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Practical Planning to Maintain Premature Infants' Safety During Magnetic Resonance Imaging

A Systematic Review

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ABSTRACT

Background: Magnetic resonance imaging (MRI) makes a significant contribution to diagnose brain injury in premature infants and is a diagnostic procedure that requires the infant to be taken out of the controlled environment established for growth and development. To ensure safe procedures for these vulnerable patients, practical planning and surveillance are paramount.

Purpose: This systematic review summarizes and evaluates the literature reporting on practical planning to maintain required safety for premature infants undergoing MRI.

Methods: Literature identified through various search strategies was screened, abstracted, appraised, and synthesized through a descriptive analysis. Thirteen research studies, 2 quality improvement projects, and 10 other documents, including practice guidelines, general reviews and articles, a book chapter, and an editorial article, were retained for in-depth review.

Conclusions: Various procedures and equipment to ensure the safety of premature infants during MRI have been developed and tested. Although the results are promising and increasingly consistent, our review suggests that more research is needed before conclusive recommendations for the use of magnetic resonance–compatible incubators, the "feed-and-sleep" approach to avoid sedation, or the specific noise-cancelling ear protection for the premature infants' safety during MRI can be established.

Key Words: feed-and-sleep, magnetic resonance imaging, MR–compatible incubator, MRI, multidisciplinary teamwork, noise protection, premature infant, safety

Magnetic resonance imaging (MRI) techniques to support diagnosis and treatment and the availability of magnetic resonance (MR)–compatible equipment specialized for neonates have advanced.[1] Magnetic resonance imaging is considered a safe technique[2,3] and is currently the diagnostic procedure of choice for neonates with encephalopathy or suspected brain injury.[4] For this procedure, the infant leaves the controlled environment established for growth and development. If performed under nonoptimal circumstances, an MRI can be a hazardous procedure. Near misses and accidents, such as burns, device failure, contrast reactions, and even death, have occurred in the MR environment.[5] Although the magnitude of these problems is difficult to establish, MRI of critically ill premature and term infants is a practice challenge.

Effective noise protection and monitoring of respiratory and cardiovascular functions and fluid-electrolyte and thermoregulatory homeostasis must be maintained during transfers and execution of the MRI.[1,3] Special steps necessary to prepare premature infants for MRI and facilitating actions should (*a*) ensure safety during the entire MRI procedure and (*b*) secure the likelihood of obtaining interpretable "good images." Therefore, steps to ensure physiologic stability, immobilize, protect against acoustic noise, and avoid threats from the static magnetic field of the MR system, need careful investigation. Because clinical expertise is integrated with the best available external evidence in evidence-based practice,[6] evaluation of currently available research is important. The aim of this systematic review was to summarize and appraise the literature reporting current best evidence that inform practical planning to maintain the premature infant's safety and concurrently obtain interpretable, high-quality images for diagnosis and treatment.

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The authors declare no conflict of interest.

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DOI: 10.1097/ANC.0000000000000142

METHODS

This systematic review was carried out in line with methodological strategies from Fink,[7] a modified version of the *Guide to Community Preventive Services* from Briss et al[8] and Zaza et al[9] for data abstraction and quality assessment, and specific principles for the synthesis process by Pinch.[10] Despite initial application in different settings, the modified *Guide to Community Preventive Services* provided an expedient instrument for the abstraction and appraisal of available evidence. Our goal is to contribute to evidence-based practical planning by "*[…] specific recommendations […] as activities that prevent […] injury […] in a group of people.*"[8(p36)]

Search Strategies

The electronic bibliographic databases searched were MEDLINE, EMBASE, Cochrane Library, CINAHL, PsycINFO, Maternity and Infant Care, and SweMed+. In addition, a weekly search in PubMed (MEDLINE) was performed from November 2011 through October 2012. A search through the latest 500 titles (of 7857) of the online version of *Pediatric Radiology* was carried out on August 15, 2012, because this journal's de facto status as a key source of progress in all areas of pediatric and fetal imaging.[11] Reference lists from all the retrieved full-text articles were reviewed. Finally, an expert on MRI security and safety reviewed the list of retained studies and documents to ensure that important sources were not missed.[7] We repeated the bibliographic searches in October 2013 combined with an automatic weekly search in PubMed until May 2014 to check for possible new publications relevant for this review. The identified publications of Reilly et al[12] and Sirin et al[13] support findings from the systematic review presented here.

The search terms were adjusted to each bibliographic database's thesaurus.[7] Truncation was added to expand the search results. The terms used are given in Table 1.

TABLE 1. Search Terms

Population	Intervention	Outcome
Premature	MRI	Safety
Preterm	MRI	Patient safety
Neonatal	MR	Physiologic stability
Infant		Hazard
Small for gestational age		Noise
Low birth weight		Noise reduction
Very low birth weight		Acoustic noise
Extremely low birth weight		Acoustic noise reduction
Neonatal nursing		Ear protective devices
Neonatal intensive care		Incubator
Neonatal intensive care unit		MRI compatible

Abbreviations: MR, magnetic resonance; MRI, magnetic resonance imaging.

