones. Naturally, our study participants had routines for these devices, but they occasionally found it problematic to fit the earplugs properly and thus adopted other strategies. These included using sound-dampening putty, ANR sequences, extra foam or pillows, and active noise-cancelling headphones. Study II provides a compelling example of how human factors come into play. In at least one workplace there is occasional tampering with earplugs, involving cutting them with scissors to ensure a proper fit in patients' (*people's*) ears. Although this practice is not recommended due to the potential compromise of the earplugs' dampening integrity [159], providing patients with ill-fitting earplugs is

also not ideal, as such conditions will negate the noise-attenuating effect of the hearing protection. From a SEIPS and PETT perspective, these findings underscore the need for improved design and implementation of hearing-protection measures (*tools* and *tasks*). Such measures should not only effectively mitigate the risk of noise exposure, but also align with personnel's (*people's*) preferences and work routines [106; 160]. Furthermore, the organization (*environment*) could provide different tools and sizes, and raise awareness of the risks of tampering with earplugs, providing the radiographers with options and informed choices. This example illustrates the importance of understanding the reasons behind workarounds and safety violations [160], and is not intended to pass judgement on individual radiographers. Rather, it highlights the importance of *system orientation* and *person centredness* within a healthcare organization [108]. These notions emphasize a holistic system view where invested efforts should support the people who are central to the system and be fitted to their capabilities, limitations, and needs.

This approach is equally applicable to the safety of MR personnel, particularly in terms of their own use of hearing protection. The National Institute for Occupational Safety and Health (NIOSH) in the U.S [78] states that "the best hearing protection for any worker is the removal of hazardous noise from the workplace. Until that happens, the best hearing protector for a worker is the one he or she will wear willingly and consistently" (p. 64). All of the MR radiographers interviewed in Study II acknowledged the necessity of wearing earplugs or headphones when they are needed in the active scanner room, but some admitted to not wearing them during scanning on some occasions – although these were the exception rather than the rule. Interestingly, in Study I, 66–68% of the radiographers who worked with MR reported always wearing hearing protection inside an active scanner room, possibly indicating wiggle room from a third of the personnel here. Thus, it seems that the protective tools provided do not fully align with the willingness of some personnel to use them. This could be due to a variety of reasons which, as exemplified in Study II, may include the perceived inconvenience of using them, a sense of complacency stemming from the acceptance of scanner noise as an inherent aspect of their work, or even cultural norms that consent carelessness [160; 161]. The way some participants talked about not wanting to disrupt the workflow – the added time to put on hearing protection, coupled with the impaired ability to communicate with the patient – sometimes outweighed the benefits of wearing hearing protection.

Several participants described using multiple layers of passive hearing protection, especially for noise-sensitive patients (Study II) – although, as noted above, such a second layer only adds up to 5 dB of attenuation. [16]. Where possible, combining hearing-protection and noise-control methods might more effectively reduce the total sound pressure [158]. Software-optimized ANR sequences, as evaluated in Studies III and IV, proved to be an effective way of reducing sound propagation from within the MR system. Study III also demonstrated a reduction in switched gradient field exposure, which suggests a decreased risk of inducing PNS and potentially reducing the risk of interference with medical implants [11].

Software-optimized ANR sequences were consistently perceived as significantly quieter than conventional sequences by both patients (Study III) and healthy volunteers (Study IV). This is in line with other studies where ANR imaging was rated as quieter and more comfortable than conventional scanning [75; 91; 93; 162]. Given acoustic noise is a considerable contributor to discomfort in MRI [12; 27; 44; 53], these findings carry significant clinical implications. Notably, the radiographers interviewed in Study II identified certain patient groups as being more sensitive to MR noise than others – individuals with anxiety, pediatric and geriatric patients, patients with tinnitus or impaired hearing, those under sedation, and those suffering from headaches or migraines – and this is corroborated in several other studies [75; 90; 93]. Other study participants have also expressed a need for better hearing protection, and a desire for information prior to upcoming loud pulse sequences in order to be better prepared [27]. For the noise-sensitive or anxious patient, ANR sequences could be a valuable tool to help them manage through the exam. This option might be particularly useful for MR systems where the head coil does not fit headphones, as tends to be the case with 7 T head coils designed to keep the transmit coil diameter small [163], including the one we used in Study IV. Under such circumstances, software-based ANR emerges as a powerful tool by reducing peak SPLs by 19–22 dBA on average, as demonstrated in Study IV. Furthermore, ANR sequences demonstrated higher success rates, fewer instances of complimentary sedation doses, and fewer motion artifacts when compared to the conventional sequences during sedation of children between 3 and 36 months undergoing brain MRI [157].

