Image quality associated with the use of an MR-compatible incubator in neonatal neuroimaging

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Objectives: MRI in the neonate poses significant challenges associated with patient transport and monitoring, and the potential for diminished image quality owing to patient motion. The objective of this study was to evaluate the usefulness of a dedicated MR-compatible incubator with integrated radiofrequency coils in improving image quality of MRI studies of the brain acquired in term and preterm neonates using standard MRI equipment.

Methods: Subjective and objective analyses of image quality of neonatal brain MR examinations were performed before and after the introduction of an MR-compatible incubator. For all studies, the signal-to-noise ratio (SNR) was calculated, image quality was graded (1–3) and each was assessed for image artefact (e.g. motion). Student's *t*-test and the Mann–Whitney *U*-test were used to compare mean SNR values.

Results: 39 patients were included [mean gestational age 39 weeks (range 30–42 weeks); mean postnatal age 13 days (range 1–56 days); mean weight 3.5 kg (range 1.4–4.5 kg)]. Following the introduction of the MR-compatible incubator, diagnostic quality scans increased from 50 to 89% and motion artefact decreased from 73 to 44% of studies. SNR did not increase initially, but, when using MR sequences and parameters specifically tailored for neonatal brain imaging, SNR increased from 70 to 213 ($p=0.001$).

Conclusion: Use of an MR-compatible incubator in neonatal neuroimaging provides a safe environment for MRI of the neonate and also facilitates patient monitoring and transport. When specifically tailored MR protocols are used, this results in improved image quality.

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MRI of the brain is an important clinical tool for the evaluation of neonates with encephalopathy, suspected brain injury or developmental brain anomalies. Specific MR techniques may also provide information on myelination, metabolism and functional capabilities of the neonatal brain [1–3].

Neuroimaging in the neonate presents a number of challenges. Transporting the critically ill neonate to the MRI unit presents significant practical problems. These infants require a carefully controlled microenvironment with a need for thermoregulation and constant haemodynamic monitoring and may need ventilatory support [4]. Handling the infant immediately prior to image acquisition can cause distress, and resultant movement may produce non-diagnostic images due to motion artefact. Sedation of neonates and infants can be performed but is not without risk, and a sedated neonate requires continuous monitoring during the examination with MR-compatible pulse oximetry and electrocardiogram [5, 6].

MR-compatible neonatal incubators have been developed to provide a safe and efficient method of transporting neonates to the MR suite and to allow monitoring of the baby during the examination. Stabilisation of the neonatal head within the incubator and close attention to

swaddling technique are necessary to reduce patient movement during image acquisition, thereby reducing the need for sedation. Many of these incubators are equipped with an integrated radiofrequency (RF) coil, specifically tailored to the size of the neonate, which should improve image quality by increasing the signal-to-noise ratio (SNR). Previous studies have shown promising results with regard to patient safety [7, 8]. Currently, there is little information on how image quality from an integrated incubator-coil unit compares with standard MR equipment [8]. Maximising image quality can be achieved by using a closely fitting RF coil (a dedicated neonatal head coil or a knee coil) and by modifying MR sequences which need to be specifically tailored to the neonatal brain because of its higher water content [5].

The aim of our study was to compare the imaging performance of an MR-compatible incubator with integrated RF coils with standard MRI equipment in both term and preterm neonates.

Methods and materials

Study population

Brain MR examinations of term and preterm neonates ($n=49$) performed during a 2 year period (December 2006–December 2008) were retrospectively reviewed.

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Table 1. MR acquisition parameters in Groups A, B and C. All sequences were performed on a Siemens Magnetom Avanto 1.5 T (Siemens, Erlangen, Germany). Parameters were changed in Group C in order to optimise signal-to-noise ratio

Results	Group A (Standard MR equipment and parameters)	Group B (MR-compatible incubator with standard parameters)	Group C (MR-compatible incubator with modified parameters)
TR	4750	4750	4000
TE	140	140	118
Section thickness (mm)	4	4	5
Slice interval	1.3 mm	1.3 mm	1.6 mm
FOV	18 × 18 cm	18 × 18 cm	20 × 20 cm
Matrix size	216 × 384	216 × 384	192 × 256

FOV, field of view; TE, echo time; TR, repetition time.

