BJR
https://doi.org/10.1259/bjr.20170680
Received: 08 September 2017 | Revised: 22 November 2017 | Accepted: 30 November 2017

Cite this article as:
Kim HG, Choi JW, Yoon SH, Lee S. Image quality assessment of silent T_2 PROPELLER sequence for brain imaging in infants. *Br J Radiol* 2018; **91**: 20170680.

FULL PAPER

Image quality assessment of silent T_2 PROPELLER sequence for brain imaging in infants

[1]HYUN GI KIM, MD, PhD, [1]JIN WOOK CHOI, MD, [2]SOO HAN YOON, MD, PhD and [3]SIEUN LEE, MS

[1]Department of Radiology, Ajou University School of Medicine, Ajou University Medical Center, Yeongtong-gu, Suwon, Korea
[2]Department of Neurosurgery, Ajou University School of Medicine, Ajou University Medical Center, Yeongtong-gu, Suwon, Korea
[3]Department of Humanities and Social Medicine, Office of Biostatistics, Ajou University School of Medicine, Yeongtong-gu, Suwon, Korea

Address correspondence to: Dr Hyun Gi Kim
E-mail: *catharina315@aumc.ac.kr*

Objective: Infants are vulnerable to high acoustic noise. Acoustic noise generated by MR scanning can be reduced by a silent sequence. The purpose of this study is to compare the image quality of the conventional and silent T2 PROPELLER sequences for brain imaging in infants.
Methods: A total of 36 scans were acquired from 24 infants using a 3 T MR scanner. Each patient underwent both conventional and silent T2 PROPELLER sequences. Acoustic noise level was measured. Quantitative and qualitative assessments were performed with the images taken with each sequence.
Results: The sound pressure level of the conventional T2 PROPELLER imaging sequence was 92.1 dB and that of the silent T2 PROPELLER imaging sequence was 73.3 dB (reduction of 20%). On quantitative assessment, the two sequences (conventional *vs* silent T2 PROPELLER) did not show significant difference in relative contrast (0.069 *vs* 0.068, p value = 0.536) and signal-to-noise ratio (75.4 *vs* 114.8, p value = 0.098). Qualitative assessment of overall image quality (p value = 0.572), grey-white differentiation (p value = 0.986), shunt-related artefact (p value > 0.999), motion artefact (p value = 0.801) and myelination degree in different brain regions (p values ≥ 0.092) did not show significant difference between the two sequences.
Conclusion: The silent T2 PROPELLER sequence reduces acoustic noise and generated comparable image quality to that of the conventional sequence.
Advances in knowledge: This is the first report to compare silent T2 PROPELLER images with that of conventional T2 PROPELLER images in children.

INTRODUCTION

MRI scanning generates acoustic noise and its clinical importance is well documented.[1–3] The noise generally results in patients' anxiety and disturbs communication between radiographers.[1,2] If the ear is not properly protected during scanning, transient hearing impairment could occur.[3] For these reasons, ear protection is provided during MRI scanning. Although children are more vulnerable to acoustic noise of MRI scanner,[4] many institutions cannot provide proper ear protection due to the lack of suitable earplugs for this population. More importantly, since children are more likely to undergo sedation during scanning, controlling noise level to the lowest level is important to sustain sedation.[5]

Acoustic noise during MRI scanning is due to vibration of the gradient coil. The vibrations produce an air compression wave and result in the acoustic noise of the scanner.[6–8] Techniques have been introduced to reduce acoustic noise such as implementing a noise control method that could reduce the bore diameter,[9,10] filtering the gradient waveform,[11,12] or applying a band-width limited soft gradient pulse.[13] The most recent clinical applicable technique that shows a considerable amount of noise reduction is the silent PROPELLER technique.[14] The PROPELLER technique acquires data in a series of concentric blades and can compensate for head motion.[15] By optimizing the gradient waveform with fewer changes in excitation levels, it is possible to reduce the acoustic noise generated by the sequence.[14,16] With slightly longer scanning time, the spatial-resolution-matched silent technique resulted in images of comparable quality to conventional PROPELLER images in terms of overall image quality and grey matter–white matter differentiation.[14]