As we have only evaluated software-optimized ANR with a minimal portion of the sequences available in MRI, we must be cautious in generalizing our findings across different vendors, systems, and/or

image weightings. Importantly, minor adjustments in parameter settings, such as increased TR, TE, ESP, and/or receiver bandwidth, are potentially necessary trade-offs when applying ANR software [58; 65]. Such changes may influence the overall utility of the sequence, depending on its intended use. For instance, in Study III, applying ANR limited the maximum available slices for a given TR. Consequently, more slices necessitates an increased TR compared to conventional (non-ANR) sequence, which will prolong the scan time. Although this effect was minimal in Study III (3-9 sec longer scan time), there may be greater differences depending on how demanding a sequence is in terms of slew rate. Nevertheless, several studies using various ANR software and B_0 field strengths have demonstrated maintained image quality with T2W FSE/TSE specifically [74; 81; 91; 92; 162].

Interestingly, for both T2W TSE and FSE (Studies III and IV, respectively), the few notable differences in image quality between ANR and conventional scanning were slight improvements in the ANR version. In Study III, the signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were increased using QS. Similar findings with QS were reported by Fuelkell et al. [65], where algorithmic programming was suggested as a possible explanation. In Study IV, one radiologist noted marginally less artifact interference with the use of SofTone. This reduction could potentially be attributed to the increased receiver bandwidth, which may help in reducing chemical-shift and susceptibility artifacts [10; 93].

Notably, despite us opting for a higher receiver bandwidth when applying SofTone, the minimum allowed TE was still higher than for conventional imaging, which testaments of a prolonged gradient activity prior to readout [47; 58]. This may have been the reason why two of the radiologists in Study IV assessed that SofTone provided worse differentiation between white and grey matter in 3D T1W TFE, although still within an acceptable diagnostic range. The loss of contrast could possibly be due to the slightly extended TE, which allows for more T2*-relaxation and consequently less T1-contrast. Similarly, Jacobs et al. [85] observed a decreased CNR between grey and white matter when using an ANR-optimized T1W magnetization-prepared rapid gradient echo (MPRAGE) in conjunction with a silent gradient coil. Reduced CNR was also reported with software-based ANR fluid-attenuated inversion recovery (FLAIR) at 7 T [89]. Other studies evaluating ANR software have reported a minor decrease in SNR and/or CNR compared to conventional equivalents, although this did not affect the diagnostic value in qualitative assessments by radiologists [75; 81; 89]. This is in

agreement with the results of Study IV, where – despite the subjective worse white and grey matter contrast – neither of the two radiologists' assessments of the general image quality differed significantly between SofTone and conventional 3D T1W TFE.

Conversely, the one radiologist in Study IV who did not conclude any significant differences in white and grey matter differentiation was the only one who assessed a significant difference in general image quality, with the average score for 3D T1W SofTone leaning closer towards "good" rather than "excellent" as for the conventional sequence. While the quality remained diagnostically acceptable, these results introduce a degree of uncertainty regarding the potential impact of software-optimized ANR on subjective preferences. As such, for any given MR scanner, a trial-and-error approach may be needed before ANR sequences can be implemented routinely.

Not every MR unit has access to state-of-the-art equipment and software. We have demonstrated that optimizing and smoothing the gradient forms, as done using the QS algorithm, can result in even quieter exams. Notably, this effect can be further increased by manually extending the echo spacing and increasing the receiver bandwidth, allowing more time for gradient ramping and thus decreasing the slew rate further [81]. However, not all MR systems have access to such gradient-optimizing software – and even those who do, not all sequences can be combined with such – and so it is useful to know that simple slew-rate restriction remains effective at both 1.5 T (e.g, Whisper Mode; Study III) and 7 T (e.g., SofTone; Study IV).

Given the above discussion, it is understandable that the MR radiographers in Study II expressed some reservations and concerns regarding ANR software. These concerns included uncertainty of correct application due to potential sequence limitations, degradation of image quality, and prolonged scan time. Despite this, most participants viewed ANR imaging positively as a practical tool. However, a discrepancy emerges when manual optimization appears necessary in order to further decrease the SPLs (as in Studies III and IV), but personnel lack the necessary support, training, and education from manufacturers and organizations to do so. This is particularly concerning as radiographers are often the ones who decide whether to use ANR sequences. From a SEIPS perspective, these factors explain a deficient system interaction, which I will discuss further in the next section.

Working proactively *for* safer MR

Improving MR safety in relation to acoustic noise and SMF exposure can only go so far through individual efforts; sustainable changes necessitate a comprehensive system-level approach [108; 109; 160]. A proactive approach involves identifying and addressing risks in the work and healthcare environment before adverse events occur. As such, the focus should be on the prevention of adverse incidents, rather than merely reacting to them [106; 164].