Literature Screening Processes

The retrieved citations were subject to practical screening using the inclusion and exclusion criteria.[7] Literature, including "grey" literature such as studies with more limited distribution (eg, unpublished research reports, conference papers, and dissertations),[14] published in English, German, or Scandinavian languages, was relevant for inclusion. Experimental and nonexperimental studies or other types of literature reporting strategies to keep premature infants safe when undergoing MRI were eligible for inclusion. The study population had to include some infants born prematurely (<37 weeks' gestational age) and hospitalized in the neonatal intensive care unit (NICU). Literature focusing solely on the diagnostic features of MRI of premature infants was not within the scope of the review. Likewise, literature exclusively discussing regimens for sedation of premature infants during MRI was excluded because the sedation's adverse effects, such as bradycardia, apnea, and desaturation raise another set of safety concerns for this patient group.[15]

The body of knowledge and evidence on practical handling to maintain the safety of premature infants undergoing MRI is small, and comparative research studies are few. The appraisal of quality improvement projects, along with research studies, may be questioned; however, we chose to include this body of work because all methods can provide some information on the appropriateness of interventions.[16]

Data Analysis

The modified data abstraction form[8,9] facilitated consistent data extraction and assisted the methodological screening process to establish the suitability of the study design and the quality of the study execution. Determining the suitability of the study design classifies the particular studies' attributes and evidence of effectiveness as *greatest*, *moderate*, or *least*.[8] Determining the quality of the study execution considered 6 categories of possible validity threats: (1) study population and intervention descriptions, (2) sampling, (3) exposure measurement and outcome measurement, (4) data analysis, (5) interpretation of

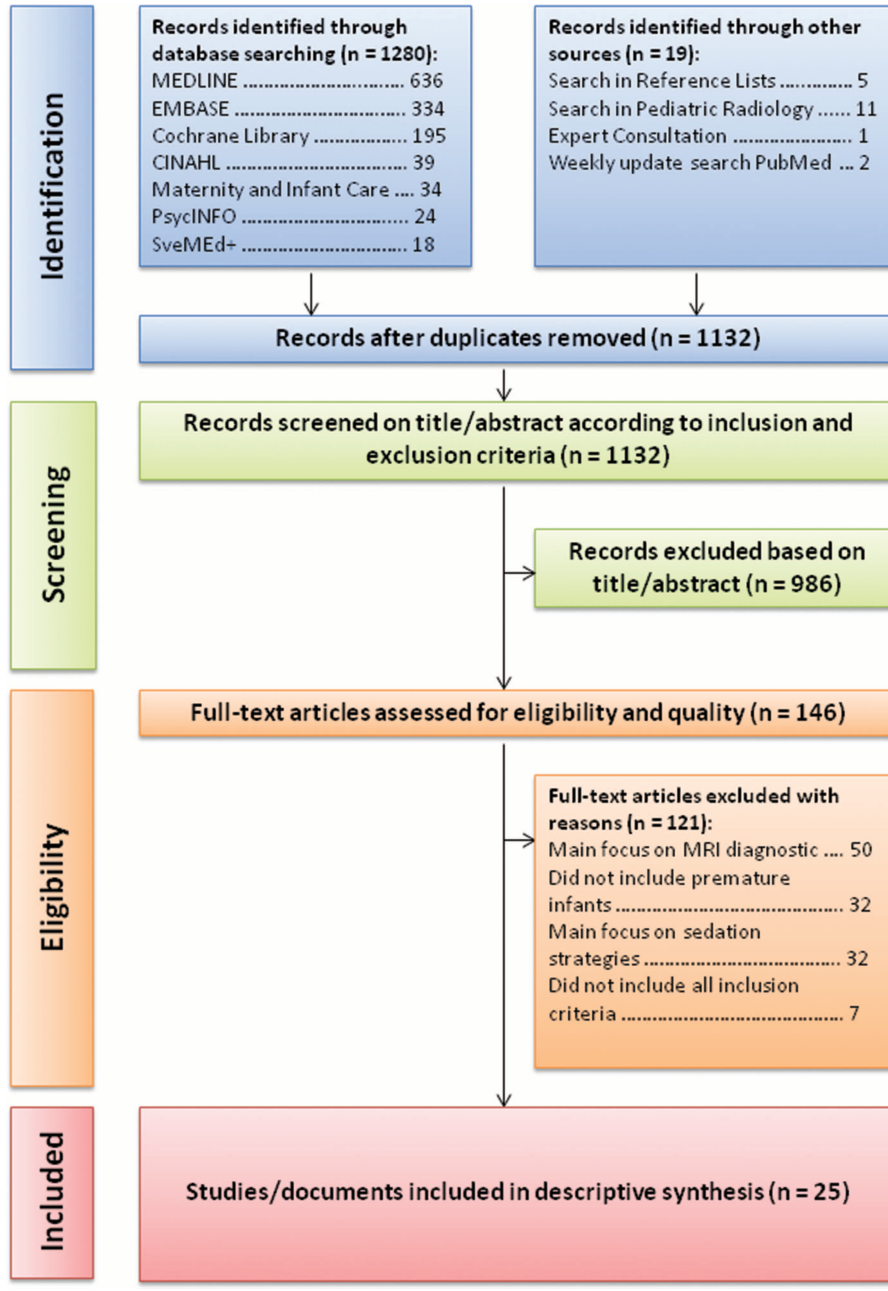
results (including follow-up, bias, and confounding factors), and (6) all other important limitations not identified elsewhere.[8] The quality of the study execution was deemed as *good*, *fair*, or *limited* on the basis of the number of limitations.[8]

Heterogeneity in purpose, design, and form in the studies ruled out the feasibility of a meta-analysis.[7] Therefore, we report a descriptive synthesis focusing on similarities and differences. The data were analyzed in 2 steps. First, the research studies and the quality improvement projects were separated from the other types of literature to assess the strength of evidence of different interventions. Second, the retained literature as a whole was synthesized using content analysis.[10]

RESULTS

As presented in Figure 1, 1107 references of the 1132 identified references were excluded according

FIGURE 1.