Mean gestational age was 38 weeks (range 30–42 weeks) and the mean postnatal age was 13 days (range 1–56 days). Mean weight was 3.5 kg (range 1.4–5.7 kg). The patients were divided into three groups as follows: Group A, patients imaged prior to the introduction of the MR-compatible incubator using standard MR sequences and equipment (knee coil); Group B, patients imaged using the MR-compatible incubator and standard MR sequences; and Group C, patients imaged using the MR-compatible incubator and modified MR sequences.

MR-compatible incubator

The system used was a LMT Nomag IC 1.5 MR Incubator System (Lammers Medical Technology, Lubeck, Germany). The system comprises an incubator (dimensions 186 × 34 × 35 cm), a non-magnetic trolley, an independent

gas (non-magnetic gas cylinders) and power supply for transport and an integrated RF coil (LMT Neonatal Head Coil 1.5 T; Lammers Medical Technology) and built-in pulse oximetry. The system is suitable for neonates and infants up to 4.5 kg in weight and 55 cm in length. The incubator provides air temperature control (28–39°C; 82.4–102.2°F) and humidity control (30–70%).

MR examinations

All MR examinations were performed on a Siemens Magnetom Avanto 1.5 T MR system (Siemens, Erlangen, Germany). Routine imaging consisted of sagittal and axial T_1 weighted spin echo imaging, axial T_2 weighted spin echo imaging and T_2 weighted coronal and diffusion-weighted sequences. In Groups A and B, the following parameters for T_2 weighted imaging were used

Figure 1. Subjective grading system of image quality: axial T_2 weighted fast spin echo images from three patients demonstrating the different categories of grading system for subjective analysis of image quality. A Grade 1 quality image (a) shows sharp, clear grey–white matter interfaces and outline of the basal ganglia. A Grade 2 (b) quality image demonstrates blurring of the grey–white matter interfaces and indistinct outline of the basal ganglia. A Grade 3 quality image (c) shows severe blurring of the grey–white matter interfaces and is further degraded by motion artefact.

Figure 2. The percentage of studies which were judged to be of Grade 1 or Grade 2 (diagnostic) quality in each of the three magnetic resonance (MR) Groups A, B and C. The highest quality scans were seen in Group C, in which patients were scanned in the MR-compatible incubator with optimised MR parameters.

(Table 1): repetition time/echo time (TR/TE), 4750/140; section thickness, 4 mm; section gap, 30%; field of view (FOV), 18 × 18 cm; matrix size, 216 × 384. In Group C, the parameters were altered to attempt to maximise the SNR as follows: TR/TE, 4000/118; section thickness, 5 mm; section gap, 30%; FOV, 20 × 20 cm; matrix size, 192 × 256. The study duration was also recorded by documenting the time from the first image acquisition to the last.

Image analysis

Images were reviewed and analysed on a Siemens Leonardo workstation (Siemens). For comparative purposes, a single sequence was chosen from each study [axial T_2 weighted fast spin echo (FSE) sequence] for data analysis. This sequence was chosen as the study parameters (TR, TE) were uniform across all three groups. Subjective and objective measures of image quality were assessed by two radiologists (NF, KO'R). Both readers were blinded to patient details and to whether the patient was scanned using standard equipment or using the MR-compatible incubator.

First, overall image quality was assessed on a three-point rating system based on image sharpness and clarity of the grey–white matter interfaces. The grading system is shown in Figure 1. Second, it was documented whether motion artefact was present or absent on the examination in any of the sequences performed (Figure 2). Any pathological findings on the studies were also documented.