Undoubtedly, the most straightforward way to eliminate the adverse effects of SMF exposure is to remove the SMF entirely [138]. However, since the B_0 is fundamental to MRI functionality, this is neither feasible nor realistic. While the B_0's stray field around the scanner vicinity is contained to smaller areas in modern scanners – due to the advancements in active shielding – the transition from a nearly zero B_0 field to its almost full strength increases drastically in a shorter distance (i.e., larger spatial gradient) [11; 12]. MR personnel sometimes also need to reach into the gantry to assist the patient or clean the gantry tunnel. Therefore, as long as MR scanners are producing stray fields to which personnel are exposed, it is crucial for MR departments to ensure that personnel are aware of the risks associated with SMF exposure [16; 37]. Importantly, personnel should be encouraged to report any experienced adverse health effects to their safety manager [46]. This means acknowledging risks, which motivates addressing efforts, enabling surveillance and possibly evaluating changes over time [138]. While the EU Directive 2013/35/EU [37] mandates health surveillance for workers who experience adverse effects or exceed the recommended exposure limits, it was recently reported by Hansson Mild et al. [165] that this is not being implemented to any considerable extent in most EU countries. A proactive strategy for MR departments could include encouraging reporting of adverse effects, providing tools and strategies to mitigate such effects, incorporating education and training sessions, implementing a rotation schedule to distribute (or minimize) personnel time in the scanner room, and arranging for health surveillance or other appropriate medical examinations to address health concerns [37; 98; 138].

From a SEIPS perspective [109], the findings of Study II position noise as a barrier to safety, comfort, and productivity, and recognize radiographers and patients as the primary *people* affected in terms of physical and cognitive burden. As such, investing in soundproofing and auditory ergonomic site planning would not only benefit the work and

healthcare environment. It also prioritizes the well-being of personnel over the mere use of hearing protection devices, thereby improving the overall physical setting. In line with the European Directive 2003/10/EC [166], Swedish legislation (AFS 2005:16) [167] sets requirements regarding the noise environment that employers must meet. While there is no set lower limit below which noise-reducing efforts are no longer motivated, workplaces are encouraged to reduce noise as much as reasonably possible, taking into account any difficulties experienced by employees. By extension, MR personnel need to speak up if they have complaints, and employers should provide environments that are conducive to such feedback.

It is somewhat alarming that some radiographers in Study II appeared to be willing to risk their own health in order to keep up exam production, thereby ensuring that patients' access to MRI is not compromised throughout the day. Decisions to not wear hearing protection or not report poor working-environment conditions (loud noise) are plausible consequences of a lacking safety climate [160]. Considering how our participants had witnessed both patients and colleagues experiencing acute tinnitus following an MRI, without such incidents being reported, attest to this. There seems to be an implicit understanding that incidents relating to occupational noise are seldom reported, as if personnel attribute these incidents to their own negligence in not using proper hearing protection and are thus "deserving" of symptoms such as temporary tinnitus and headaches. Interestingly, similar attitudes were found among ICU nurses [144], where personnel more frequently discussed their loud working environment with colleagues than reported it to managers. Despite regulations like the Swedish Patient Safety Act (SFS 2010:659) [168] enforcing systematic preventive work in Swedish healthcare, including incident reporting, MR-related incidents are severely underreported in Sweden [169]. While Kihlberg et al. [169] note that willingness to report incidents varies significantly across sites, they also found a correlation between lacking MR safety knowledge and fewer incident reports being made.

On a system level, the safety climate concept refers to "shared employee perceptions of the priority of safety at their unit and the organization at large, especially in situations where safety competes with other performance facets such as care speed or its quality" [170] (p. 1312). In short, if the work organization mainly rewards quantity (e.g., number of scans performed per week) rather than quality (e.g., safe procedures, incident reporting, quality assurance), it incentivizes complacency and perpetuates at-risk or, worse, unsafe procedures. For changes to occur,

MR units need to establish which outcomes to pursue. These outcomes must of course adhere to the demands posed by *external environments*, such as authorities, policy-makers, and legislation, but they should also include practical insights, and have the interests of both personnel and patients in mind [108; 109]. Given the research questions posed throughout this thesis, I cannot answer such outcome-related questions. However, the findings in Study II underscore the importance of fostering a safety culture within the work organization. This involves identifying risks and adverse effects, developing proactive strategies, guidelines, and routines for risk prevention, allocating time for quality-improvement activities, investing in continuous training and education, encouraging interprofessional teamwork, and maintaining an open dialogue with manufacturers.