Search strategies and screening process. *Abbreviation*: MRI, magnetic resonance imaging.

to inclusion and exclusion criteria. Twenty-five references were retained for review: 13 research studies, 2 quality improvement projects, 2 guidelines, 4 reviews, 2 articles, 1 books chapter, and 1 editorial.

Evidence From the Research Studies

The 13 research studies included 1 study with comparison of 2 different imaging modalities in the same group, 3 studies with comparison between groups (before–after), 2 studies with comparison between different settings for the same patients, and 7 noncomparative studies (see Table 2 for details).

Evidence From the Quality Improvement Projects

Haney et al[17] and Plaisier et al[18] reported work drawing from a "Plan Do Study Act Quality Improvement" model,[19,20] which included study elements such as comparison between groups (before-after) and comparison between settings, respectively (see Table 3 for details).

Evidence From Guidelines, Reviews, Articles, Book Chapter, and Editorial

To display the full extent of the currently available information, we included all types of articles reporting planning and maintenance of safety for premature infants during MRI. Practice guidelines, general reviews and journal articles, a book chapter, and an editorial were added (see Table 4). In the final synthesizing process, their data were abstracted in a similar way as the research studies and quality improvement projects. Data from the guidelines, reviews, and articles[21-30] elaborate clinical experience and expert opinions about details and specifics of practical patient handling, preparations, and the specialized equipment needed.

Study Classification and Study Quality Assessment

The methodological screening process indicated that none of the research studies and quality improvement projects ($n = 15$) could be categorized as having the "greatest design suitability." One study that compared image quality between MRI and ultrasound images[31] was judged to have the "moderate design suitability" for assessing evidence of the effectiveness of an intervention. Fourteen studies were judged as having the "least suitable study design" to provide evidence of effectiveness because they were either single before-after studies with no concurrent comparison group, or studies with comparison of different settings for the same patients, or studies that did not include comparison at all. To illustrate the variation in these 14 studies, 4 studies[17,32-34] compared patient outcomes from MRI with a historical group of patients, 3 studies[18,35,36] measured and compared physiologic vital signs from the same patients starting at departure from the NICU, time in the radiology department, and return to the NICU, 5 studies[37-41] tested their MRI procedures and MR-compatible equipment without any comparison, and 2 studies[42,43] tested devices for life support and an acoustic hood, respectively.

In several studies, the design did not allow for application of all the "quality of study execution" criteria. Limitations in description reflected a lack of details, such as actual postconceptual age, weight at the time of MRI,[17,32-34,38] and weight at the time of birth.[36,40] Sampling limitations included lack of specified screening criteria, reports of convenience sampling rather than probability sampling from the eligible population,[18,33,38,40,41] or possible bias in the number of MR examinations that used an MR-compatible incubator.[32] Limitations in the interpretation of results with respect to confounders included reports of cold air/oxygen during the MR procedure[18] and insufficient noise protection that could contribute to heart rate fluctuations.[36] Furthermore, a lack of descriptions of patient handling, for example, swaddling techniques and ear protection,[17] made interpretations hard to follow or difficult to assess causes of degraded image quality.[33,34] The "all others" category of validity threats reflects that partial information was missing. There was limited information about the total effect of a recommended noise-protective regimen,[43] whether or not ear protection was provided,[32,38,41] or reports of physiologic vital signs when concluding that an MR-compatible incubator allows safe, efficient MRI of nonsedated neonates[38] or unstable critically ill premature infants.[32]

Six studies with the least suitable design and a fair quality of study execution suggested that an MR-compatible incubator could provide a safe microenvironment for premature infants during MRI.[32-34,38,40,41] Even though the number of studies consistently reporting these results compensate for the limitations in study design and study execution, the heterogeneous outcome measurements did not allow for feasible effect size calculation.

Given the overall assessment of the suitability of the study design, the quality of the study execution, and effect size, the included studies does not allow conclusive recommendations such as the use of an MR-compatible incubator for a safe microenvironment, a feed-and-sleep approach to replace sedation during MRI, or explicit approaches for acoustic noise protection during MRI.

Taken together, the literature included for the review revealed the following 4 themes pertinent to establish current best practice to maintain safety for premature infants during MRI: *multidisciplinary teamwork*, *monitoring*, *patient handling*, and *equipment* (see Figure 2).