There was one previous study comparing images of the silent T_1 and T_2 weighted image (T1WI, T2WI) PROPELLER technique with that of T1WI spin echo and T2WI fast spin-echo sequences in children in terms of myelination degree.[17] The study compared both the sequences that were acquired by different imaging planes, slice thickness, or matrix, which made hard to match the quality of silent

PROPELLER imaging. In addition, the study included patients of a wide age range. Therefore, the aim of this study was to compare the image quality of the silent T2 PROPELLER sequence with that of the conventional T2 PROPELLER sequence in infants.

METHODS AND MATERIALS

Patients

After obtaining institutional review board approval, we conducted a retrospective review of all brain MRI examinations that included both conventional T2 PROPELLER and silent T2 PROPELLER. The requirement for informed consent was waived. We included 34 patients who are under 2-years-old from April 2016 and November 2016. Among the patients, 10 patients were excluded due to lack of proper brain tissue to assess image quality from severe hydrocephalus or encephalomalacia. Therefore, 24 infants (14 males and 10 females) with 36 MRI scanning were included in this study. The mean age of patients at the time of MRI scanning was 8.8 ± 6.0 months (range: 1–23 months). Among 36 MRI scans, 21 cases had the shunt-related artefact and 18 cases had the intracranial haemorrhage. Among cases with the shunt-related artefact, 13 cases had metallic shunt valve and 4 cases had shunts without metallic valves.

All the patients underwent brain MRI for as part of routine clinical care and all infants were given ear protective equipment when undergoing MR examination. All the patients were sedated for MRI examination.

MRI protocol

All scans were acquired using a 3 T MRI scanner (GE MRI 750 w, GE Healthcare, Milwaukee, WI). The axial slices of the two scans were obtained through the brain, parallel to the anterior commissure-posterior commissure line. The same slice location was used for each pair-wise comparison. The sequences were obtained using a 32-channel head coil. Sequence parameters are summarized in Table 1.

Table 1. MRI acquisition parameters

	T2 PROPELLER	Silent T2 PROPELLER
TR (ms)	3906	3608
TE (ms)	117	124
Field-of-view (cm)	20 × 20	20 × 20
Matrix	352 × 352	352 × 352
Slice thickness (mm)	5	5
Slice gap (mm)	0	0
Bandwidth (Khz)	41.6	41.6
Refocus flip angle	160	160
Echo-train length	32	20
Number of excitations	1.5	1.5
Acceleration factor	2	2
Scan time (min)	1:34	2:17

TE, echo time; TR, repetition time.

Acoustic noise

The noise was measured using a sound level meter (TES-1350A, TES Electrical Electronic Corporation Taipei, Taiwan). The sound level meter was placed on the patient table of MR scanner, 3 m outside from where the patient's ear might during the scanning. Noise level was measured for 30 s and averaged before scanning to measure background level. During each sequence, the same measurement was done for 30 s and averaged. Two parameters are then calculated:

(1) Sound pressure level difference: ΔL = conventional T2 PROPELLER sequence sound level (dB) − silent T2 PROPELLER sequence sound level (dB)
(2) Loudness factor: $LF = 2^{\Delta L/10}$

Sound pressure level is the sound field quantity of a sound in a surrounded space caused by a sound source. Loudness is the sound level as perceived by an observer, so it represents the subjective perception of sound pressure.[18]

Quantitative image quality

Quantitative image evaluation was done by drawing region of interest by one radiologist with 7 years of experience. The regions of interest were drawn in the frontal white matter (WM) and deep grey matter (GM) of caudate head. Relative contrast was calculated using the following equation:

$$\text{Relative contrast} = abs\left[\frac{SI_{WM} - SI_{GM}}{SI_{WM} + SI_{GM}}\right]$$

where SI_{WM} is signal intensity (SI) in the WM and SI_{GM} is SI in the GM. Signal intensity was measured at the level of foramen Monro.

