Radiology

Stefan Blüml, PhD
Philippe Friedlich, MD
Stephan Erberich, MD
John C. Wood, MD, PhD
Istvan Seri, MD, PhD
Marvin D. Nelson, Jr, MD

Index terms:
Magnetic resonance (MR), coils
Magnetic resonance (MR), in infants and children, **.1214[2]
Magnetic resonance (MR), safety
Magnetic resonance (MR), spectroscopy, **.12145
Magnetic resonance (MR), technology, **.1214

Published online
10.1148/radiol.2312030166
Radiology 2004; 231:594–601

Abbreviations:
NICU = neonatal intensive care unit
RF = radiofrequency
SNR = signal-to-noise ratio

[1] From the Department of Radiology (S.B., S.E., M.D.N.) and Divisions of Neonatal Medicine (P.F., I.S.) and Cardiology (J.C.W.), Children's Hospital Los Angeles, 4650 Sunset Blvd, MS 81, Los Angeles, CA 90027; and Rudi Schulte Research Institute, Santa Barbara, Calif (S.B.). Received January 31, 2003; revision requested April 21; final revision received September 17; accepted September 18. Supported by the Rudi Schulte Research Institute, Santa Barbara, Calif. **Address correspondence to** S.B. (e-mail: *sbluml@chla.usc.edu*).

[2] **. Multiple body systems

Author contributions:
Guarantors of integrity of entire study, S.B., M.D.N., I.S.; study concepts, S.B., J.C.W., I.S.; study design, S.B., S.E., P.F., I.S., M.D.N.; literature research, S.B.; clinical studies, S.B., P.F., J.C.W.; experimental studies, S.B.; data acquisition, S.B., S.E.; data analysis/interpretation, S.B., J.C.W., S.E., M.D.N.; statistical analysis, S.B.; manuscript preparation and editing, S.B.; manuscript definition of intellectual content, S.B., I.S., M.D.N.; manuscript revision/review and final version approval, all authors

MR Imaging of Newborns by Using an MR-compatible Incubator with Integrated Radiofrequency Coils: Initial Experience[1]

To meet the needs of term and preterm neonates undergoing magnetic resonance (MR) imaging, an MR-compatible incubator with air, temperature, and humidity regulators and integrated radiofrequency coils was evaluated. Nine brain, two cardiac, and two pelvic examinations were performed by using a 1.5-T clinical MR imaging unit. The axillary temperature of the newborns varied by less than 0.8°C, their vital signs remained stable, and no complications were encountered. The diagnostic quality of images obtained with the MR-compatible incubator was superior to that of images obtained with the standard MR imaging equipment. The use of an MR-compatible incubator for examinations of ill neonates is feasible and safe and yields excellent MR images.

Magnetic resonance (MR) imaging of critically ill preterm and term neonates is difficult to perform because of the need for thermoregulation and ventilation support and consistent hemodynamic monitoring throughout the examination (1–4). Therefore, the patient preparation time often exceeds the MR imaging time and thus leads to prolonged periods away from the controlled environment of the neonatal intensive care unit (NICU). As a result, many NICU physicians postpone performing MR imaging in the most severely ill patients, relying entirely on inferior portable imaging technologies. This is unfortunate, because MR imaging can yield essential anatomic information, including important insights regarding the state of myelination and data on the metabolism and functional capabilities of the developing brain (5–9).

Patient safety is not the only limitation to performing MR imaging in newborns. Manufacturers of MR imaging systems usually provide only general "one fits all" coils—for example, a head coil designed for use on adults, the use of which results in inferior image quality in children, especially newborns. The use of smaller coils tailored to the size of the neonate body facilitates an improved signal-to-noise ratio (SNR) and image contrast. SNR improvements, in turn, could be used to reduce the imaging time or improve the spatial image resolution.

The goals of this study were twofold: *(a)* to demonstrate that an MR-compatible incubator with air flow, humidity, and temperature regulators can provide a safe and controlled environment for preterm newborns and *(b)* to demonstrate that the use of integrated radiofrequency (RF) head and body coils that are optimized for newborns improves the diagnostic quality of MR imaging.

Materials and Methods

Thirteen neonatal patients—nine male babies and four female babies—were enrolled in the study, and nine brain, two cardiac, and two pelvic MR imaging examinations were performed. The newborns in this study were recruited from among patients in the NICU of Childrens Hospital Los Angeles who were already scheduled to undergo clinically indicated MR imaging examinations. In each case, the physicians in charge of the patients were approached and their approval to conduct the study was obtained. To qualify for this study, the newborn needed to

have a weight and length that matched the specifications of the MR-compatible incubator. The gestational ages of the babies at birth ranged from 24 to 41 weeks, and their postnatal ages at the time of the MR imaging examinations ranged from 4 to 12 weeks. Their body weights were between 1.2 and 4.5 kg, and their head circumferences were between 29 and 37 cm.

The use of the MR-compatible incubator with integrated RF coils for clinically indicated MR imaging was approved by the investigational review board of Childrens Hospital Los Angeles, and informed consent was obtained from the parents prior to all examinations. The diagnostic quality of the MR images acquired by using the MR-compatible incubator was evaluated by comparing these images with six MR studies obtained in age-matched patients. The examinations of the age-matched patients were clinically indicated and performed by using standard MR imaging equipment and procedures established in this hospital.

The investigational review board approved our retrospective review of the clinically obtained MR imaging data on the age-matched patients for the evaluation of techniques and the establishment of baseline values. The requirement to obtain parental consent for this retrospective review was waived by the board.