TABLE 2. Research Studies

Type	Author, Country	Intervention	Patient Population	Outcome
Prospective comparison: Groups and setting, double blind	Whitby et al,[31] UK	Comparison of image quality between MRI and ultrasound images of the brain	*Group 1, infants with suspected pathology, (n = 43)* 23 premature + 20 term neonates GA at birth: 24 term weeks (median = 30) Age at scan: 5 h-332 days (mean = 16.2 days) Birth weight: 670–4110 g (median = 1415) Weight at scan: 880–4900 g (median = 2000) *Group 2, control group (n = 89)* 40 premature + 49 term neonates	All neonates tolerated the scans MRI gave more information and detected more pathology than ultrasound images in 56% of the cases compared
Comparison study—groups: Before-after study	Blüml et al,[33] UK	MR-compatible incubator with integrated RF coils	*Group 1, intervention group (n = 13)* GA at birth: 24–41 weeks Postnatal age at scan: 4–12 weeks Use of MR-compatible incubator *Group 2, control group (n = 6)* Age matched with intervention group	Physiologic stability during MRI Improved image quality using the MR-compatible incubator
Retrospective Comparison—groups: Before-after study	O'Regan et al,[34] Ireland	MR-compatible incubator with integrated RF coils	*Group A (n = 15)* Standard MR equipment and parameters GA at birth: 30–41weeks (mean = 38) Postnatal age at scan: 2–56 days (mean = 18.9) Weight: 1.4–4.1 kg (mean = 3.1) *Group B (n = 15)* MR-compatible incubator and standard parameters GA at birth: 31–42 weeks (mean = 38) Postnatal age at scan: 1–49 days (mean = 11.3) Weight: 1.6–4.4 kg (mean = 3.6) *Group C (n = 9)* MR-compatible incubator and modified parameters GA at birth: 35–41 weeks (mean = 40) Postnatal age at scan: 5–15 days (mean = 9) Weight: 2.9–4.5 kg (mean = 3.8)	An MR-compatible incubator provides a safe environment for MRI Image quality improved when using MR-compatible incubator in combination with modified parameters in the MRI scan protocol Achievement of better image quality and a higher number of diagnostic MR studies requires close cooperation among the neonatal team, radiographers, and radiologists

(*continues*)

TABLE 2. Research Studies, Continued

Type	Author, Country	Intervention	Patient Population	Outcome
Retrospective Comparison—groups: Before-after study	Rona et al,[32] Austria	MR-compatible incubator	*Intervention group (n = 99)* Used an MR-compatible incubator Mean GA = 38.82 weeks Mean weight: 2766 g *Comparison group (n = 30)* Mean GA = 43.0 weeks Mean weight: 3308 g	Increased number of examinations Significantly decreased mean age and mean weight at imaging time Mean imaging time decreased
Comparison: Setting	Benavente-Fernandez et al,[35] Spain	Evaluation of MRI procedure; vacuum immobilizer	*Premature, VLBW infants (n = 33)* GA at birth: 25–33 weeks (mean = 29.44) Birth weight: 900–1750 g (mean = 1258.48) 23 males + 10 females	No significant changes in heart rate, SaO_2, and temperature during the procedure Safe MRI of VLBW infants require intensive monitoring and multidisciplinary coordination
Comparison: Setting	Taber et al,[36] US	Vital sign changes throughout the MRI procedure	*Premature (n = 2)* Age at scan: 28 days *Term neonates (n = 10)* Age at scan: 2–22 days	Abrupt changes in heart rate recorded at prescan and during scan SaO_2 just slightly changed Greater fluctuations in heart rate during MRI compared to the nursery
Noncomparison	Battin et al,[39] UK	Monitoring of physiological stability during MRI	*Premature infants (n = 23)* GA at birth: 23–32 weeks (median = 27) Postnatal age at initial MRI: 1–42 days (median = 3) Birth weight: 610–1780 g (median = 920)	Small increase in heart rate and SaO_2 and slight increase in temperature during MRI Noise levels 67–72 dBA
Noncomparison	Erberich et al,[41] US	MR-compatible incubator	*Premature infants (n = 7)* GA at birth: 24–39 weeks (mean = 28.6) Postconceptual age at scan: 34–58 weeks (mean = 41.4) Birth weight: 701–2636 g (mean = 1230.86) Weight at scan: 1200–4590 g (mean = 2702.14) 5 males + 2 females	Variations in skin temperature <0.5°C, and SaO_2 levels <3% MR images obtained with the MR-compatible incubator had an SNR improvement by a factor of >2.3

(*continues*)

TABLE 2. Research Studies, Continued

Type	Author, Country	Intervention	Patient Population	Outcome
Noncomparison	Groenendaal et al,[42] The Netherlands	Effects of a 1.5 Tesla MR scanner on devices for life support	Patients not included A ventilator, an infusion pump, an MR incubator, and monitoring equipment were tested in the environment of a 1.5 Tesla MR scanner Acoustic noise levels were measured	MRI can be performed safely in ill preterm neonates who require life-support devices Noise level in the patient area 80 dB
Noncomparison	Merchant et al,[37] UK	A system for 3.0 Tesla MRI of VLBW infants who did not require mechanical ventilation	*Premature, VLBW infants (n = 70)* PMA at birth: 24.57–36.29 weeks (median = 27.29) PMA at scan: 25.29–37.14 weeks (median = 30.0) Postnatal age at scan: 1–45 days (median = 14) Birth weight: 580–1575 g (median = 965) Weight at scan: 590–1490 g (median = 940)	No patients were significantly hypo- or hyperthermic Heart rate and SaO_2 remained stable during examination No significant adverse events
Noncomparison	Nordell et al,[43] Sweden	Acoustic hood	Sound pressure measurements with and without the acoustic hood were performed during a clinical neonatal scan protocol including 8 imaging sequences	Noise levels 87.37—102.43 dBA Peak sound pressure reduced 16.18-22.21 dBA with the acoustic hood Recommends dental putty, pediatric ear muffs and the acoustic hood
Noncomparison	Paley et al,[40] UK	MR-compatible incubator	*Premature + term neonates (n = 8)* No details about GA and weight	Stability during transport and scanning High quality MR images
Noncomparison	Whitby et al,[38] UK	MR-compatible incubator	*Premature + term neonates (n = 7)* GA at birth: 24 weeks to full term Age at scan: 2 d to 4 months after birth	Stability throughout scanning Imaging successful Good-quality images

Abbreviations: GA, gastrointestinal; MR, magnetic resonance; MRI, magnetic resonance imaging; PMA, postmenstrual age; RF, radio frequency; SaO_2, oxygen saturation; SNR, signal-to-noise; VLBW, very low birthweight.