Signal-to-noise ratio (SNR) was calculated using the following equation:

$$SNR = \frac{SI_{GM}}{SD_{Air}}$$

where SD_{Air} is standard deviation value measured outside the cranial vault.

Qualitative image quality

For qualitative analysis, images acquired with T2 PROPELLER and silent T2 PROPELLER was reviewed by two radiologists: Radiologist 1 and Radiologist 2 with 7 and 14 years of experience, respectively. The radiologists were blinded to the two sets of images. The images were displayed using PACS in our institution. Each radiologist independently assessed and graded the image quality based on the following parameters: overall diagnostic quality, gray-white differentiation, shunt-related artefact, detection of intracranial haemorrhage, motion artefact, and lesion localization. We used a 3-point scale for overall diagnostic quality: (1) poor/non-diagnostic; (2) average and (3) excellent. Grey-white differentiation, detection of intracranial haemorrhage and lesion localization were graded as (1) poor delineation; (2) average delineation and (3) excellent delineation. Shunt-related and motion artefact parameters were graded as (1) severe artefact with poor image quality; (2) average image quality and (3) excellent image quality without artefact. For shunt-related artefact and detection of intracranial haemorrhage assessment, cases without shunt or haemorrhage were not graded.

For myelination degree assessment, the following anatomical locations were used: (1) middle cerebellar peduncle, (2) posterior limb of internal capsule, (3) anterior limb of internal capsule, (4) genu of corpus callosum, (5) splenium of corpus callosum, (6) frontal WM, (7) occipital WM, (8) parietal WM and (9) centrum semiovale. We used a 3-point scale for myelination: 0, no myelination; 1, intermediate myelination and 2, full myelination.

Statistics

We compared variables for quantitative and qualitative image quality between the conventional T2 PROPELLER and silent T2 PROPELLER groups. The paired *t*-test was used for quantitative image quality variables of relative contrast and SNR comparison. The McNemar–Bowker test was used to compare the qualitative image quality between the two sequences using a 3-point scale. A *p*-value less than 0.05 was considered statistically significant. SPSS v.23.0 (SPSS, Chicago, IL) and SAS 9.4 (SAS Institute Inc., Cary, NC) was used for analysis.

RESULTS

Acoustic noise

The sound pressure level of background before scanning was 67.5 dB. The sound pressure level of T2 PROPELLER imaging sequences was 92.1 dB and that of silent T2 PROPELLER imaging sequences was 73.3 dB. Therefore, the sound pressure level difference between the conventional and quiet sequences was 18.8 dB (20% reduction). The sound pressure level measured during silent T2 PROPELLER sequences was 5.8 dB higher than the background. The difference of loudness factor was 3.7.

Quantitative analysis

Relative contrast and SNR of the two sequences did not show a significant difference. The mean ± standard deviation of relative contrast of silent T2 PROPELLER imaging and T2 PROPELLER were 0.068 ± 0.087 and 0.069 ± 0.084, respectively (*p*-value = 0.536). The mean ± standard deviation of SNR of silent T2 PROPELLER and that of T2 PROPELLER imaging were 114.8 ± 151.2 and 75.4 ± 27.6, respectively (*p* value = 0.098).

Qualitative analysis

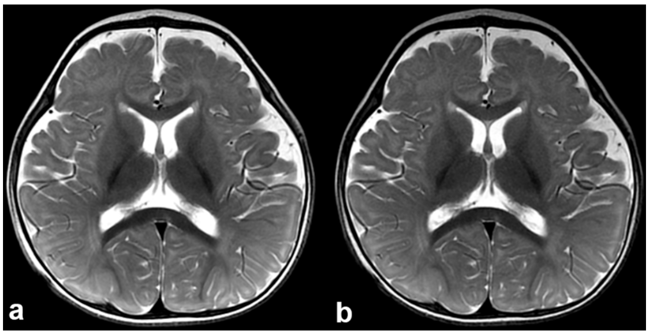
On image quality assessment, all the six parameters showed no significant difference between the two sequences by the two radiologists (Table 2). In terms of overall diagnostic quality, all the 36 cases for T2 PROPELLER imaging were excellent. For silent T2 PROPELLER imaging, Radiologist 1 rated two cases as average quality and Radiologist 2 rated four cases as average quality. No cases were rated as poor for the overall image quality assessment. The image quality for the detection of intracranial haemorrhage or lesion localization was excellent in all the cases by the two radiologists. Example images are in Figures 1 and 2.