The MR-compatible Incubator

The MR-compatible incubator provided by the manufacturer (Lammers Medical Technology, Lübeck, Germany) is equipped with RF coils constructed by Advanced Imaging Research (Cleveland, Ohio) (10). This incubator is designed for temporary use during MR imaging examinations of neonates with body weights of up to 4.5 kg or body lengths of 55 cm. The main features of the MR-compatible incubator used for this study are an air circulation system with a blower wheel and air channels, air heating with an electric resistor, humidification rendered by means of vaporization of demineralized sterile water, a closed-loop control via a microprocessor, air temperature sensors, and a humidity sensor. The double-walled patient-holding section has several handle ports for easy access from either side of the incubator and is completely made of plastic. Metal components—especially magnetic parts—would have interfered with the RF deposition, caused severe image distortions, and encountered electromagnetic forces in the vicinity of strong magnetic fields.

The remaining components of the MR-compatible incubator consist of as few magnetic parts as possible, and special shielding and filtering of the electronic components were applied to ensure MR compatibility. The functions on the incubator fulfill the criteria cited in International Electrotechnical Commission publications 60601–2-19 and 60601–2-19-am1 (11). The MR-compatible incubator used in this study also features custom-designed head and body RF coils. These coils are specifically designed to be used in combination with the incubator. The coils were fitted over the patients without obstructing the ventilator, nasal cannula and endotracheal tubes, or monitoring leads. The tubes and leads were routed through the portals on the incubator and connected to the respective devices inside the MR imaging suite.

Patient Handling

Twelve patients were sedated with chloral hydrate (25–50 mg/kg) (Notec Syrup; Morton Grove Pharmaceuticals, Morton Grove, Ill), and anesthesia was induced in one patient by means of continuous infusion of propofol (Baxter, Deerfield, Ill). The MR-compatible incubator had been positioned on the MR table. After a patient was transported to the MR imaging suite by using standard transport procedures, he or she was placed inside the MR-compatible incubator and connected to life-sustaining equipment, such as ventilators, oxygen cannulas, infusion pumps, and vital sign–monitoring instruments (ie, noninvasive blood pressure cuff, electrocardiograph, and pulse oximeter) according to standard hospital protocols (Fig 1).

The patient's axillary temperature was measured before and after the MR imaging examination by using standard disposable temperature probes (Medical Indicators, Pennington, NJ). In addition, a commercially available fluoro-optic temperature monitor (Luxtron, Santa Clara, Calif) was used to measure the patient's skin temperature during the examination. The probe was placed on the body part being studied (ie, head, chest, or pelvis). Blood pressure and electrocardiographic status were monitored, and the blood oxygen saturation, heart rate, and skin temperature were continuously recorded during the course of MR imaging. The manufacturer-quoted accuracies of the temperature probes and the fluoro-optic temperature monitor were ±0.1°C. The total time the patient spent in the MR-compatible incubator was recorded.

To allow the appropriate warm-up of the incubator, approximately 20 minutes before the patient arrived in the MR imaging suite, the operator set the air temperature in the incubator (28.5°–36.0°C) according to the request of the NICU staff. MR imaging examinations were performed at less than 50% relative humidity inside the incubator. To assess the stability of the MR-compatible incubator, the incubator temperature and humidity readings were recorded throughout the MR imaging examinations.

Coil Preparation and Initial Testing

Before the patient examinations were initiated, the RF coils designated for the incubator were tuned and matched on a few patients to study loading considerations and optimize performance over the wide range of patient sizes. These adjustments were made in the NICU and were approved by the local investigational review board. Thereafter, MR imaging experiments were performed by using a phantom with loading characteristics similar to those of a newborn head to test the performance of the RF coils *(a)* without the MR-compatible incubator, *(b)* with the incubator but with the incubator functions switched off, and *(c)* with the incubator and the incubator functions turned on. The SNRs of MR images acquired in the different conditions were within 1%–2%. These variations are within the daily tolerance for MR imaging system operation suggested by the manufacturer. The SNRs of images obtained by using the custom-designed head coil for newborns was compared with the SNRs of images acquired with the standard head coil (GE Medical Systems, Milwaukee, Wis). With use of the head coil for newborns, the SNR was improved by a factor of approximately 3.

The basic functions of the MR-compatible incubator—in other words, those functions not specifically associated with MR imaging—were assessed to ensure electric safety and other safety features, including software-generated alarms and hardware cutoffs, device functions in defined single-fault conditions, the uniformity of temperature inside the patient compartment, and various performance characteristics (eg, heat-up time, settling time, and offsets). Then, before any patient examinations were performed, the reliability and safety of the incubator in terms of maintaining the appropriate temperature and humidity inside the MR imaging unit were tested extensively.

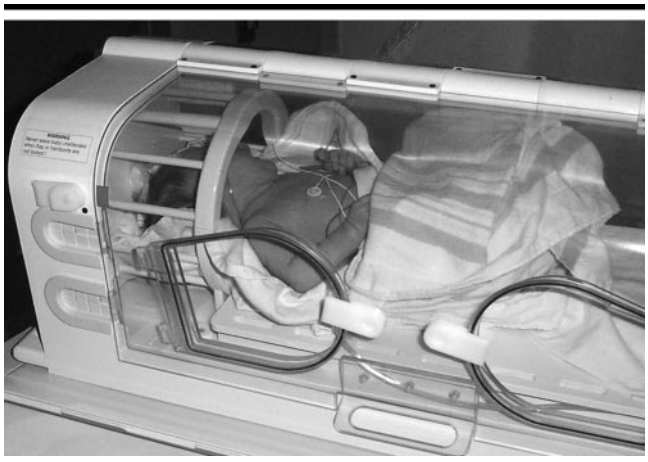

Figure 1. Preparation of neonatal patient for MR imaging examination. The MR-compatible incubator with the integrated neonatal RF head coil, set on a standard patient bed is shown with a patient inside and prepared for a brain examination.