Software-based ANR holds much promise as a proactive strategy for minimizing the physical impact of acoustic noise on both patients and personnel. However, the findings of this thesis have revealed some challenges that complicate the implementation of ANR software, and that – in SEIPS terms – act as barriers. During the development of medical devices or tools, such as earplugs or ANR software, Carayon et al. [160] emphasize the importance of integrating the organizational contexts in which the device or technology is to be used. Otherwise, the tool might not be used safely or as intended, personnel may develop workarounds, or the technology might simply be rendered as not useful [106; 160]. The fact that most MR systems lack a feedback system, such as estimated or real-time SPLs, makes it difficult to concretely ascertain the noise-reducing effect of an ANR sequence. This, combined with the uncertainty of potential image quality impacts, might add stress, workload, or other negative connotations for personnel. Of course, manufacturers could aim for easier-to-implement use, but that does not address other rooted aspects of safety culture [109; 111; 170]. For sustainable improvements, work organizations must make time for and provide training and education to personnel, and encourage them to pursue this, as was expressed by some participants in Study II.

Finally, as illustrated in the ‘people map’ shown in Figure 8 (p. 49), the radiographer holds a most central role in clinical MR, serving both the patient and the technology, and thus plays a pivotal role in ensuring safety. However, in Sweden, most safety decisions within MR have traditionally been made by radiologists and physicists. Sustainable and proactive safety solutions within MR departments need interprofessional dialog between the different roles. As expressed in Study II, the distinct responsibilities and interests of personnel, such as radiographers and

radiologists, can sometimes be in conflict. For example, in some workplaces, ANR software is a standard tool for examining noise-sensitive patients; in others, radiologists prohibit its use on adult patients. The American College of Radiology (ACR) [46] recommends dividing responsibilities by assigning distinct safety roles to form an MR safety committee – a systematic approach that, admittedly, has not yet been widely implemented in Sweden. However, the adoption of such roles, i.e., MR Safety Expert (MRSE; physicist), MR Medical Director (MRMD; radiologist), and MR Safety Officer (MRSO; radiographer), is also being proposed by the Swedish Alliance for MRI-Safety (SAMS) [171]. Such a safety framework could provide a means of discussing issues, fostering a common purpose, and structuring local MR teams and development groups. It is hoped that this will become the standard in the near future, thereby encouraging systematic follow-up.

Methodological considerations

In the context of doctoral education, the pragmatic approach to our research questions required familiarization with various methodologies. My quantitative research has been deductive, employing descriptive, analytical, and experimental designs; my qualitative research inductive and exploratory [113; 129; 172]. Despite these differences, the four studies are internally coherent in terms of epistemology, axiology, and ontology; they are action-oriented and practice-driven, and construct knowledge based on interactions between people and their environments [173].

While empirical evidence and experience inform clinical practice, they do not fit every unique situation or healthcare context [7]. Even with standardized workflows, practice routines, treatment schemes, and optimized imaging protocols, we often need to tailor our approach to meet an individual's specific needs in their unique time and context. Thorne [7](pp. 28–29) articulates this beautifully, noting that practical fields (e.g., nursing) are typically oriented around an interplay between objective (general) and subjective (individual-specific) information. By conducting research and learning from patients, personnel, and technology in general, we can better customize our care for, and examination of, the unique patient, and better support individual personnel in staying proficient at work and protecting their well-being. In light of this, and throughout this thesis, I have explored and evaluated both subjective and objective outcomes.

As with most, if not all, research, my findings are not without limitations. Therefore, it is essential to critically appraise and discuss the trustworthiness of my findings [105; 172], and invite readers to draw their own conclusions about what holds true. Given my use of both quantitative and qualitative research, the traditional terms to consider are internal validity (credibility), external validity (transferability), reliability (dependability), and objectivity (confirmability) [105; 172]. In addition, a central presumption of the thematic analysis presented in Study II is *reflexivity* [129]. I will discuss some of these notions below, including methodological considerations that are important for understanding and contextualizing my study results.

Regarding representation and transferability, we included both male and female participants in all studies, with varying ages and backgrounds. The distribution of sex varied, partly because of our design choices. In Studies III and IV, consecutive sampling of referred patients and voluntary research participants meant that we accepted participants as they came. In Study II, where sampling was primarily convenient but purposive, in order to include participants from different hospitals, 60% of our participants were women. In Study I, the MR, CT, and mixed personnel groups were 71–84% women, closely matching the Swedish national demographics of radiographers (78% women, reported for the year 2022 [174]). Regardless, our main consideration was to include perspectives and experiences from both women and men of various ages, experiences, and hospital affiliations, in order to enhance the transferability of our findings. Including participants on both a local and national level also strengthens the transferability [172].