Table 2. Qualitative image quality analysis of the T2 PROPELLER and silent T2 PROPELLER sequences

	Radiologist 1			Radiologist 2		
	T2 PROPELLER	Silent T2 PROPELLER	*p*-value	T2 PROPELLER	Silent T2 PROPELLER	*p*-value
Image quality						
Overall diagnostic quality	0/0/36	0/2/34	0.572	0/0/36	0/4/32	0.261
Grey-white differentiation	0/3/33	0/4/32	0.986	0/0/36	0/1/35	0.801
Shunt-related artefact	13/0/7	13/0/7	>0.999	1/12/7	1/12/7	>0.999
Intracranial haemorrhage detection	0/0/17	0/0/17	>0.999	0/0/17	0/0/17	>0.999
Motion artefact	0/0/36	0/1/35	0.801	0/2/34	0/1/35	0.954
Lesion localization	0/0/36	0/0/36	>0.999	0/0/36	0/0/36	>0.999
Myelination degree						
Middle cerebellar peduncle	0/0/36	0/0/36	>0.999	0/0/36	0/0/36	>0.999
Posterior limb of internal capsule	0/3/33	0/3/33	>0.999	0/4/32	0/4/32	>0.999
Anterior limb of internal capsule	11/13/12	10/18/8	0.228	14/6/16	14/6/16	>0.999
Genu of corpus callosum	12/7/15	5/16/13	0.092	0/8/26	0/8/26	>0.999
Splenium of corpus callosum	4/9/15	0/12/16	0.228	3/2/23	3/2/23	>0.999
Frontal white matter	18/12/6	18/13/5	0.801	23/7/6	23/7/6	>0.999
Occipital white matter	15/11/10	13/16/7	0.261	17/2/17	18/2/16	0.572
Parietal white matter	18/11/7	21/9/6	0.261	18/5/13	18/6/12	0.801
Centrum semiovale	0/10/26	0/11/25	0.954	0/0/36	1/0/35	0.801

Number of cases graded in 3-point scale are presented in order; Image quality, 1 point/2 point/3 point; myelination degree, 0 point/1 point/2 point.

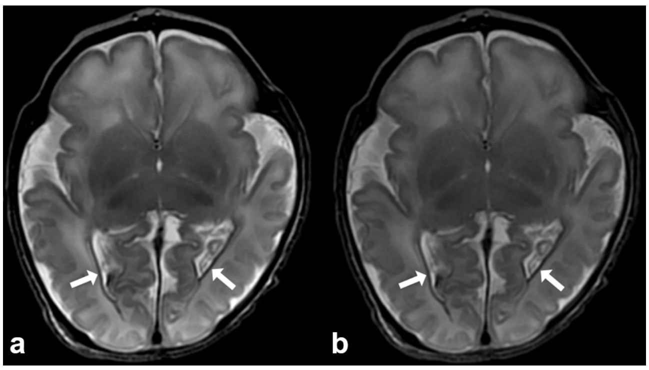
Figure 1. A 10-month-old infant. Comparison images of the conventional (a) and silent (b) T2 PROPELLER sequence are shown.



For shunt-related artefact, 13 cases with intracranial signal loss were rated as poor or average by the two radiologists. The remaining 7 cases without intracranial signal loss were rated excellent by the two radiologists.