MR Imaging Examinations and Image Analysis

All examinations were performed by using a 1.5-T clinical MR imaging unit (CVi; GE Medical Systems). A small head coil with a length of 15 cm and a diameter of 18 cm was used for all brain examinations, while a slightly larger coil with a length and diameter of 18.2 cm and that fit over the chest and pelvis was used for all other (ie, nonbrain) examinations. Standard clinical MR images were obtained with established parameters, except for the section thickness. Anticipating an improved SNR, we reduced the section thickness of the MR images from the typically used 5 mm to 3 mm.

Proton (hydrogen 1) MR spectroscopy was performed in all nine newborns who were scheduled for brain MR examinations. Spectra from 4–5 cm^3 of occipital gray matter and parietal white matter were obtained by using a point-resolved spectroscopic sequence with a short echo time, 35 msec, and a repetition time of 1,500 msec. The regions of interest for MR spectroscopy were placed by one author (S.B.) and were selected so that any obvious lesions and focal MR imaging–detectable abnormalities would be excluded.

To assess the MR-compatible incubator imaging examinations, the brain MR images and brain MR spectra obtained with the MR-compatible incubator were compared with six brain images that were obtained in age-matched patients as follows: *(a)* The SNR of in vivo brain MR images was determined by selecting a small homogeneous region of interest in normal-appearing white matter at a consistent anatomic position. In each case, the regions of interest were placed by two authors (S.B., M.D.N.) in consensus. The apparent SNR was calculated by dividing the mean signal intensity of the region of interest by a noise power estimate derived from a background region of interest. *(b)* At our institution, all images are stored in digital format on an image server (Synapse; Fuji, Stamford, Conn); the identification numbers of the study and control patients were forwarded to a senior pediatric neuroradiologist (M.D.N.) with 15 years experience. The delineation of gray matter and white matter on T2-weighted fast spin-echo MR images of the brain was assessed on the basis of the clarity of the tissue interfaces (ie, gray matter–white matter interface and pial surface–cerebrospinal fluid interface), and the images were ranked. Information as to whether the subjects were study patients or control patients was not forwarded. *(c)* Two authors (S.B., M.D.N.) analyzed the images for any artifacts other than motion artifacts. *(d)* ^{1}H MR spectra of the brain were processed and quantified by using fully automated processing software (SA/GE IDL; GE Medical Systems). The reported SNR of the spectra was recorded.

The feasibility of performing heart and pelvic examinations with the MR-compatible incubator was tested, but heart and pelvic MR images were not evaluated quantitatively because an insufficient number of patients were evaluated with the MR-compatible incubator in these initial examinations.

Statistical Analyses

Paired Student *t* tests were performed to determine the statistical significance of axillary and skin temperature changes recorded before and at the end of MR imaging examinations performed in individual patients. To test the hypothesis of a significant improvement in the mean SNR of MR images and MR spectra obtained in the study and control patients, one-tailed *t* tests for unpaired samples were performed. $P < .025$ was considered to indicate significance. The Mann-Whitney *U* test was used to compare the T2-weighted MR images obtained in the study and control patients.

Results

The mean length of time patients spent in the MR-compatible incubator for MR imaging was 47 minutes ± 14 (SD). The incubator provided a stable, well-controlled environment, and the mean temperature divergence from the set temperature was 0.4°C ± 0.4, while the mean change in relative humidity from the initial level was less than 2.4% ± 1.3.

The initial blood oxygen saturation level in the patients varied between 88% and 99%, with the lowest level measured in one of the patients undergoing cardiac examinations. However, blood oxygen saturation readings remained constant during the course of the MR imaging examination performed with the incubator and varied by less than 2.3%. The pulse rates of the sedated or anesthetized newborns were normal (120–150 beats per minute). As the patients awakened from sedation or anesthesia toward the end of MR imaging, their heart rates generally increased. Electrocardiographic status and blood pressure (monitored but not recorded) remained stable throughout all examinations.

The skin temperatures recorded with the Luxtron equipment versus the time spent in the incubator for patients are shown in Figure 2. The mean initial and final temperatures and the maximum temperature changes in individual patients are summarized in the Table. A small increase in mean skin temperature was observed over time. In general, temperature variations of less than 0.5°C were observed in all except two patients. In one patient, an increase of 1.2°C was noted at the end of the 1-hour-long MR imaging examination of heart function that was conducted with the neonatal body coil. A rapid 0.8°C decrease in skin temperature over a 10–15-minute period was noted in another patient (Fig 2); the MR imaging examination was interrupted to examine this patient, and the

NICU nurse noted that the temperature sensor on the forehead was loose. Axillary temperatures measured within 5 minutes after the completion of MR imaging were 0.2°C above the baseline temperature for the first patient and 0.3°C below the baseline temperature for the second patient.

The mean axillary temperatures measured by the nurse before and after MR imaging were not significantly different ($P > .5$). The measured axillary temperature stayed within 0.5°C in all but one patient, in whom a 0.7°C decrease was noted. The mean SNR of the brain images obtained with the MR-compatible incubator was significantly increased ($P < .001$), by a factor of 2.3, compared with the SNR of the MR images obtained with the standard head coil. No artifacts caused by the new equipment were noted. In some cases, patient movement caused degraded image quality and several iterations were necessary to obtain diagnostic images. However, this problem is frequently encountered when imaging moderately sedated babies and is unrelated to the use of the incubator or the coil performance (Figs 3, 4).

At blinded review of the T2-weighted MR images to assess the quality of the delineation of white and gray matter, the images obtained at all nine brain examinations performed with the MR-compatible incubator were ranked higher than those obtained at the six control examinations owing to an improved SNR and a reduced section thickness ($P < .01$, Mann-Whitney U test). The mean SNR of the ^{1}H MR spectra obtained with the MR-compatible incubator was significantly increased ($P < .001$), by a factor of 2.8 (Fig 5). With use of the neonatal body coil, diagnostic-quality pelvic and heart images were obtained (Fig 6).