SNR was measured for each MR examination. This was performed by placing a region of interest (ROI) with an area of 0.2 cm² over a constant point in the frontal white

matter and determining the mean signal intensity at this point. A further ROI was placed over the background. The SNR was then calculated using the following formula:

$$\text{SNR} = \frac{\text{mean signal of tissue}}{\text{standard deviation of background noise}}$$

Phantom study

In order to directly compare the SNR of the neonatal head coil (which was integrated into the MR incubator) with the knee extremity coil in an environment unaffected by motion, a phantom study was performed. Briefly, a 500 ml waterbath was imaged using the MR incubator head coil and the knee coil and similar parameters were used for T_2 weighted FSE neonatal head MR (TRs 4000 and 4750 ms, respectively).

Data collection

Data collection was performed using Microsoft Excel (Microsoft Corporation, Albuquerque, NM). Standard descriptive statistics were calculated. The independent samples Student's *t*-test and the Mann–Whitney *U*-test were performed to compare mean SNR values for the three groups. Statistical analysis was performed using SPSS v.14.0 (IBM Corporation, Armonk, NY).

Results

39 patients were included in the final analysis. The patient demographics in the three groups, A, B and C, are shown in Table 2. 10 patients were excluded owing to incomplete examinations ($n=3$) and non-standard MR parameters ($n=7$). The commonest indication for MR brain examination was neonatal encephalopathy ($n=26$), followed by investigation of hydrocephalus (detected on cranial ultrasound) ($n=4$), meningoencephalitis ($n=3$) and central hypotonia ($n=2$).

The mean durations of MRI examination in the three groups were 14 min for Group A, 15 min for Group B and 17.5 min for Group C, and there was no statistically significant difference in scan time between the groups. There were no adverse clinical events relating to the transport of the infant or the scan itself in any of the three groups.

Image quality

In Group A (examinations performed using standard MR equipment and a knee coil), 50% ($n=8$) of studies

Table 2. Patient demographics in Groups A, B and C. The study included 39 neonates in total and patient characteristics were comparable across all three groups

Characteristics	Group A ($n=15$)	Group B ($n=15$)	Group C ($n=9$)
Mean gestational age (weeks, range)	38 (30–41)	38 (31–42)	40 (35–41)
Mean postnatal age at scan (days, range)	18.9 (2–56)	11.3 (1–49)	9 (5–15)
Mean weight (kg, range)	3.1 (1.4–4.1)	3.6 (1.6–4.4)	3.8 (2.9–4.5)

Figure 3. Percentage of magnetic resonance (MR) brain examinations with motion artefact present in Groups A, B and C. Movement was reduced but not eliminated with the use of the MR-compatible incubator (Groups B and C).

were judged to be of diagnostic quality (Grades 1 and 2). In Group B (following the introduction of the MR-compatible incubator), 66% ($n=10$) of studies were found to be of diagnostic quality. In Group C (scans performed using the MR-compatible incubator with modified MR parameters), 89% ($n=8$) of studies were of good or diagnostic quality (Figure 2). The commonest reasons for non-diagnostic quality studies were the presence of motion artefact and blurring of the grey-white matter interfaces. Motion artefact was present in 73% ($n=11$) of scans in group A, 47% ($n=7$) of scans in Group B and in 44% ($n=4$) of scans in Group C (Figure 3).

Signal-to-noise ratio

The phantom study used to compare the performance of the knee extremity coil with the neonatal head coil at TRs of 4000 ms and 4750 ms showed that both were comparable with similar SNRs (Table 3).

The SNR of frontal white matter to background noise was measured for all three groups. The mean SNR for Groups A, B and C were 70, 76 and 213, respectively (Figure 4). There was a statistically significant difference between the SNR in Group C compared with Groups A and B (Mann-Whitney U -test, $p<0.001$; two-sided independent samples t -test, $p=0.001$). These results suggest that the improvement in SNR is not due to the introduction of the incubator with the integrated head coil, but due to the modification in the MR parameters used for the study.

Discussion

The results of this study show an improvement in image quality following the introduction of an MR-compatible incubator with modified MR parameters. The proportion of

MR brain scans in neonates which were deemed to be of "diagnostic quality" increased following the introduction of the incubator, and SNR was shown to increase approximately threefold once MR parameters specifically tailored to imaging the neonatal brain were introduced. Improvements in image quality and reduction in motion artefact may reduce the need for repeat imaging and improve the ability of the reporting radiologist to accurately assess the neonatal brain and provide a definitive diagnosis.