All four of my studies involved interdisciplinary cooperation, involving radiographers, nurses, physicists, and radiologists, and/or expertise from statistics and logopedics, phoniatrics, and audiology. These collaborations helped to minimize instances of tunnel vision and researcher-biased decisions, facilitate methodological and researcher triangulation, and increase confirmability and overall credibility through the incorporation of diverse perspectives and expertise [105; 172].

To provide a detailed understanding of the methodological considerations specific to each study, I will now discuss some of the approaches used in and limitations of Study I, Study II, and Studies III and IV.

Study I

Given the cross-sectional nature of the data, our epidemiological design cannot (and was not intended to) explain causality between symptoms

and exposure to SMF or acoustic noise. Additionally, we lack specific exposure data. However, the study provides a solid overview of the prevalence of subjectively reported symptoms between an exposed (MR) and unexposed (CT) population. Therefore, it can be seen as a hypothesis-generating study, wherein logistic regression enabled us to test possible associations between variables. This was complemented by descriptive data that provided an overview of symptom occurrence, attribution, and mitigation strategies. Exploring prevalence on a national level with CT personnel as controls added novelty in the attempt to minimize confounding and selection bias.

Although our survey items were partly derived from validated surveys, such as the MM questionnaires and The Occupational Stress Questionnaire [120; 122], they had not been specifically construct-validated for the MR/CT context. This limitation could affect internal validity, as such items may not have fully captured the intended constructs [175; 176]. Other considerations are potential recall bias, and/or induced ambiguity given the estimation of weekly symptom prevalence over a one-year period. Nevertheless, several items had been previously adapted to the MR context and tested by Wilén and de Vocht [28], which arguably contributes to the content and face validity of our survey [176].

Self-reported hearing function should always be interpreted with caution, as perceived ratings may not correlate with audiometric data and hearing impairment is often underreported [177]. However, audiometric testing was not feasible given our study design. Still, our participants' experiences of acoustic noise at work and their mitigation strategies demonstrated that occupational noise can be problematic in both MR and CT environments.

With regard to external validity and representativeness, the way the questionnaires were distributed provided no control over how many personnel received an invitation to participate in the study. However, a brief overview of the MR personnel in Sweden at that time, which produced an estimate of n = 620, suggests a response rate approximating 60% [117], which is generally deemed to be acceptable [176]. Given our primary aim was to explore symptoms reported by MR personnel, we wanted our controls (CT) to work within the same hospitals in order to minimize external influences between the groups. Therefore, we opted not to distribute the questionnaire to hospitals that did not have access to MRI. Considering the national demographics, this decision resulted in our CT controls being less numerically

representative compared to the MR cohort, and might introduce selection and sampling bias. Accordingly, 392 out of approximately 1300 active CT radiographers [117] among the sites that also had MR answered our survey, resulting in a ~30% response rate. While this limited the representation of the workforce and generalizability of the results, our participants spanned a varied range of ages, work experiences, and geographical areas. The distribution of women and men was also fairly similar to the national demographic [174]. Additionally, the fact that personnel from 86 out of the 92 hospitals in Sweden known to have MR units answered the questionnaire means that more than 90% of the Swedish hospitals/facilities that provide MRI were included, which should be recognized to be substantial representation overall. However, since virtually all of our participants were radiographers, the inclusion of other healthcare professionals in the survey was negligible, limiting the generalizability of our findings outside of radiographers.

We set a cut-off value at 50% for working hours within MR and CT in order to exclude participants who primarily worked in other imaging modalities. This compromise allowed us to more sufficiently gather data for both analytic and descriptive interpretations. By focusing on personnel that were consistently exposed to MR work for at least 20 hours per week (i.e., ≥ 50% of their total working hours), we were able to differentiate between this MR group, a defined control (CT) group that was not exposed to MR at all, and a mixed control-exposure group. We hypothesized (although this was disproved) that the MR group would experience the most symptoms, followed by the mixed group, with the CT group experiencing the least symptoms. This stratification was a pragmatic approach that facilitated the inclusion of more participants from this national cohort, as radiographers who work exclusively with MR are relatively few. In Sweden, MR and CT radiographers typically work with other imaging modalities in addition to MR and/or CT, such as conventional radiography, which was also the case for several participants in our study. However, this occasional work with other modalities might have introduced working environment factors or organizational biases that cannot be ruled out as potential confounders. It is even plausible that these factors explain why adverse symptoms were not more prevalent in our study.