Axillary and Skin Temperatures of Newborns Examined with MR-compatible Incubator

Measurement	Axillary	Skin
Initial temperature (°C)*	3.6 ± 0.7	35.7 ± 0.6
Final temperature (°C)*	3.6 ± 0.6†	36.1 ± 0.7‡
Maximum temperature decrease (°C)	0.7	0.8§
Maximum temperature increase (°C)	0.5	1.2

* Data are mean temperatures ± SDs.
† Nonsignificant difference between initial and final temperatures.
‡ $P < .02$ for difference between initial and final temperatures at paired t test.
§ One patient with a loose temperature sensor was excluded from this measurement.

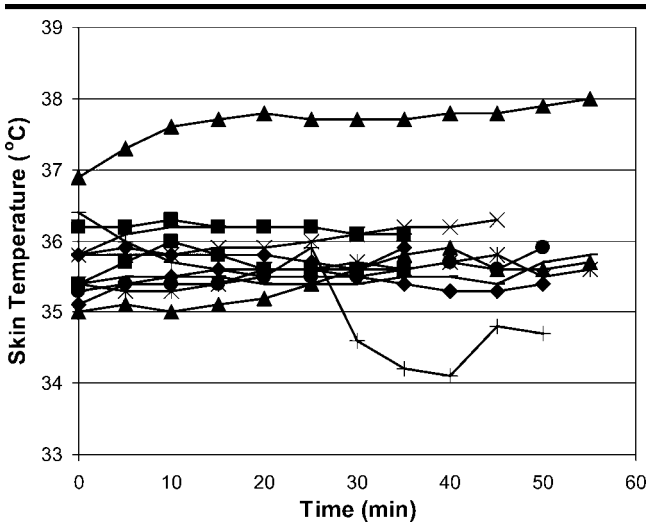

Figure 2. Graph of skin temperature measurements. The main purpose of the MR-compatible incubator is to maintain the neonate's core body temperature. Skin temperature measurements versus time spent in the incubator for subjects are shown. These measurements demonstrate that the neonates were able to maintain their skin temperatures. The sudden decrease in temperature in one patient was due to a loose temperature sensor.

Discussion

The use of a fully MR-compatible incubator has the potential to facilitate substantial reductions in the logistic challenges of performing MR imaging in neonates. Many of the steps currently performed in the MR imaging suite, such as attaching the MR-compatible physiologic monitoring equipment to the patient and positioning the subject with respect to the RF coil, could be performed within the NICU before transporting the patient to the MR imaging suite to further enhance patient safety and improve the efficiency of the MR imaging unit. Once the patient fell asleep or calmed down in the safe environment of the NICU, the complete assembly could be transported to the MR imaging unit and moved onto the patient bed. The RF coil would already be positioned, with monitoring equipment in place, and imaging could start immediately after a landmark at the center of the coil was established. After imaging was completed, the patient could be transported back to the NICU while in the MR-compatible incubator and then transferred back into a regular incubator.

This procedure would minimize the time patients spend outside of the NICU and outside of the controlled environment of an incubator. For this initial evaluation of the MR-compatible incubator, the patients in the present study were transported from the NICU by using standard procedures. Since we have now demonstrated the safety of using this system in the MR imaging suite, our next study will focus on the use of the MR-compatible incubator for both transporting and imaging patients.

The need for improved handling of neonates has been realized by several groups. Maalouf and Counsell (12) used a specially designed nonmagnetic transport trolley with a cradle to minimize the handling of neonates during continued physiologic monitoring and ventilation. However, this system does not enable one to regulate and control airflow, humidity, or temperature settings. MR-compatible incubator systems that are comparable to the one evaluated in this study are being tested or used by Boesch and Martin (13,14), Groenendaal et al (15), and Dumoulin et al (16).

Functions of the MR-compatible Incubator

For the MR imaging examinations performed in the present study, the air temperature and humidity inside the incubator were set to meet the needs of

