Simulation and Measurement of Signal Intensity for Various Tissues near Bone Interface in 2D and 3D Neurological MR Images

Done-Sik Yoo

Brain Wave Information Team,
Telecommunication Basic Research Laboratory,
Electronics and Telecommunications Research Institute, Taejon 305-350

Purpose: To simulate and measure the signal intensity of various tissues near bone interface in 2D and 3D neurological MR images.

Materials and Methods: In neurological proton density (PD) weighted images, every component in the head including cerebrospinal fluid (CSF), muscle and scalp, with the exception of bone, are visualised. It is possible to acquire images in 2D or 3D. A 2D fast spin-echo (FSE) sequence is chosen for the 2D acquisition and a 3D gradient-echo (GE) sequence is chosen for the 3D acquisition. To find out the signal intensities of CSF, muscle and fat (or scalp) for the 2D spin-echo(SE) and 3D gradient-echo (GE) imaging sequences, the theoretical signal intensities for 2D SE and 3D GE were calculated. For the 2D fast spin-echo (FSE) sequence, to produce the PD weighted image, long TR (4000 ms) and short TE_{eff} (22 ms) were employed. For the 3D GE sequence, low flip angle (8°) with short TR (35 ms) and short TE (3 ms) was used to produce the PD weighted contrast.

Results: The 2D FSE sequence has CSF, muscle and scalp with superior image contrast and SNR of 39 - 57 while the 3D GE sequence has CSF, muscle and scalp with broadly similar image contrast and SNR of 26 - 33. SNR in the FSE image were better than those in the GE image and the skull edges appeared very clearly in the FSE image due to the edge enhancement effect in the FSE sequence. Furthermore, the contrast between CSF, muscle and scalp in the 2D FSE image was significantly better than in the 3D GE image, due to the strong signal intensities (or SNR) from CSF, muscle and scalp and enhanced edges of CSF.

Conclusion: The signal intensity of various tissues near bone interface in neurological MR images has been simulated and measured. Both the simulation and imaging of the 2D SE and 3D GE sequences have CSF, fat and muscle with broadly similar image intensity and SNR's and have succeeded in getting all tissues about the same signal. However, in the 2D FSE sequence, image contrast between CSF, muscle and scalp was good and SNR was relatively high, imaging time was relatively short.

Key Word: MRI, Signal intensity, CSF, Fat, Muscle

Introduction

In neurological proton density (PD) weighted images, every component in the head including cerebrospinal fluid (CSF), muscle and scalp, with the exception of bone, are visualised. It is possible to acquire images in 2D or 3D. A 2D fast spin-echo (FSE) sequence is chosen for the 2D

Table 1. Comparison of 2D FSE and 3D GE acquisitions.

Parameter	2D FSE acquisition	GE acquisition
Acquisition time	Short (6 min)	Long (20 min)
Isotropic voxel	No	Yes
Slice thickness	Thick (3-5 mm)	Thin (1-2 mm)
Distortion in slice reconstruction	Yes	No
Partial volume effect	Yes (more)	Yes (less)
Chemical shift artefact	Yes	Yes
Susceptibility artefact (shift)	Yes	Yes
Susceptibility artefact (signal loss)	No	Yes

Table 2. Imaging parameters for 2D and 3D acquisitions.

Imaging Parameter	2D Fast Spin Echo	3D Gradient Echo
TR (ms)	4000	35
TE (ms)	22 (TE_{eff})	3
Flip angle (degree)	-	8
Echo train length	8	-
NEX	1	1
FOV (cm^2)	24.0 x 24.0	24.0 x 24.0
Matrix	256 x 256	256 x 256
Slice thickness (mm)	3.0	1.5
Voxel size (mm^3)	0.9 x 0.9 x 3.0	0.9 x 0.9 x 1.5
Number of slices	68	128
Scan time (min:sec)	6:25	19:10

acquisition and a 3D gradient-echo (GE) sequence is chosen for the 3D acquisition. Although 2D GE and 3D FSE sequences are also available, they are not considered here since their image quality and acquisition time are not as practical as those from the 2D FSE and 3D GE sequences.

The 2D FSE sequence has several advantages: high signal intensity, short acquisition time and no signal loss due to susceptibility artefact. On the other hand, the advantages of the 3D GE acquisition include isotropic voxel, less partial volume effect due to smaller voxel size and thinner slice thickness.

The disadvantages of the 2D FSE acquisition include non-isotropic voxel, partial volume effect due to bigger voxel size, the difficulty of reconstructing an arbitrary slice orientation without distortion and chemical shift artefact. The 3D GE acquisition has several disadvantages such as lower signal intensity due to smaller voxel, longer acquisition time, which could cause an additional artefact due to movement of the subject, chemical shift artefact and susceptibility artefact including signal loss and geometric distortion. The advantages and disadvantages of 2D FSE and 3D GE acquisitions are summarised in Table 1.