TABLE 3. Quality Improvement Projects

Type	Author, Country	Intervention	Patient population	Outcome
Quality improvement project	Haney et al,[17] US	Vacuum immobilizer and prescan feed instead of sedation	GA at birth: 23–42 wks (mean 36). Age at scan: 0-370 d (mean 28), weight at scan: 1.3-6.7 kg (mean 3.1)	Mean time away from the NICU significantly decreased with the immobilizer and prescan feed rather than sedation
Comparison groups: before and after study			*Baseline group (n = 154)*: MRI with sedation *Nonsedated group (n = 155)*: prescan feed + vacuum immobilizer	3% mild complications without sedation compared with 5% mild and 4% moderate patient complications when using sedation Fewer incomplete images not using sedation Multidisciplinary teamwork important
Quality improvement project	Plaisier et al,[18] The Netherlands	Evaluation of MRI procedure using an MR-compatible incubator	*Premature, VLBW infants (n = 52)*: GA at birth: mean 26.8 wks ±1.4 (SD) PMA at scan: 30.1 wks ±0.3 (SD) (range $29^4/_7$–$30^4/_7$). Birth weight: mean 967 ± 247 g (SD), weight at scan: mean 1133 ±197 g (SD) 30 males + 22 females. Use of an MR-compatible incubator	Minor adverse events after MRI scan were common and should not be underestimated
Comparison setting				A checklist, including a time-out procedure, may reduce the risk of adverse events caused by incorrect execution of the procedure A multidisciplinary-based approach with continuous reevaluation of the guidelines necessary for VLBW infants' safety

Abbreviations: GA, gastrointestinal; MR, magnetic resonance; MRI, magnetic resonance imaging; NICU, neonatal intensive care unit; PMA, postmenstrual age; VLBW, very low birth weight.

DISCUSSION

Critically ill infants hospitalized in the NICU require complex multiprofessional care because their small size and immature physiology leave little margin for error.[44] Specific care and consideration are important when a diagnostic procedure requires to take the infant out of his or her stable microenvironment.

Multidisciplinary Teamwork

A substantial part of the literature reports close multidisciplinary teamwork, understood as cooperation and communication between the NICU and MR staff, as essential for the safe and successful MRI of neonates.[17,18,21,22,24-26,29,34,35] Comprehensive procedures and guidelines to ensure safe MRI are core dimensions of this teamwork.[18,22,25,26] Use of a checklist, including a time-out-procedure, can be very helpful to strengthen teamwork and reduce the possibility of adverse events and incorrect execution of the procedure.[18] A time-out procedure includes a quick recheck before leaving the NICU, ensuring that the correct infant is properly prepared, physiologically stable and comfortable, and the MR department is ready to scan the infant.[18] Concurrently, NICU and MR staff need to understand the use of special MR-compatible equipment to maintain patient safety and ensure the MR image quality.[17,22,24-26,34] Specifically, planning for emergency situations entailing multidisciplinary teamwork is highlighted.

TABLE 4. Guidelines, Reviews, Articles, Book Chapter, and Editorial

Type	Author, Country	Content	Patient population	Conclusion
Best practice guideline article	Van Wezel-Meijler et al,[21] The Netherlands	Presentation of practice and experience on neonatal MRI	*Premature ± full term neonates*: Ventilated and/or unstable neonates. Stable, nonventilated neonates. Sedation used. ± MR-compatible incubator.	Addresses: indication and timing, safety, patient preparation and transportation, feeding and sedation, technical aspects, sequences, and scan protocols
Review/ guideline	Mathur et al,[22] US	Presentation of experience and guideline for MRI	*Premature ± full term neonates*: Critically ill neonates and noncritically ill neonates. No use of sedation. ± MR-compatible incubator.	Given appropriate equipment, training, and staff, neonatal MRI is routinely and safely performed without sedation A core group of nurses and neonatologists should serve as resources
Review	Arthurs et al,[23] UK	Challenges in neonatal MRI, MR practicality, and nursing practice		MRI of neonates is an emerging field where considerable advances remain to be made Focus on imaging the sick infant, including equipment compatibility and consideration of acoustic noise
Review	Hillenbrand and Reykowski,[24] US	Particular needs, equipment, and techniques for neonatal MRI		Integration of a dedicated MR systems in the NICU, improvements in incubator technology and handling, and more efficient use of scan/sedation time by choosing dedicated neonatal imaging equipment
Review	Purdy and Wiley,[25] US	Familiarization of MRI of VLBW infants		The nurse must be familiar with the advantages and disadvantages of MRI, and the MRI procedure to be better prepared for monitoring the infant undergoing MRI
Review	Stokowski,[26] US	Potential hazards associated with MRI and strategies to promote safety for neonatal MRI		The MR-compatible incubator is promising for safe MRI of small and less stable infants Proper education of staff and attention to detail in preparing the infant for MRI are keys to safety Safety remains a top priority for clinical and research applications of MR technology for the vulnerable infant