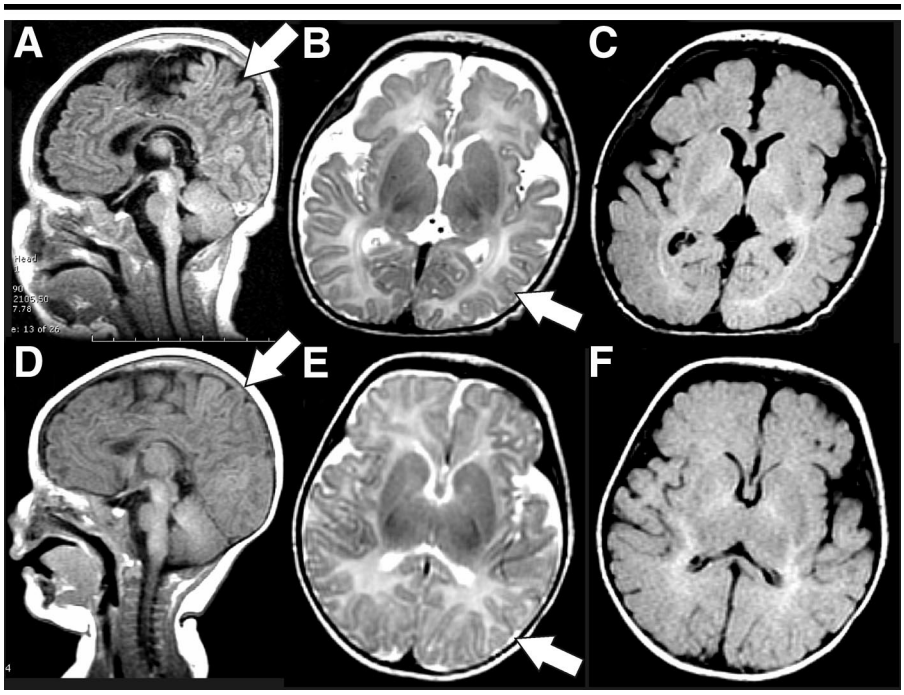

Figure 3. MR images of the brain obtained in two 2-month-old babies: one evaluated for intracranial hemorrhage after extracorporeal membrane oxygenation *(A–C)* and the other examined because of increased seizure activity *(D–F)*. *A,* Sagittal T1-weighted fluid-attenuated inversion-recovery (2,000/7/750 [repetition time msec/echo time msec/inversion time msec], 256 × 256 matrix, one signal acquired, echo train length of six, acquisition time of 2 minutes 8 seconds); *B,* transverse T2-weighted fast spin-echo (3,500/85 [repetition time msec/echo time msec], 256 × 192 matrix, two signals acquired, echo train length of 16, acquisition time of 2 minutes 48 seconds); and *C,* transverse fluid-attenuated inversion-recovery (9,000/120/2,200, 256 × 192 matrix, one signal acquired, acquisition time of 4 minutes 48 seconds) MR images acquired with the MR-compatible incubator (180-mm field of view, 3-mm section thickness) are shown. *D,* Sagittal T1-weighted fluid-attenuated inversion-recovery (2,000/7/750, 256 × 256 matrix, two signals acquired, echo train length of six, acquisition time of 4 minutes 16 seconds); *E,* transverse T2-weighted fast spin-echo (3,500/85, 256 × 192 matrix, three signals acquired, echo train length of 16, acquisition time of 3 minutes 12 seconds); and *F,* transverse fluid-attenuated inversion-recovery (9,000/120/2,200, 256 × 192 matrix, one signal acquired, acquisition time of 4 minutes 48 seconds) MR images acquired with the standard MR imaging equipment (220-mm field of view, 3-mm section thickness) also are shown. The images acquired with the MR-compatible incubator *(A–C)* have two times higher spatial resolution than the corresponding images acquired with the standard head coil *(D–F)*. Note the superior delineation of the gray and white matter (arrows in *A* and *B*) on the images acquired with the MR-compatible incubator compared with the delineation of the gray and white matter (arrows in *D* and *E*) on the images acquired by using regular equipment. The improved SNR of images acquired by using the MR-compatible incubator can be used to generate diagnostic images with improved spatial resolution and thus better definition of anatomic structures within equal or shorter imaging times.

individual neonatal patients according to the instructions of NICU personnel. Vital signs such as blood oxygenation level, electrocardiographic status, and blood pressure remained stable throughout all examinations, and even the preterm neonates were able to maintain stable temperatures. We conclude that the environment generated by the MR-compatible incubator meets the unique needs of neonates undergoing MR imaging. A 0.7°C temperature decrease was observed in one patient, in whom anesthesia with propofol rather than sedation with chloral hydrate was induced. We speculate that the anesthetic may have contributed to the greater change in axillary temperature during the examination.

Image Quality

In this study, we also sought to evaluate whether improvement in the quality of MR imaging can be demonstrated with the use of integrated RF coils tailored to the neonatal body habitus. A close to threefold increase in the SNR of the MR spectra acquired with the integrated RF coil was measured and determined by using the automated processing software (GE Medical Systems). These findings are consistent with the observations obtained in phantom experiments. The SNR of images acquired with the MR-compatible incubator was 2.3 times the SNR of images acquired with standard equipment at MR imaging of age-matched patients. Determination of the SNR from in vivo images is more subjective because the region of interest is selected interactively; this may explain the observed discrepancy between the evaluation of SNR with MR imaging and that with MR spectroscopy. The delineation between gray and white matter on T2-weighted MR images was improved, and no artifacts other than motion artifacts were observed.

A more quantitative comparison of coil performance is currently underway and was not the specific goal of this study. In these ongoing studies, a larger cohort of patients is being studied owing to the challenges of matching subjects with rapidly changing anatomies and biochemical features in this age group.

Potential Risks Associated with Using MR-compatible Incubator

The functions (ie, air heating, circulation, and humidification) of the described MR-compatible incubator are not associated with any risk in addition to those known to be related to the use of standard NICU incubators. However, the combined effect of an environment with an above-normal temperature and the absorption of RF energy warrant consideration.

According to International Electrotechnical Commission code 601–2-33, which represents the particular standard for MR imaging units (17), the standard environmental conditions for patients are less than 24°C (75.2°F) and less than 60% relative humidity. Depending on the patient, with the settings of the MR-compatible incubator, temperatures and relative humidity levels of up to 39°C (102.2°F) and 90%, respectively, can be reached. International Electrotechnical Commission code 601–2–33 mandates that patients with unaffected thermoregulation capability can tolerate a specific absorption rate of 4 W/kg and that, independent of their health, all patients should be able to tolerate a specific absorption rate of 1.5 W/kg. However, these guidelines were set for adults and for standard environmental conditions. Neonates who are kept in an incubator at higher baseline temperatures and with

lower heat dissipation may require stricter guidelines, especially since damage to the central nervous system of fetuses whose mothers had prolonged hyperthermia (>39°C) has been documented (18). We, therefore, monitored the patients' temperatures carefully throughout the MR imaging examinations to detect any possible excessive deposition of RF power.