The aim of this study is to simulate and measure the signal intensity of various tissues near bone interface in 2D and 3D neurological MR images.

Methods

To find out the signal intensities of CSF, muscle and fat (or scalp) for the 2D SE and 3D GE imaging sequences, the theoretical signal intensities for 2D SE (S_{SE}) and 3D GE (S_{GE}) are calculated using Eqs. [1] and [2][1-4]:

$$S_{SE} = \rho_H e^{-TE/T2} [1 - e^{-TR/T1}] \quad [1]$$

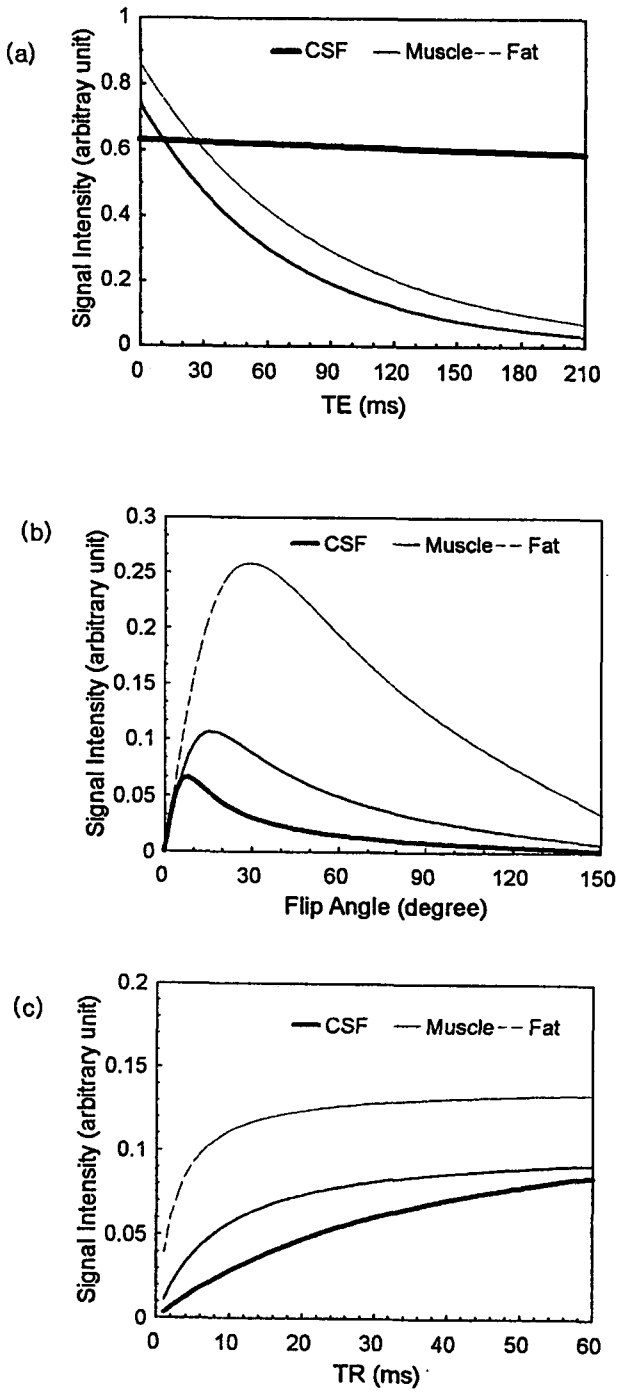

Fig 1. Signal intensities of CSF, muscle and fat from the theoretical equations for (a) 2D spin-echo sequence against the echo time (TR = 4000 ms), (b) 3D spoiled gradient-echo sequence against the flip angle (TR = 35 ms and TE = 3 ms) and (c) Intensity change in the 3D GE sequence against TR.

$$S_{GE} = \rho_H \, e^{-TE/T2^*} \frac{[1 - e^{-TR/T1}]\sin\alpha}{1 - e^{-TR/T1}\cos\alpha} \quad [2]$$

where ρ_H is the proton density, and TE is the echo time, TR is the repetitions time, T1 is the longitudinal relaxation time, T2 is the transverse relaxation time, $T2^*$ is the effective transverse relaxation time, α is the flip angle.