In the myelination degree assessment, no anatomic region showed a significant difference between the two sequences (Table 2). The development pattern of myelination followed the know spatiotemporal course in the two sequences. Middle cerebellar peduncle and posterior limb of internal capsule were graded as "intermediate to full myelination" in all the 36 cases including the case of the 1-month-old neonate in the both sequences by the two radiologists. Centrum semiovale was graded as "intermediate to full myelination" in all the cases, except for the one case with the silent T2 PROPELLER sequence by Radiologist 2. Anterior limb of internal capsule showed myelination in infants who were 4 months or older. The number of cases graded as "intermediate to full myelination" in anterior limb of internal capsule were 25–26 cases by Radiologist 1 and 22 cases by Radiologist 2. Genu and splenium of corpus callosum were graded as "full myelination" in patients 9 months or older. Myelination degree assessment in corpus callosum varied in patients under 9 months of age by Radiologist 1 (intermediate to full myelination; 22 cases with conventional T2 PROPELLER and 29 cases with silent T2 PROPELLER). Frontal and parietal WM were the least myelinated regions by the two radiologists.

Figure 2. A 2-month-old infant with intraventricular haemorrhagic residuals (arrows) and thinning of corpus callosum. Comparison images of the conventional (a) and silent (b) T2 PROPELLER sequence are shown.



DISCUSSION

We compared the silent T2 PROPELLER imaging with that of conventional T2 PROPELLER imaging in infants. Reduction of acoustic noise by 20% with the silent technique was possible and the image acquired with the silent sequence was comparable to that of conventional T2 PROPELLER.

It is predictable that lower acoustic noise level will disrupt sedation less during scanning.[5] Therefore, scanners or sequences with low acoustic noise should be used for the paediatric population and adequate hearing protective devices should be used during scanning. Several MRI system vendors have provided noise-reduction systems, such as vacuum-sealed gradient chambers to diminish the mechanical vibration.[10] Another way of reducing acoustic noise is to mask the noise by MRI-compatible audio systems. However, this system has no significant effect in infants.[19] As less sedation is more important in neonates because growing evidence suggests that sedation in this population induces neuronal apoptosis and apnea,[20,21] a more universal application to reduce acoustic noise by adjusting image techniques was thought necessary. Therefore, a method to optimize gradient waveforms was developed and the sequence is called either the "Silent" or "Quiet" sequence.[14,16,22] The technique has been applied to T1WI, T2WI and FLAIR,[14,17] but not yet in other sequences such as DWI.

The sound reduction rate of ours (20%) is similar to the previous study comparing silent T2 PROPELLER and conventional T2 PROPELLER in adults (26% reduction). However, the absolute noise level differs from the previous study. The relatively lower sound pressure level of the T2 PROPELLER sequence in our results compared to that of the previous study (conventional sequence; 92 *vs* 101 dB) is probably due to the longer distance from the bore to the sound level meter placement. The acoustic noise level is affected by z-direction from the bore entrance and the level of field-strength;[23] closed to the bore and higher field-strength results in higher acoustic noise level. On the other hand, the sound level of the silent T2 PROPELLER sequence in our study was higher compared to the previous study using the same 3.0 T MR scanner (73.3 *vs* 59.0 dB).[17] This is possibly because of the higher back ground sound level in our MRI scanning room compared to the previous study (67.5 *vs* 52.4 dB). The 73.3 dB of scanning sound pressure level was comparable to that of permitted level of transient sound level (70 dB) in neonatal intensive care unit of staff work areas.[24] Given that infants are having proper ear protection during scanning, which reduces noise by 10–30 dB, the actual sound level during the scanning would be around 40–60 dB, which is close to the normal conversational level of 50–60 dB.[25]

The comparable image quality using the silent T2 PROPELLER technique is consistent with previous studies.[14,22] The first study that applied the silent T2 PROPELLER technique in a clinical practice evaluated 34 adults with 1.5 T MR scanner.[14] The study applied spatial-resolution-matched silent sequence and showed similar qualitative scores of the images taken with the conventional and silent sequences. Following the study, there was the study using the silent T2 PROPELLER technique using 3.0 T MR scanner for children.[22] The study used the T2 FSE sequence as a conventional sequence and used different scanning parameters (*i.e.* different imaging plane, matrix, and slice thickness in the two sequences) and concluded that silent T2 PROPELLER is comparable to the conventional sequence. Our study is the only study that compared spatial-resolution-matched conventional and silent T2 PROPELLER sequences in infants. Both quantitative and qualitative parameters were comparable in images taken with the two sequences. Although it was statistically not significant, SNR was higher in the silent T2 PROPELLER technique. Even higher SNR could have been achieved with longer TR or higher number of excitations, but this was undesirable since longer scanning time is already one major disadvantage of using the silent sequence.