In one patient, a substantial increase in skin temperature, of 1.2°C, was noted. In this patient, the MR imaging examination was stopped twice for periods of approximately 5 minutes owing to patient movement at 25 and 45 minutes into the examination. A review of the skin temperature readings (Fig 2, top line) revealed that at 20–25 minutes into the examination, immediately before the first interruption, a decrease of 0.1°C was noted despite RF power being applied, while during the interruption (ie, with no application of RF energy), the skin temperature remained constant. During the second interruption, a 0.1°C increase in skin temperature was noted. These observations indicate that the increase in skin temperature in this patient was probably due to intrinsic factors rather than RF power deposition. Nevertheless, when the 1.2°C temperature increase was observed, MR imaging was stopped. The axillary temperature measured shortly after completion of the MR imaging examination was 0.2°C above the baseline temperature in this patient. The temperature settings of the incubator varied from 28.5°C to 36.0°C, which was the temperature set for this patient. The temperature increase in this case could have been avoided by adjusting the incubator to a lower temperature.

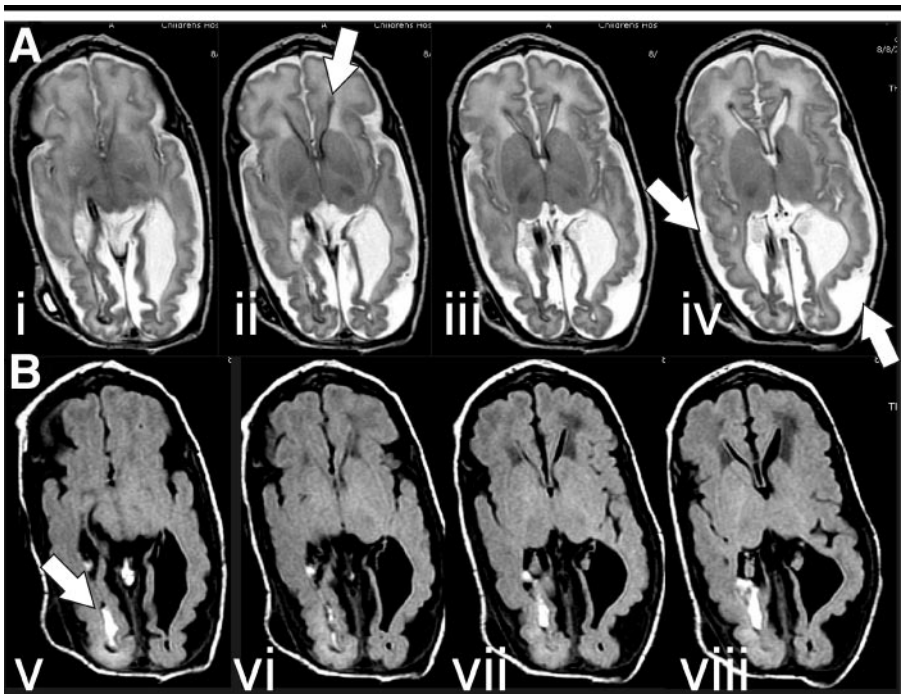

Figure 4. *A,* Fast spin-echo (3,500/85, 180-mm field of view, 3-mm section thickness, 256 × 192 matrix, one signal acquired, acquisition time of 2 minutes 48 seconds), and, *B,* fluid-attenuated inversion-recovery (9,000/120/2,200, 180-mm field of view, 3-mm section thickness, 256 × 192 matrix, one signal acquired, acquisition time of 4 minutes 48 seconds) MR images of the brain acquired with the MR-compatible incubator in a preterm (born at 32 weeks) 2-month-old baby with hemorrhagic hydrocephalus. Hemosiderin lining the ventricles, especially the frontal horns (arrow in *ii*), and old red blood cell debris (arrow in *v*) in the posterior horns of the lateral ventricles are seen. Bilateral extraaxial fluid collections (arrows in *iv*) are also seen.

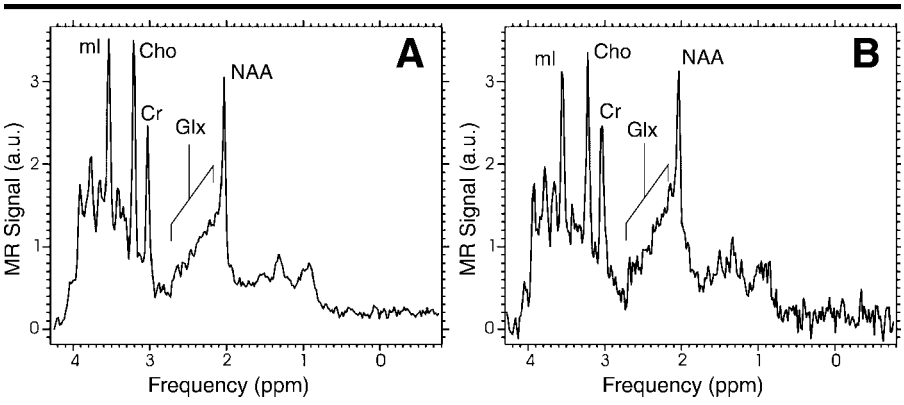

Figure 5. ^{1}H MR spectra obtained *A,* with the MR-compatible incubator in a 2-month-old baby after extracorporeal membrane oxygenation, and, *B,* with the standard head coil in a 2-month-old term baby examined because of increased seizure activity. (The MR images obtained in these two patients are shown in Fig 3.) The spectra acquired with the RF coils optimized for use in newborns and integrated with the MR-compatible incubator showed a three times higher SNR. The spectra for both patients were acquired by using single-voxel point-resolved MR spectroscopy (1,500/35, 128 signals acquired from a 4.2-mL region of interest in occipital gray matter). *a.u.* = arbitrary units, *Cho* = choline-containing compounds, *Cr* = creatine plus phosphocreatine, *Glx* = glutamate and glutamine, *mI* = myo-inositol, *NAA* = *N*-acetylaspartate.