(*continues*)

TABLE 4. Guidelines, Reviews, Articles, Book Chapter, and Editorial, Continued

Type	Author Country	Content	Patient population	Conclusion
Article	Dumoulin et al,[27] US	MR-compatible incubator		The MR-compatible incubator table permits performance of MRI on infants otherwise excluded
Article	Whitby et al,[28] UK	MR-compatible incubator		MR-compatible incubators can double as transport incubators and reduce the amount of handling and maintain required environmental conditions Sedation reduced by decreased overall scanning time
Book chapter	Maalouf and Counsell,[29]	Practical issues related to MRI of the preterm infant using a MR system installed in the NICU		MRI of premature infants receiving intensive care safely performed using a dedicated neonatal MR scanner in the NICU Attention to detail when transferring a sick ventilated infant into the scanner Fast imaging sequences decrease examination time and avoid unnecessary sedation
Editorial	Stokowski,[30] US	MR-compatible incubator		A key advantage of MR-compatible incubator is that the infant is not moved from a transport incubator to the MR scanning table

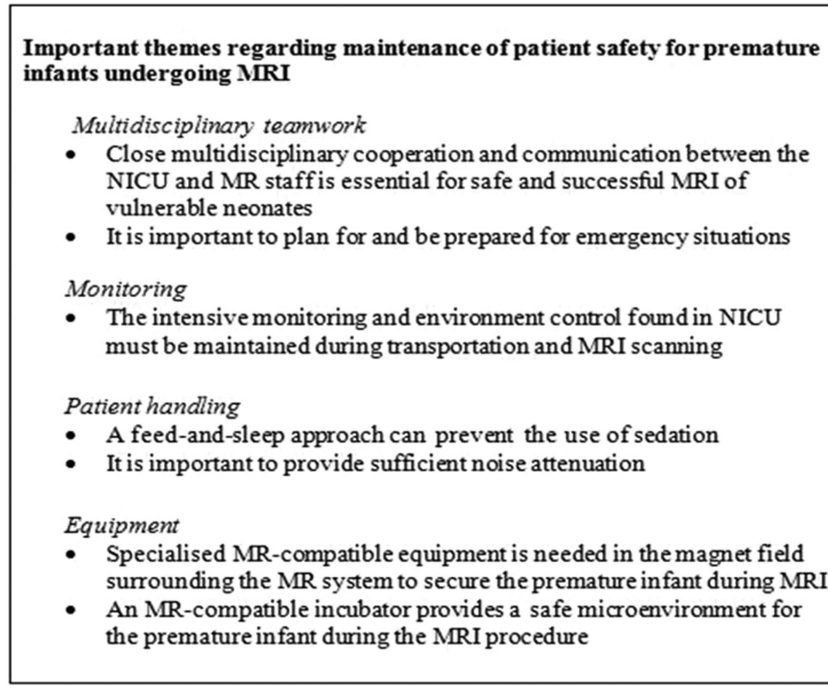
Abbreviations: MR, magnetic resonance; MRI, magnetic resonance imaging; NICU, neonatal intensive care unit; VLBW, very low birth weight.

Full, appropriate resuscitation equipment for premature infants and staff trained in neonatal resuscitation must be available during the transportation and the MRI scan.[21-24,27,31,40] However, important emergency equipment may not be MR-compatible. To avoid harm from ferromagnetic resuscitation equipment inadvertently brought into the MR room,[5] all resuscitation equipment should be kept outside. Therefore, in case of an emergency, the infant must be taken out of the MR room for stabilization[21-24,26,27,29,37] to allow participation from all specialties in the resuscitation procedure without influence of the strong magnetic field.[45] Team training where NICU and MR staffs participate should be conducted regularly, emphasizing handling resuscitation outside the MR room.[23,24,26]

Monitoring

To maintain patient safety, the intensive monitoring and controlled environment of the NICU must be maintained throughout the MRI procedure,[24,27-29] from the time the infant leaves the NICU, during the MRI scan, and until return to the NICU. A safe thermal environment and the monitoring of vital signs and parameters such as temperature, heart rate, and oxygen saturation are pivotal. Several studies reported physiologic stability during MRI.[17,31,33-35,37-41] However, in one study, episodes of bradycardia, apnea, desaturations, and hypothermia (<36°C) were reported within the 24 hours *after* the MRI.[18] Plaisier et al[18] suggested that the increased incidence of hypothermia could be explained by cold air or oxygen in the ventilation circuit during the transportation and the MRI scan. In this specific study, the subjects were very low-birth-weight (VLBW) infants, all weighing less than 1500 g, at the time of MRI examination. Their reported vulnerability may relate to underdeveloped or poorly functioning systems for thermal regulation.[46-48] Symptoms of hypothermia and cold stress in premature infants include

FIGURE 2.