The safety of critically ill term and preterm infants during MR scanning presents a number of challenges, including transport to and from the MR unit, maintaining a suitable environment for the baby during the study and monitoring of vital signs. The MR-compatible incubator used in this study provides constant airflow, humidity and temperature and allows physiological monitoring of the baby during the scan, all of which improve patient safety. In our study, all infants remained stable during transport to and from the MR unit and during the MR study. Studies by Bluml et al [7] and Whitby et al [8], evaluating 13 and 7 neonates, respectively, have shown that the MR-compatible incubator provides a safe and stable environment and no adverse outcomes were recorded in these patients.

The MR-compatible incubator also enables preparation and handling of the neonate to be performed in the controlled environment of the neonatal intensive care unit (NICU), including the attachment of monitoring equipment and positioning the head within the RF coil. This minimises the need for patient handling in the MR unit, eliminates the need to move the patient from the incubator in the MR suite and guarantees a stable temperature and environment. As a result, neonates are more likely to be asleep or relaxed during the MRI study and movement is less likely to be an issue. In order to reduce motion artefact, neonates may be imaged during natural sleep, immediately following a feed, but this method is not always successful [6]. Refinement of conventional MR techniques includes the use of ultrafast MR sequences in moving patients and the Periodically Rotated Overlapping Parallel Lines with Enhanced Reconstruction technique for motion correction [9, 10]. If motion artefact continues to affect image quality, sedation or anaesthesia may be required, but this approach carries a small but definite risk of adverse events and sedated neonates require careful monitoring [5, 6, 11–13]. At our unit, we do not routinely administer sedation to neonates who are imaged using the MR-compatible incubator. Neonates are imaged following a feed and careful attention to good swaddling technique and head stabilisation in the RF coil performed within the NICU result in a still patient during scanning in most cases. NICU staff also receive regular training in these techniques. Although our results show that motion artefact has not been

Table 3. Results from the phantom study comparing SNR in the adult knee coil with the SNR of the dedicated neonatal head coil. The performance of both coils was similar at TRs of 4750 ms and 4000 ms

Repetition time	SNR of adult knee coil	SNR of integrated neonatal head coil
TR 4750 ms	93	69
TR 4000 ms	217	239

SNR, signal-to-noise ratio; TR, repetition time.

Figure 4. The mean signal-to-noise ratio (SNR) for T_2 weighted axial fast spin echo neonatal brain magnetic resonance (MR) images in Groups A, B and C. SNR in Group C was significantly higher than in Groups A or B ($p < 0.001$).

eliminated following the introduction of the MR-compatible incubator, its incidence has reduced from 73% to 44% of studies.

SNR is influenced by many factors and may be increased by increasing the field strength of the magnet, FOV, slice thickness or the TR. SNR may also be increased by decreasing the TE, receiver bandwidth, slice interval and by increasing the number of excitations (N_{ex}) [14]. The use of a closely fitting coil such as an adult knee coil or a dedicated neonatal head coil also maximises the SNR [6]. The results of the phantom experiment in this study showed no difference in the SNR between the neonatal head coil and the knee coil and accordingly, *in vivo*, the SNR in neonatal brain MR did not improve initially when the same MR parameters were used. Following the introduction of the modified MR parameters in Group C patients (increased FOV, slice thickness; decreased TE), the SNR increased threefold, which contributed to the greater proportion of good or excellent quality images in this group.

In conclusion, the use of an MR-compatible incubator in neonatal neuroimaging provides a safer environment and transport mechanism and improves image quality. SNR improvements are only achieved, however, following the tailoring of MR sequences and parameters to the neonatal brain. The combination of these two approaches results in better quality and a greater number of diagnostic MR studies. The achievement of this goal requires close co-operation between the neonatal team, radiographers and radiologists.

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