Imaging parameters for the PD weighted image of the head by the FSE and GE sequences are compared in Table 2. To produce the PD weighted image, for the 2D FSE sequence, long TR (4000 ms) and short TE_{eff} (22 ms) were employed. A long TR value assures that the longitudinal magnetisation in all of the tissues is recovered to close to its equilibrium value before excitation pulse in the image sequence. This minimises the dependence on T1. The short TE value assures that the transverse magnetisation is decayed very little before sampling the signal minimising the dependence on T2 (see Fig 1 (a)). T2 of fat is quite short and signal would be decreased at large TE's. In addition, for the complete recovery of the longitudinal magnetisation in the CSF, which has the longest T1 value in the tissues of interest, the TR (4000 ms) was chosen to match with the T1 of CSF (4000 ms). Selection of the echo train length (ETL) is important due to its influence on image contrast, blurring and SNR. In general, as the selected ETL increases, the number of echoes contributing to T2 decay is increased. Furthermore, acquisition time and the number of slices available are decreased as the ETL increases. After taking into account the factors of ETL, images were acquired with an ETL of 8.

For the 3D GE sequence, low flip angle (8°) with short TR (35 ms) and short TE (3 ms) was used to produce the PD weighted contrast. At very small flip angle in the 3D GE sequence, the intensities are independent of the T1 relaxation time since the longitudinal magnetisation remains

near equilibrium for low flip angle (see Fig 1 b). In addition, the short TR (35 ms) was employed for the 3D GE sequence in order to reduce the scan time. As TR decreases, the scan time is reduced but the signal decreases as well (see Fig 1 c). For example, if TR is reduced from 35 ms to 10 ms, then the scan time can decrease to around 6 minutes (compared to 19 minutes) but the signal is reduced by 14-57% depending on the tissue type. Since the same field of view (FOV) and matrix size are applied in both 2D FSE and 3D GE sequences, the pixel size is same for the two acquisitions. Because of the difference in slice thickness, the voxel in the 3D GE images is smaller than that in the 2D FSE images. It should be noted that although 3D GE sequence can produce smaller voxel (or thinner slice thickness) compared with 2D FSE sequence, the scan time of the 3D sequence is approximately three times longer than that of the 2D sequence (see the last column in Table 2).

Results

1. Simulation of signal intensity for 2D and 3D images

The results of the modelling are shown in Fig 1. The intensity for the 2D SE sequence was plotted against the echo time in Fig 1 (a), while that for the 3D GE sequence was plotted against the flip angle in Fig 1 (b) and the intensity change in the 3D GE sequence was plotted against TR in Fig 1 (c). Imaging parameters for the scan of 2D SE and 3D GE sequences in Table 2 were employed for the simulation. For the simulation, employed relaxation times and proton density for CSF , muscle and fat were: T1 = 4000/900/260 ms, T2 = 3000/47/84 ms, $T2^*$ = 4.9/4.5/4.7 ms, ρ_H = 1.00/0.75/0.86[4,5].

In the spin-echo simulation curve (Fig 1 a), signals from muscle and fat decrease exponentially as the echo time increases whilst the signal from CSF decreases exponentially and very gradually as the echo time increases. At early echo time (10 ms), the signal intensity of fat is the brightest in the image while CSF is the darkest. After long echo time, for example, 200 ms, signals from muscle and fat almost disappear, while those from CSF still maintain approximately 93% of their initial intensity.

In the gradient-echo simulation curve (Fig 1 b), signals from CSF, muscle and fat increase at the beginning then decrease as the flip angle increases. CSF has its peak at around 7° while peaks of muscle and fat appear at 15° and 30°. Fat appears as the brightest, whereas CSF is the darkest in the image for the higher flip angles.

The signal intensities of CSF, muscle and fat (or scalp) for the 2D and 3D imaging sequences can be predicted with the realistic imaging parameters. From the simulation curves in Fig 1, the intensity values for CSF, muscle and fat (or scalp) were selected at TE = 24 ms for the 2D sequence and at α = 8° for the 3D sequence.

2. Measurement of signal intensity in 2D and 3D images

A subject was scanned using both the 2D FSE and 3D GE sequences with the imaging parameters discussed in above. The 2D FSE and 3D GE images are shown in Fig 2. In the FSE image, skull edges (CSF, muscle and scalp) appeared clearer than those in the GE image for all slices due to the edge enhancement effect in FSE . Furthermore, in the GE image, the skull edges appeared to be blurred in certain regions such as the left superior lobe and the right temporal lobe regions. In general, the GE sequence has poorer SNR than the FSE sequence since the echo is formed by an α° pulse rather than a 180° pulse, which leads to reduce echo intensity. But there is averaging of a factor of $\sqrt{n_z}$ to improve