Patient safety themes emerged from the synthesized literature.
Abbreviations: MR, magnetic resonance; MRI, magnetic resonance imaging; NICU, neonatal intensive care unit.

bradycardia; shallow, irregular breathing; a decreased respiratory rate; acidosis; hypoxia; and restlessness.[47] Merchant et al[37] reported the use of an MR-compatible humidifier for warming the gases for those requiring respiratory support to maintain physiologic stability in VLBW infants. Ventilated infants can experience high fluid and heat losses from the respiratory tract.[48] Hence, adequate humidification and heating of the gases in all ventilator circuits can contribute to safety throughout the MRI procedure. Although minor adverse events were reported when imaging VLBW infants,[18] 3 studies[35,37,39] indicated that MRI of VLBW infants is feasible and safe if a stable thermal microenvironment is maintained. A safe thermal environment can be achieved by control of the immediate environment using metal-free clothing, prewarmed sheets and blankets, bubble wrap, a prewarmed gel mattress, a vacuum bag, or an MR-compatible incubator.[17,18,21-26,29,32,33,38] Safety is inspected by close visual monitoring of the infant's well-being and physiologic state by a neonatal staff member staying with the infant in the scan room at all times.[22,25-27,29,31,38]

Patient Handling

Preparations to stabilize the premature infant—to prevent excessive patient handling, reducing the need for unwrapping, awakening, or repositioning—should be performed in the NICU before transport to the radiologic department and the MR room.[17,21,24,26-30,32-34,37,39,40] Swaddling can help to maintain a safe thermal environment, increase comfort and well-being, reduce the use of sedation, and optimize immobilization and workflow to increase the likelihood of good image quality.[17,22-26,29,31,34,35,40] Pacifiers can enhance comfort and sleep during MRI,[22,23,25] although there is a concern that a pacifier might produce motion artifacts.[22,26]

A Swaddling-Feed-Sleep Approach

Good-quality MR images require that the patient remain motionless.[49] The slightest movement of the body part being imaged will cause motion artifacts and blurred images. Sedation has been a common strategy to ensure that the infant lies still during MRI.[50] Several of the reviewed studies[17,21,32,33,36,39,41,43] had sedation as one of the strategies to ensure high-quality MRI. Sedation during MRI is relatively safe.[51,52] However, attention has been drawn to the premature infant's vulnerability for adverse effects of sedation, for example, prolonged medical effect causing bradycardia, apnea, and desaturation.[15] Haney et al[17] compared sedation to a "swaddling-feed-sleep" approach. The swaddling-feed-sleep approach included giving the infant a prescan feed, stabilizing by a gentle swaddling in blankets after applying

monitoring devices, and finally adding a vacuum-immobilizing bag to cover the infant. Significantly fewer complications were encountered in patients who did not receive sedation.[17] These results are supported by the recent study from Reilly et al.[12] Several papers suggest replacing sedation with a swaddling-feed-sleep approach to enhance sleep during MRI.[22-26,29,34,43] Other publications have reported that most infants lay still under natural sleep following prescan feed and immobilization by gentle swaddling.[12,53–63] This is very promising in terms of clinical use value. However, because of the lack of controlled comparison in several of the reviewed studies, more evidence of the swaddling-feed-sleep approach for premature infants would be appreciated to allow for conclusive recommendations. Given the study population's vulnerability and frequency of MRI examinations, it is probably not likely or feasible to set up full-scale randomized controlled trials. However, well-elaborated and well-executed "before-after" studies will yield knowledge to recommend strategies that maintain safety during the MRI procedure.

Noise Protection

Acoustic noise produced by an MR system is of high intensity. This high-intensity noise is likely to cause anxiety and temporary hearing loss and may, in extreme cases, cause hearing impairment.[2,5,64,65] Premature infants' immaturity makes them especially vulnerable to noise exposure.[66,67] Protection from excessive noise emanating from the MRI scanner is crucial.[22–26,28,29,39,42] Taber et al[36] documented a sharp increase in heart rate synchronized with the onset of the prescan and/or the scan portion of the MRI scan, even though the study subjects' heads and ears were covered with foam padding for stabilization. Standard recommendations for noise in the NICU state that transient sound should not exceed 70 dB.[66,68] This conflicts with the sound level exposure during MRI. The report of Price et al[69] on acoustic noise levels of 118.3 dB(A) in a high-field strength MRI scanner underlines the importance of providing sufficient noise protection for premature infants undergoing MRI. Different types of earplugs and earmuffs used alone or in different combinations have been suggested.[17,18,21,22,24-26,35,37,40] Specialized equipment covering the infant's ears and head, for example, vacuum bags, bags filled with polystyrene balls, layers of blankets, or a double-walled MR-compatible incubator may provide additional auditory shielding.[23,24,26,27,29,32,39,40] Evidence supporting the effect of different noise attenuators used in combination is scarce. Nordell et al[43] reported that a patient-independent *acoustic hood* inserted into the bore of the MR scanner covering the infant reduced acoustic noise of 16.18 to 22.21 dB depending on the pulse sequence. They recommended using dental putty and pediatric ear muffs together with the acoustic hood.[43] Purdy and Wiley[25] stated that combining earplugs with 32-dB noise-reduction ratings, soft-shell earmuffs, and infant-sized MRI headphones decreased noise levels to approximately 50 dB. However, Arthurs et al[23] warned that the combination of earplugs and headphones together did not provide a sum total of the individual single number rating/noise reduction ratings; instead, around 6 dB of additional reduction is achieved.[70] Therefore, at this point there is not sufficient evidence to recommend decisive strategies for noise protection for premature infants undergoing MRI. The true noise-reducing effects of different noise attenuators used in combination during MRI need further investigation.