In terms of acquisition parameters, the difference in scanning time between the conventional and silent T2 PROPELLER sequences was 43 s. Although there is a protective effect of motion artefact using the PROPELLER sequence, an acquisition time that is 45% longer compared to the conventional sequence raises concern on issues such as increased risk of motion and additional usage of sedative agents. In fact, the PROPELLER sequence itself is robust to motion artifacts compared to the spin echo technique.[15,17] The ETL differed between the two sequences (32 *vs* 20) as well. When setting the TR/TE and ETL of the silent T2 PROPELLER sequence, there were inevitable alterations from the conventional T2 PROPELLER sequence. We wanted to compare the two sequences with a similar TR/TE. To achieve this, the ETL in the silent T2 PROPELLER sequence had to be reduced because of the adjusted gradient waveform. Variations between the two sequences due to this reduction might have affected the imaging appearance.

When the degree of myelination was compared, the graded low WM SI was not different between the two sequences. This is consistent with a prior study showing the good intermethod agreement of myelination degree in children using silent T2 PROPELLER images and T2 FSE images.[17] Our study lacks T1WI for comparison, however, the authors in the previous study compared myelination degree of the T1WI spin echo sequence and silent T1WI based on the 3D gradient-echo imaging technique (slice thickness: 0.8–1 mm) and concluded that silent T1WI may be more sensitive to cerebellar myelination compared to spin echo sequences.[17] Still, since T1 spin echo sequence were acquired using a 2D axial plane with slice thickness 4–5 mm, comparing the two sequences for the myelination degree seems to have limitation. Since myelination of middle cerebellar peduncle appears from the birth and T1WI is more sensitive on early myelination than T2WI, further study on this subject comparing conventional and silent T1WI might be needed.

There are some limitations in our study. Firstly, we did not include T1WI or FLAIR sequences in the comparison. This was because our study was conducted in the clinical setting with limited sequences of MRI, which was performed on children who underwent frequent repeated brain MRI examinations for follow-up purposes. Including the silent sequences for T1WI or FLAIR, and decreasing acoustic noise throughout the scanning may have higher clinical importance. Still, decreasing the time period of high acoustic noise exposure itself is important, since the permitted period of time a person can be exposed is increased with decreased noise level.[25] Therefore, reducing the overall duration of high acoustic noise level exposure is meaningful in infants. Secondly, since our study was retrospective, and as no additional sedation was done during the scanning, it was hard for us to tell if there was reduced awakening during scans with the silent technique. A prospective study on this subject might be helpful, but both ethical and technical issues need to be resolved first. Applying a louder sequence to a neonate when it has no superior image quality to that of the silent sequence would be unethical. Also, while we could monitor tolerance during sedation using an electroencephalogram,[26] acquiring an electroencephalogram and MRI simultaneously is a technical challenge.[27] Thirdly, we did not evaluate interobserver variability between the two radiologists. Although there was no significant difference between the two sequences regarding qualitative image quality assessment, there were some discrepancies between the two radiologists for several parameters, such as the shunt-related artefact or myelination degree in corpus callosum. This was mainly because the two radiologists assessed image quality independently and because no additional consensus was made before or after evaluation. However, we believe the importance of this study lies mainly in the difference between the two sequences, and not these discrepancies. Lastly, the study population in this study was not a normal group. Among the assessment parameters, myelination degree is affected by the patients' condition such hydrocephalus.[28] Therefore, the two sequences we have compared are not going to reflect the myelination degree of normal population.

In conclusion, the silent T2 PROPELLER sequence reduces acoustic noise to a comfortable level and produces images comparable to that of the conventional T2 PROPELLER sequence. The sound reduction is critical to infants who are vulnerable to acoustic noise itself. Myelination degree, which needs to be assessed in infants, is not affected by the silent technique.