Study II

To improve our understanding of clinical acoustic noise management, we needed to gather personnel's insights and experiences by engaging directly with them. As such, we decided that individual interviews were the most suitable method. One of the few positive outcomes of the

COVID-19 pandemic was the widespread acceptance of and improved infrastructure for video conferences [178], which enabled us to conduct these interviews nationwide. While video interviews have limitations compared to in-person meetings, we believed the benefits of including participants from across Sweden – including significant increases in both our comprehension and study transferability – outweighed the risks of loss of real-life dynamics and authenticity. Additionally, Zoom interviews facilitated video and audio recording as part of the "natural" setting [178], which enabled more detailed transcripts.

Qualitative research acknowledges the researcher as both the primary data-collecting instrument and the person responsible for the analytic process [172]. In thematic analysis [128; 129] and interpretive description [7], a key consideration is *reflexivity*; how we position ourselves as researchers, what assumptions we hold, and how we can constrain our influence. Consequently, the question is not *whether* our assumptions influence our research; the question is *how* they influence it [129]. Conducting all 15 interviews myself introduced a significant subjective influence on the collected data. This subjectivity, while both necessary and meaningful, may have introduced biases, such as overlooking different perspectives or relevant details during the interviews [113]. Given my insider perspective as a clinical MR radiographer, there is a risk of taking shared experiences for granted [7; 179]. However, there are also several advantages to the interviewer being familiar with the topic; in this case, my clinical familiarity with MRI and methodological knowledge of acoustic noise facilitated technical discussions and validation of the participants' experiences [113; 128; 179; 180].

Given our common research background in MR safety and acoustic noise, my supervisors and I discussed and identified preunderstandings to ensure that we approached our research questions with an open mind, as curious learners, before beginning the interviews. Additionally, due to my direct involvement in data collection, it was necessary for me to maintain a reflexive awareness and distance during the analysis process [129]. We used a shared document for coding and thematizing as an audit trail for recording and following thoughts and discussions regarding contextual interpretations. Not only were three authors involved in coding the data extracts, but all five authors contributed to the data-analysis process, participating in collaborative discussions. This investigator triangulation should be considered to have strengthened the confirmability, dependability, and trustworthiness of the study [105; 172].

I was acquainted professionally with some participants, which could have influenced their responses due to concerns about our relationship [179]. On the other hand, this acquaintance may also have helped by increasing their comfort, resulting in more open and honest responses [180]. Importantly, during the recruitment process and before starting each interview, the participants were reassured that their contributions would be anonymous and that their experiences and insights were not a matter of right or wrong, but simply theirs, and crucial to our learning.

Regarding sample size; rather than striving for data "saturation," which has been criticized for being vague and difficult to conceptualize [7; 181], we opted for information power [118]. Information power considers the richness of the data; the more information power a sample (e.g., an interview) provides, the fewer samples are needed, and vice versa. Despite our relatively narrow aim, we sought to explore experiences across Sweden. As these experiences had not, to our knowledge, been previously described, we could not realistically estimate the number of interviews needed beforehand. Thus, we established that additional interviews might be necessary, even if the initial ones provided relevant themes on acoustic noise management in a clinical context. Conveniently, being the sole interviewer allowed me to appraise the information richness throughout the data-collection period. After discussing my impressions of the interviews with my co-authors, we concluded that these 15 interviews provided sufficient information to meet our study's aim.

Limiting our sample to radiographers may have narrowed the study's transferability. For example, interventional personnel and researchers, who generally stay in the MR scanner room or provide instructions during scanning, might have different experiences. Although our study participants independently described similar experiences, we cannot rule out the possible influence of participation bias, as only radiographers who were interested in the study contacted us or agreed to participate. Nevertheless, it seems likely that our findings are relevant to other MR settings beyond these 15 hospitals, given the globally increasing standardization of MR work divisions, organizational structures, and safety protocols [46; 171; 182].

Studies III and IV

We used a within-subject design for both Studies III and IV; this was an effective way to increase power, since the participants functioned as their own controls, thus eliminating potential between-subject confounders [183]. Additionally, we randomized the scanning order of conventional

and ANR pulse sequences, and blinded both the participants and the radiologists to the control and test data. While this control over confounding variables strengthens the internal validity [172], we cannot speculate on the utility of ANR software outside these specific systems. However, evaluating similar ANR techniques (WM and SofTone) across different systems, vendors, and field strengths, can be seen as an attempt to increase external validity, reliability, and clinical applicability. Additionally, the comparison of two techniques on the same system (QS and WM) adds to the generalizability of the potential of software-based ANR.