Equipment

Ferromagnetic objects inadvertently brought into the MRI environment represent significant safety risks. They can become projectiles attracted violently into the bore of the MR scanner if they come within the magnet field surrounding the scanner.[23-26,28] It is obvious that all monitoring equipment must be compatible with the MR magnet and the MR protocols in use. It adds significant challenges to practical handling that older equipment and devices tested with a 1.5-Tesla MR magnet cannot be assumed to be safe with a 3.0-Tesla MR magnet and vice versa.[5] Therefore, the infant, staff members, and other people present must be checked for metal inside the body, on the body, or close to the skin before entering the MRI room.[21,23-27,29,40]

MR-Compatible Incubator

An MR-compatible incubator can maintain a safe microenvironment during MRI. This equipment was highlighted as advantageous in a substantial number of the retained articles[21,22,26-28,30,32-34,38-42] and the most recent study from Sirin et al.[13] The MR-compatible incubator is promising to provide safety for an infant with monitoring equipment and stabilizing devices. This enables a stable temperature and microenvironment and maintains an effective workflow. A key advantage is reduced disturbances from excessive handling of the infant, minimizing the use of sedation.[13,23,26,28-32] However, the 6 reviewed studies testing the use of an MR-compatible incubator [32-34,38,40,41] had outcome measures that were too heterogeneous, making it infeasible to calculate any effect size across these studies. Therefore, there is currently no sufficient evidence to support conclusive recommendations for an MR-compatible incubator as the strategy of choice to secure a safe microenvironment for the premature infant during MRI. The MR-compatible incubator's double-walled construction may provide auditory shielding.[26,27,32] However, evidence of the true auditory shielding effect of an

MR-compatible incubator in different MR-systems and during different MR-scanning protocols is limited. Caution is also warranted since some MR-compatible incubators may be incompatible with some field strengths and MR systems.[21] In addition, the results of the combination of radio frequency heating by particular rapid MRI sequences and a controlled heated environment in an incubator are unknown.[23] Finally, a disadvantage is the expense of MR-compatible incubators,[21,23] although tests of a low-cost, low-weight MR-compatible incubator showed a maintained safe microenvironment.[40] The reviewed literature demonstrates the increasing use of the MR-compatible incubators. For future research, we suggest studies to consider cost-effective MR-compatible equipment, a head-to-head comparison of the MR-compatible incubator versus the vacuum bag focusing on the infant's vital signs and well-being, image quality, and time away from the NICU, together with an estimation of material and personnel resources. Likewise, studies comparing costs, quality, and possible side effects of sedation versus the feed-and-sleep technique combined with the vacuum bag or the MR-compatible incubator, would be useful to establish more uniform practical handling strategies for safety during MRI.

Limitations and Strengths

This systematic review includes currently available literature (within the limitations of language) about practical planning for safety for premature infants undergoing MRI. Because no randomized trials were found, the work started with the next-best sources of evidence.[6] Given the limited amount of literature available, the review was all-inclusive, covering research studies, quality improvement projects, and other sources of literature (guidelines, reviews, articles, book chapter, and editorial). Although the inclusion strategy can be questioned, appraisal of quality improvement projects along with research studies adds information on the appropriateness of interventions. In addition, an obvious strength is the thorough presentation providing a transparent and reproducible base for recommendations of different interventions (access to data abstraction work can be made available on request). We demonstrate by example areas where research is lacking. Another apparent limitation of this systematic review is the available time and resources to perform the review. The journal *Pediatric Radiology* was singled out for hand searching because of these constrains.

CONCLUSION

This review of current best practice suggests that multidisciplinary teamwork with close cooperation, and communication between the NICU and MR staffs, is essential for safe, successful MRI. Maintaining the intensive monitoring and controlled NICU environment is a challenge throughout the MRI procedure. The reviewed literature reports consistently different strategies for practical planning to maintain the premature infant's safety during MRI. An MR-compatible incubator can provide a safe microenvironment. Prewarmed sheets and blankets and a vacuum immobilization bag can also secure the required thermal environment. Rather than sedation, a swaddling-feed-sleep approach can be used to reduce image artifacts. Stabilizing the infant in a vacuum immobilizer or an MR-compatible incubator in the NICU before transportation prevents excessive handling and reduces the need for unwrapping, awakening, and repositioning the infant during the procedure. More studies are needed to reveal the true noise-reducing effects of different types of noise attenuators used in combination during MRI. For conclusive recommendations on practical handling to maintain the premature infant's safety undergoing

Summary of Recommendations for Practice and Research	
What we know:	• Infants must lie still (sleeping) for a quality magnetic resonance imaging (MRI) study • Sedation to ensure a quality MRI study is not without risk • The MRI setting is a challenge to ensure physiologic stability • The MRI setting is a noise hazard
What needs to be studied:	• The best method to protect against noise exposure • Safe and effective strategies to ensure a quality MRI
What we can do today:	• Establish an MRI protocol for obtaining infant studies to include multiple disciplines from the neonatal intensive care unit and radiological department settings to include strategies for ongoing monitoring, normothermic status, immobilization, and emergency response • Use strategies to prevent excessive patient handling in the MRI setting • Explore strategies to protect against MRI noise exposure

MRI, we suggest studies of the following dimensions alone or in combination: (*a*) MR-compatible incubator versus a vacuum bag, (*b*) different stabilizing and noise-reducing strategies, and (*c*) sedation versus a feed-and-sleep technique.

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Disclosure Statement: The authors and planners have disclosed that they have no financial relationships related to this article.

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DOI: 10.1097/ANC.0000000000000163