ACKNOWLEDGEMENTS

Hyun Gi Kim and Jin Wook Choi contributed equally to the study and share first authorship. The authors thank Seung Nam Baek, Sung-Min Gho, and Young Ju Lee of GE Healthcare Korea, for technical assistance.

FUNDING

This study was supported by grant no. GA104-06 from the Central Medical Service Research Fund.

REFERENCES

1. Moelker A, Maas RA, Pattynama PM. Verbal communication in MR environments: effect of MR system acoustic noise on speech understanding. *Radiology* 2004; **232**: 107–13. doi: https://doi.org/10.1148/radiol.2321030955
2. Quirk ME, Letendre AJ, Ciottone RA, Lingley JF. Anxiety in patients undergoing MR imaging. *Radiology* 1989; **170**: 463–6. doi: https://doi.org/10.1148/radiology.170.2.2911670
3. Brummett RE, Talbot JM, Charuhas P. Potential hearing loss resulting from MR imaging. *Radiology* 1988; **169**: 539–40. doi: https://doi.org/10.1148/radiology.169.2.3175004
4. Chou IJ, Tench CR, Gowland P, Jaspan T, Dineen RA, Evangelou N, et al. Subjective discomfort in children receiving 3 T MRI and experienced adults' perspective on children's tolerability of 7 T: a cross-sectional questionnaire survey. *BMJ Open* 2014; **4**: e006094: e006094: . doi: https://doi.org/10.1136/bmjopen-2014-006094
5. Kim DW, Kil HY, White PF. The effect of noise on the bispectral index during propofol sedation. *Anesth Analg* 2001; **93**: 1170–3. doi: https://doi.org/10.1097/00000539-200111000-00022
6. Mansfield P, Haywood B, Coxon R. Active acoustic control in gradient coils for MRI. *Magn Reson Med* 2001; **46**: 807–18. doi: https://doi.org/10.1002/mrm.1261
7. Bowtell RW, Mansfield P. Quiet transverse gradient coils: Lorentz force balanced designs using geometrical similitude. *Magn Reson Med* 1995; **34**: 494–7. doi: https://doi.org/10.1002/mrm.1910340331
8. Mansfield P, Glover PM, Beaumont J. Sound generation in gradient coil structures for MRI. *Magn Reson Med* 1998; **39**: 539–50. doi: https://doi.org/10.1002/mrm.1910390406
9. Mechefske CK, Wu Y, Rutt BK. Acoustic noise reduction in a 4T whole body MR imager. *Proc Intl Soc Magn Reson Med* 2001; **9**: 1752.
10. Katsunuma A, Takamori H, Sakakura Y, Hamamura Y, Ogo Y, Katayama R. Quiet MRI with novel acoustic noise reduction. *MAGMA* 2002; **13**: 139–44. doi: https://doi.org/10.1016/S1352-8661(01)00142-9
11. Cho ZH, Chung ST, Chung JY, Park SH, Kim JS, Moon CH, et al. A new silent magnetic resonance imaging using a rotating DC gradient. *Magn Reson Med* 1998; **39**: 317–21. doi: https://doi.org/10.1002/mrm.1910390221
12. Segbers M, Rizzo Sierra CV, Duifhuis H, Hoogduin JM. Shaping and timing gradient pulses to reduce MRI acoustic noise. *Magn Reson Med* 2010; **64**: 546–53. doi: https://doi.org/10.1002/mrm.22366
13. Hennel F, Girard F, Loenneker T. "Silent" MRI with soft gradient pulses. *Magn Reson Med* 1999; **42**: 6–10. doi: https://doi.org/10.1002/(SICI)1522-2594(199907)42:1<6::AID-MRM2>3.0.CO;2-D
14. Corcuera-Solano I, Doshi A, Pawha PS, Gui D, Gaddipati A, Tanenbaum L. Quiet PROPELLER MRI techniques match the quality of conventional PROPELLER brain imaging techniques. *AJNR Am J Neuroradiol* 2015; **36**: 1124–7. doi: https://doi.org/10.3174/ajnr.A4235