Image quality is a central aspect when evaluating ANR sequences to determine their clinical significance with regard to application. We purposely mixed objective and subjective assessments, as each type is relevant in a specific context. For example, for an MR image to have diagnostic value, it needs to be evaluated in the context for which it is intended: typically, qualitatively by a radiologist. Although objective measurements, such as SNR and CNR, provide valuable quantitative input on data, they do not necessarily translate to the diagnostic value of a morphological image. In Study III, the sequence parameters of those generally relevant for relative SNR (and by extension CNR) could be kept identical for both the conventional and ANR sequences. Under these circumstances, comparing SNR and CNR adds nuance to the overall image-quality assessment. In Study IV, however, the required increase in receiver bandwidth decreased the relative SNR of the ANR sequences slightly as compared to the conventional sequences. We decided not to compare SNR and CNR under such conditions, as this would have provided invalid evidence given the differences in data sampling.

Unfortunately, there are no standardized qualitative ratings for image quality for lumbar or brain MRI [184]. We can only speculate as to whether other alternatives or scales than the ones we used would have impacted our results. However, in Study IV, our decision to assess the whole brain may have influenced the outcome, as 7 T imaging can produce notable signal losses in local areas [185]. Although focusing on specific brain areas could have offered a more detailed overview, such segmentation would not have fully addressed the intended clinical application for morphological imaging. Consequently, we opted not to separate local brain regions for the overview assessments. Our analysis was broadened by examining contrast differentiation between white and grey matter, as well as CSF from surrounding soft tissue. If standardized and validated subjective image-quality assessments existed, studies could produce more uniformly formatted data, facilitating overviews and

meta-analyses. However, perhaps the biggest challenge is the lack of a perfect reference image in real-world practice [184].

In Study III, the skewed distributions of the radiologists' image-quality assessments, such as the absence of "1" and "2" ratings, made interrater reliability tests unfeasible. Unfortunately, our choice to report percentage agreements does not account for chance input. Although the radiologists in Study IV exhibited more diverse assessments, there was still a near-absence of "1" ratings. Individual biases, i.e., different interpretations existing between the radiologists, cannot be ruled out as a possible explanation for the low Krippendorff's α. This could be attributed to individual preferences in terms of image presentation, or ambiguous item definitions. Although we developed the Study IV items in dialogue with the three radiologists and supplied them with the written item definitions during their assessments, we ideally would have also provided them with training and calibration exercises to mitigate bias. Nevertheless, we argue that the pairwise sequence comparisons of each individual radiologist, inherent to the within-subject design, represent the critical outcome of clinical significance.

Lastly, measuring SPLs means objectively expressing noise differences in dBA – a critical outcome for hearing safety – but does not convey how noise levels are perceived. To understand this, we needed to ask the participants about their subjective experiences. Including participant experiences was crucial, as these directly reflect the effectiveness of ANR software from the perspective of those exposed to the noise. While we assessed these experiences quantitatively, exploring them qualitatively, for example through interviews, would likely have provided more nuance and insight. However, to maintain consistency and publish all outcomes in the same paper, we utilized a quantitative approach.

Future research

While I have employed a radiography perspective on acoustic noise and SMF exposure in MR, there are still numerous unknowns, and other perspectives that warrant attention. The presented SEIPS 101 model (Figure 9, p. 50) suggests that there are many potential outcomes of interest that fell outside the scope of this thesis.

The importance of including a systems perspective in safety research cannot be overstated. Every change incurs costs, whether of money, time, personnel strain/stress, patient safety, or healthcare inefficiency. Therefore, studies that help to establish risks and benefits, along with

facilitators and barriers, are valuable. Ideally, such research takes external cost aspects into account, such as safety climate, patient satisfaction, and occupational health. For example, what are the financial reasons to approach ANR proactively in order to reduce noise at its source, bearing in mind the cost-effectiveness of earplugs (if we ignore their shortcomings)? What is the minimum acceptable cost for site-remodelled soundproofing in relation to personnel satisfaction? How does noise leakage into the control room affect productivity and employee wellness over time? An answer to the latter would benefit from longitudinal data and ideally involve the experiences of personnel from multiple sites, both nationally and internationally. More comprehensive research is also needed in order to better understand the impact of stress and environmental factors on MR personnel. This could include exploring organizational structures, work cultures, and other environmental stressors.