Potential Risks Associated with Using Optimized RF Coils on Neonates

The rate at which RF energy is deposited in tissue is expressed as the specific absorption rate, which is measured in watts per kilogram. The operational conditions above which patient examinations are considered to generate substantial risk are defined in Food and Drug Administration guidelines. The duty cycle of the RF during MR imaging examinations is restricted on the basis of this specific absorption rate limit. According to current guidelines, normal operating-mode values of specific absorption rate for the head are not higher than 3 W/kg for any 10-minute period (19,20).

The special RF coils designed for newborns that were used in this study did not pose any additional risk. For any volume coil, the RF field (B_1) necessary to tip the magnetization by a certain flip angle at any location for a given MR sequence is independent of the coil. Increased energy deposition would be expected only in so called "hot spots" owing to inhomogeneous excitation, which was not observed with the coils used in this study. The absorption of RF energy by tissue is a

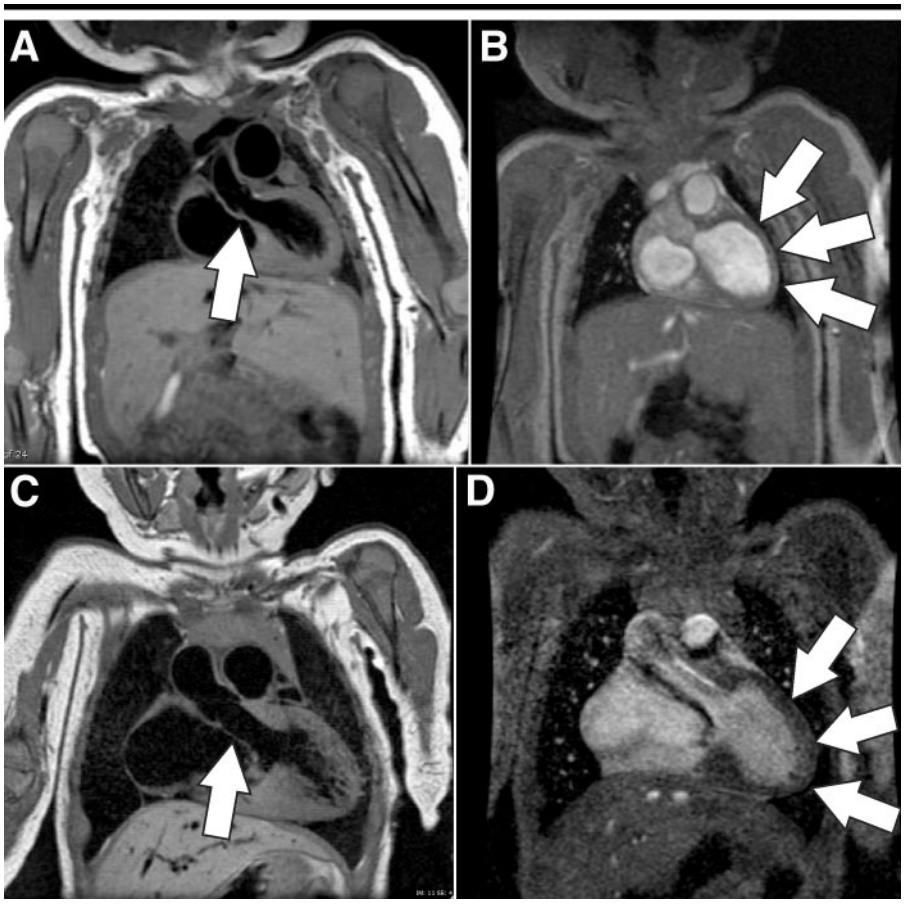

Figure 6. *A,* Coronal black-blood spin-echo (870/14, 180-mm field of view, 256 × 192 matrix, four signals acquired, 2-mm section thickness), and, *B,* coronal white-blood cine spoiled gradient-echo (11.5/5.1, 200 × 150-mm field of view, 20° flip angle, 256 × 160 matrix, 3-mm section thickness, two signals acquired) MR images of the heart acquired with the MR-compatible incubator and the integrated body coil in a 1-week-old neonate examined for assessment of vessel branching. For comparison, *C,* coronal black blood spin-echo (1,081/14, 180-mm field of view, 256 × 160 matrix, 2-mm section thickness, four signals acquired), and, *D,* coronal white blood cine spoiled gradient-echo (11.5/5.1, 200-mm field of view, 20° flip angle, 256 × 160 matrix, 3-mm section thickness, two signals acquired) MR images were obtained with the standard head coil in a 1-month-old baby examined for assessment of pulmonary and systemic venous drainage. Note the sharp definition of the left ventricular outflow tract and the aorta (arrows in *A* and *C*) and the superior blood-myocardial contrast (arrows in *B* and *D*) on the images acquired with the MR-compatible incubator.

function of B_1, and the specific absorption rate is in good approximation independent of the volume coil used for a given MR sequence. There is the remote possibility that the system will adjust the RF power to a level that is too high. For instance, a 270° rather than 90° pulse that has the same net effect as all of the magnetization in the transverse plane may be generated. To eliminate this possibility, on our system, we set up a coil configuration file that limits the maximum power delivered into the RF coils for newborns to one-ninth of the cutoff value used with standard head coils.

One limitation of this study was the small number of patients. A second limitation was our focus in this initial investigation on patients who were already scheduled for clinically indicated MR imaging examinations and were considered by the NICU staff to be stable. However, the main objective of an MR-compatible incubator is to facilitate imaging in patients who are considered too unstable for MR imaging. Obtaining diagnoses at an earlier stage for these patients is likely to have a more substantial effect on their treatment. The conclusions drawn from the results of our examinations in the described population in terms of the capability of patients to maintain constant body temperatures cannot necessarily be generalized and assumed to apply to more fragile subjects.