15. Forbes KP, Pipe JG, Bird CR, Heiserman JE. PROPELLER MRI: clinical testing of a novel technique for quantification and compensation of head motion. *J Magn Reson Imaging* 2001; **14**: 215–22. doi: https://doi.org/10.1002/jmri.1176
16. Alibek S, Vogel M, Sun W, Winkler D, Baker CA, Burke M, et al. Acoustic noise reduction in MRI using silent scan: an initial experience. *Diagn Interv Radiol* 2014; **20**: 360–3. doi: https://doi.org/10.5152/dir.2014.13458
17. Matsuo-Hagiyama C, Watanabe Y, Tanaka H, Takahashi H, Arisawa A, Yoshioka E, et al. Comparison of silent and conventional MR imaging for the evaluation of myelination in children. *Magn Reson Med Sci* 2017; **16**: 209–16. doi: https://doi.org/10.2463/mrms.mp.2016-0045
18. Salvato JA, Nemerow NL, Agardy FJ, Salvato JA. *Environmental engineering*. 5th ed. Hoboken, NJ: John Wiley & Sons; 2003.
19. Harned RK, Strain JD. MRI-compatible audio/visual system: impact on pediatric sedation. *Pediatr Radiol* 2001; **31**: 247–50. doi: https://doi.org/10.1007/s002470100426
20. Jevtovic-Todorovic V, Hartman RE, Izumi Y, Benshoff ND, Dikranian K, Zorumski CF, et al. Early exposure to common anesthetic agents causes widespread neurodegeneration in the developing rat brain and persistent learning deficits. *J Neurosci* 2003; **23**: 295–6. doi: https://doi.org/10.1097/00008506-200307000-00029
21. Coté CJ. Safety after chloral hydrate sedation of former preterm and term infants for magnetic resonance imaging: are the data clear? *Anesth Analg* 2010; **110**: 671–3. doi: https://doi.org/10.1213/ANE.0b013e3181cd4428
22. Heismann B, Ott M, Grodzki D. Sequence-based acoustic noise reduction of clinical MRI scans. *Magn Reson Med* 2015; **73**: 1104–9. doi: https://doi.org/10.1002/mrm.25229
23. Price DL, De Wilde JP, Papadaki AM, Curran JS, Kitney RI. Investigation of acoustic noise on 15 MRI scanners from 0.2 T to 3 T. *J Magn Reson Imaging* 2001; **13**: 288–93. doi: https://doi.org/10.1002/1522-2586(200102)13:2<288::AID-JMRI1041>3.0.CO;2-P
24. White RD, Smith JA, Shepley MM.Committee to Establish Recommended Standards for Newborn ICU Design Recommended standards for newborn ICU design, eighth edition. *J Perinatol* 2013; **33**(Suppl 1): S2–S16. doi: https://doi.org/10.1038/jp.2013.10
25. United States Department of Labor [https://www.osha.gov/]. Laboratory Safety Noise. 2017. Available from: https://www.osha.gov/Publications/laboratory/OSHAfactsheet- laboratory-safety-noise.pdf. [cited 2017 Sep 7]
26. Vernon JM, Lang E, Sebel PS, Manberg P. Prediction of movement using bispectral electroencephalographic analysis during propofol/alfentanil or isoflurane/alfentanil anesthesia. *Anesth Analg* 1995; **80**: 780–5.
27. Goldman RI, Stern JM, Engel J, Cohen MS. Acquiring simultaneous EEG and functional MRI. *Clin Neurophysiol* 2000; **111**: 1974–80. doi: https://doi.org/10.1016/S1388-2457(00)00456-9
28. Hanlo PW, Gooskens RJ, van Schooneveld M, Tulleken CA, van der Knaap MS, Faber JA, et al. The effect of intracranial pressure on myelination and the relationship with neurodevelopment in infantile hydrocephalus. *Dev Med Child Neurol* 1997; **39**: 286–91. doi: https://doi.org/10.1111/j.1469-8749.1997.tb07433.x