With regard to acoustic noise in particular, future research and interventions should aim to not only improve the design and accessibility of protective tools, but promote a safety culture that encourages and normalizes their use. We need to better understand the perspectives of both patients and personnel, as users, and adapt technology to their needs – rather than the other way around. As for software-based ANR, we have only evaluated parts of the available technologies. There are other promising ANR software options that deserve mention. For example, ultra-short echo time (UTE) and zero echo time (ZTE) techniques have shown promising results, achieving near-ambient noise levels [186-189]. However, there are challenges inherent to these techniques that need to be addressed, such as difficulties in producing high-quality T2W and diffusion weighted sequences, and user restrictions, e.g., limited field of view dimensions and disabled acceleration factors. A natural next step would be to investigate how artificial intelligence (AI) can facilitate application of ANR software; for example, could it utilize undersampling and similar acceleration techniques to speed up ANR sequences? Could AI further optimize gradient trajectories in order to reduce the magnetic flux density and its derivatives?

The added benefits of reducing the time derivative of the switched gradient magnetic field needs further testing in relation to applications outside of ANR. We are currently investigating its effects on the incidence and attribution of PNS, muscle activity, and other stress responses in the sympathetic nervous system, by prospectively comparing ANR software and conventional imaging.

As for SMF exposure, there is a need for more long-term studies to establish exposure variation between MR personnel, symptom regularity, and health outcomes. Additionally, we do not yet understand the mechanisms behind possible SMF adaptation, whether there are physiological explanations or socio-cultural aspects to consider. Implementing health-surveillance programs and following up on health aspects are urgent suggestions.

Finally, the noise environment of CT warrants a proper follow-up.

Clinical implications

Any effort to reduce sound propagation from within the MR system should be considered a crucial aspect of proactive measures to safeguard both patients and the personnel. This thesis has demonstrated that utilizing software techniques available in most modern MR scanners can significantly reduce acoustic noise, making MRI a more comfortable experience for patients. As these methods currently require user optimization in order to be applied optimally, MR units must provide the support, education, and training needed for personnel to effectively employ such techniques.

Importantly, acoustic noise must be addressed through additional means. MR units should review their inventories of earplugs, foam, silicone putty, headphones, pillows, and similar tools, and ensure that these items (A) offer sufficient noise attenuation, and (B) are available in various forms and sizes so as to properly fit different individuals. In clinical settings, a one-size-fits-all solution is not feasible. Until ANR development reaches a point where essentially all sequences have near-ambient noise levels, we must continue to use earplugs and/or headphones to minimize potential harm.

While radiographers working in MR environments subjectively report adverse health effects, these cannot be attributed solely to SMF and acoustic noise exposure. Stress appears to be a consistent confounder in reported symptoms, and addressing the root cause of this stress must be a priority for management and other external entities. Nevertheless, the odds of experiencing SMF-related symptoms were doubled at 3 T compared to 1.5-T systems. MR radiographers and other personnel who work close to the scanner bore must be aware of this increased risk, and be encouraged to report any symptoms and adverse effects to their safety managers promptly. Additionally, it is crucial to consider these effects on patients, who are also exposed to the SMFs, and inform and provide care for them accordingly.

Another critical aspect is fostering a safety culture, which includes the imperative of incident reporting. Meaningful improvements depend on the willingness of personnel to report issues and adverse events. Only through transparent communication can we identify trends, implement corrective measures, and ultimately improve the safety and efficacy of MR.

Conclusion

This thesis contributes with insights into acoustic noise management, gradient field applications, and health effects of SMF exposure in MR settings.

MR presents a challenging work environment. Radiographers who work with 3 T systems have a higher risk of transient adverse health effects, such as dizziness, illusions of movement, and nausea, compared to those who work with systems of 1.5 T or less. However, it is important to consider that stress and other organizational and work-related factors may also contribute to these subjectively reported symptoms.

Although some MR radiographers were concerned that their careers may have led to hearing damage, no difference was found in the prevalence of self-assessed hearing impairment when MR and CT personnel were compared. Nevertheless, MR radiographers employ strategies to mitigate the influence of acoustic noise and SMFs. They demonstrate a willingness to adapt and employ measures to mitigate acoustic noise, thereby enhancing safety and comfort for both patients and personnel, all while striving to deliver diagnostic exams. However, they require appropriate tools and support in order to manage this effectively, suggesting a need for work organizations to adopt more proactive, holistic approaches to safety initiatives.

This thesis has also evaluated software-based ANR in terms of its functionality in clinical practice. With proper optimization, T2W TSE/FSE and 3D T1W TFE can maintain acceptable subjective image quality, while considerably decreasing peak SPLs by 72–92%. This reduction in sound intensity provides a safer, quieter, and (presumably) more comfortable scan environment, making ANR software an effective tool for hearing protection during potentially lengthy MR protocols.

As MR technology advances, we must not only ensure that our practices remain diagnostically accurate, but also work to ensure that we prioritize the well-being of personnel and patients – keeping everyone involved safe and sound.

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