In conclusion, the use of an MR-compatible incubator offers the potential to obtain state-of-the-art, high-spatial-resolution, anatomic MR images and MR spectra in newborns, a particularly vulnerable patient population. Newborn patients can benefit from improved safety, efficiency, and quality of diagnostic imaging information. The safe environment of an MR-compatible incubator can result in an increased number of neonatal patients who are referred for noninvasive diagnostic MR imaging examinations.

Acknowledgments: We thank Nirupama Subramanian, MD, Martin Blahnik, MD, and Rangasamy Ramanathan, MD, for their valuable help in obtaining parental consents and for their permission to examine the patients under their care. We are particularly grateful to MR imaging technologist Gena A. Nicholson, CRT, ARRT, for help with imaging the patients. We also thank the entire nursing staff of the NICU of Childrens Hospital Los Angeles for their enthusiasm and collaboration and Linda Tesoriero, MD, for help with patient preparation. In addition, we thank J. Gordon McComb, MD, and Miriam Scadeng, MD, for their support and valuable discussions. We are grateful to Mark J. Albers of GE Medical Systems for technical support and to Torsten Lammers, director of Lammers Medical Technology, Luebeck, Germany, and Ravi Srinivasan, director of Advanced Imaging Research, Cleveland, Ohio, for allowing us to study their equipment.

References

1. Lyon AJ, Pikaar M. Temperature regulation in preterm infants: effect of birthweight and gestation. In: Okken A, Koch J, eds. Thermoregulation of sick and low birth weight neonates. Berlin, Germany: Springer, 1995; 83–91.
2. Koch J. Physical properties of the thermal environment. In: Okken A, Koch J, eds. Thermoregulation of sick and low birth weight neonates. Berlin, Germany: Springer, 1995; 103–126.
3. Sinclair JC. Thermal environment, mortality and morbidity, state of the evidence. In: Okken A, Koch J, eds. Thermoregulation of sick and low birth weight neonates. Berlin, Germany: Springer, 1995; 127–141.
4. Pennock JM. Patient preparation, safety, and hazards in imaging infants and children. In: Rutherford M, ed. MRI of the neonatal brain. London, England: Saunders, 2002; 3–15.
5. Barkovich AJ, Westmark KD, Bedi HS, et al. Proton spectroscopy and diffusion imaging on the first day of life after perinatal asphyxia: preliminary report. AJNR Am J Neuroradiol 2001; 22:1786–1794.
6. Sie LT, van der Knaap MS, Oosting J, et al. MR patterns of hypoxic-ischemic brain damage after prenatal, perinatal or postnatal asphyxia. Neuropediatrics 2000; 31: 128–136.
7. Moonen CTW, Bandettini PA, eds. Functional MRI. New York, NY: Springer-Verlag, 1999.
8. Martin E, Joeri P, Loenneker T, et al. Visual processing in infants and children studied using functional MRI. Pediatr Res 1999; 46:135–140.

9. Kreis R, Hofmann L, Kuhlmann B, et al. Brain metabolite composition during early human brain development as measured by quantitative in vivo 1H magnetic resonance spectroscopy. Magn Reson Med 2002; 48:949–958.
10. Srinivasan R, Loenneker-Lammers T, Shah R. MR compatible incubator for imaging preterm and term neonates (abstr). In: Proceedings of the Tenth Meeting of the International Society for Magnetic Resonance in Medicine. Berkeley, Calif: International Society for Magnetic Resonance in Medicine, 2002; 799.
11. International Electrotechnical Commission (IEC). Medical electrical equipment. II. Particular requirement for the safety of baby incubators. Geneva, Switzerland: International Electrotechnical Commission; 1990, 1996. CEC IEC publications 60601–2–19, 60601–2–19-am1.
12. Maalouf EF, Counsell SJ. Imaging the preterm infant: practical issues. In: Rutherford M, ed. MRI of the neonatal brain. London, England: Saunders, 2002; 17–21.
13. Boesch C, Martin E. Combined application of MR imaging and spectroscopy in neonates and children: installation and operation of a 2.35-T system in a clinical setting. Radiology 1988; 168:481–488.
14. Boesch C. Patient life support and monitoring facilities for whole body MRI. In: Grant DM, Harris RK, eds. Encyclopedia of nuclear magnetic resonance. Chichester, England: Wiley, 1996; 3467–3475.
15. Groenendaal F, Leusink C, Nijenhuis M, et al. Neonatal life support during magnetic resonance imaging. J Med Eng Technol 2002; 26:71–74.
16. Dumoulin CL, Rohling KW, Piel JE, et al. Magnetic resonance imaging compatible incubator: concepts in magnetic resonance, part B. Magn Reson Eng 2002; 15: 117–128.
17. International Electrotechnical Commission (IEC). Medical electrical equipment. II. Particular requirement for the safety of magnetic resonance systems for medical diagnosis: appendix. Geneva, Switzerland: International Electrotechnical Commission; 1995. CEC IEC publication 601–2–33.
18. International Non-Ionizing Radiation Committee of the International Radiation Protection Association. Protection of the patient undergoing a magnetic resonance examination. Health Phys 1991; 61:923–928.
19. Food and Drug Administration. Magnetic resonance diagnostic device: panel recommendation and report on petitions for MR reclassification. Federal Register 1988; 53:7575–7579.
20. Food and Drug Administration. Guidance for the submission of premarket notifications for magnetic resonance diagnostic devices: operating mode limits for RF power. Rockville, Md: U.S. Department of Health and Human Services, Food and Drug Administration; 1998. Available at: *www.fda.gov/cdrh/ode/mri340.pdf*. Accessed February 23, 2003.