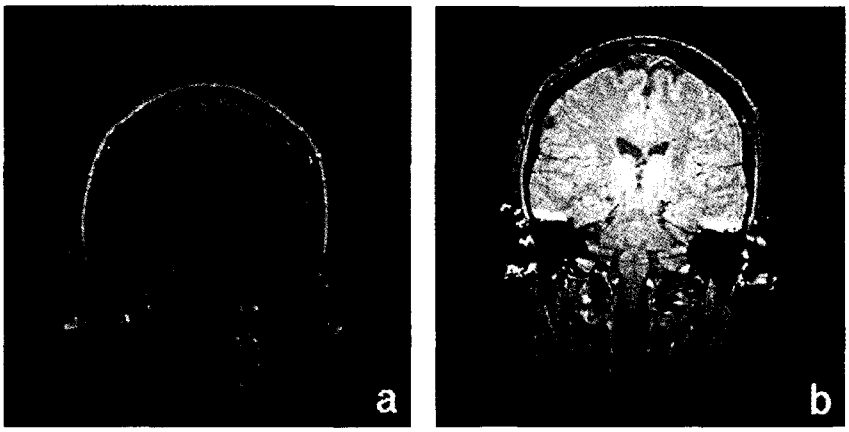

Fig 2. Images from 2D and 3D acquisitions: (a) 2D fast spin-echo image (TR = 4000 ms, TE_{eff} = 22 ms, ETL = 8, slice thickness = 3 mm) and (b) 3D spoiled gradient- echo image (TR = 35 ms, TE = 3 ms, α = 8°, slice thickness = 1.5 mm).

SNR in the GE sequence where n_z is the number of slices (4, 6).

The signal intensities of CSF, muscle and fat and background noise were measured in the simulations and the 2D FSE and 3D GE images and the results summarised in Tables 3 and 4. For the signal calculation in the 2D FSE simulation, a factor of 2 was multiplied since the slice of FSE (3 mm) was twice thicker than that of GE (1.5 mm) (see Table 2). For the signal calculation in the 3D GE simulation, a factor of $\sqrt{n_z}$ was multiplied.

Several different regions in the image for CSF, muscle and scalp (fat) were employed for the

Table 3. Simulated signal intensities, signal intensity ratio relative to muscle (SIRM) and CSF (SIRC), and signal intensity ratio between FSE and GE sequences (SIRB) of CSF, fat or muscle for 2D and 3D imaging sequences. For 2D FSE, TR = 4 s and TE = 24 ms, and for 3D GE, TR = 35 ms, TE = 3 ms and α = 8°.

Tissue	2D FSE			3D GE			SIRB
	Signal	SIRM	SIRC	Signal	SIRM	SIRC	
CSF	1.26	1.21	-	0.75	0.79	-	1.69
Muscle	1.04	-	0.83	0.95	-	1.27	1.09
Fat	1.30	1.25	1.03	1.47	1.55	1.97	0.88

Table 4. Image signal intensities, SNR, SIRM, SIRC and SIRB of CSF, fat or muscle in the 2D and 3D images. For 2D FSE, TR = 4 s and TE = 24 ms, and for 3D GE, TR = 35 ms, TE = 3 ms and α = 8°.

Tissue	2D FSE				3D GE				SIRB
	Signal	SNR	SIRM	SIRC	Signal	SNR	SIRM	SIRC	
CSF	1056±1	56.5	1.45	-	111±1	31.7	0.95	-	1.78
Muscle	728±6	38.9	-	0.69	117±4	33.4	-	1.05	1.17
Scalp*	840±2	44.9	1.15	0.80	90±8	25.8	0.77	0.81	1.74
Noise	19±4	-	-	-	4±0	-	-	-	5.34

* Scalp consists of fat and other components (scalp ≠ fat).

intensity measurement. The noise was determined by averaging the measurements of the background intensity at several different regions in the image.

Signal intensity ratio between 2D FSE and 3D GE sequences (SIRB) in the simulations and measurements for CSF, muscle and scalp (fat) were calculated and the results are plotted in Fig 3 (a). This graph was generated in order to examine the performance of the image sequences compared with theoretical calculations. SIRB's of CSF and muscle in the measurements agreed well with those in the simulations. However, SIRB of scalp in the measurement was twice greater than SIRB of fat in the simulation. This can be explained by the fact that scalp consists of several layers of different tissues such as skin, connective tissue, aponeurosis and so on and that the signals are tuned to water and the fat precesses away from water for TE > 0. In Fig 2, it is clearly seen that the scalp in the superior lobe region appears a multi layer object. In fact, the signal intensity measurement of the scalp is the mean intensity from the scalp tissues. In addition, signal intensity ratio relative to muscle (SIRM) and CSF (SIRC) were calculated and the results were plotted in Figs 3 (b) and (c). The graphs showed again that there was disagreement between the simulation and measurement for scalp.

The intention of simulation was to find similar intensities for all the tissues. This succeeded since the results in the image agreed well with simulation.

Discussion

From the results from simulations and images, the 2D FSE sequence has CSF, muscle and scalp with superior image contrast and SNR of 39 - 57 while the 3D GE sequence has CSF, muscle and scalp with broadly similar image contrast and SNR of 26 - 33. SNR in the FSE image were better than

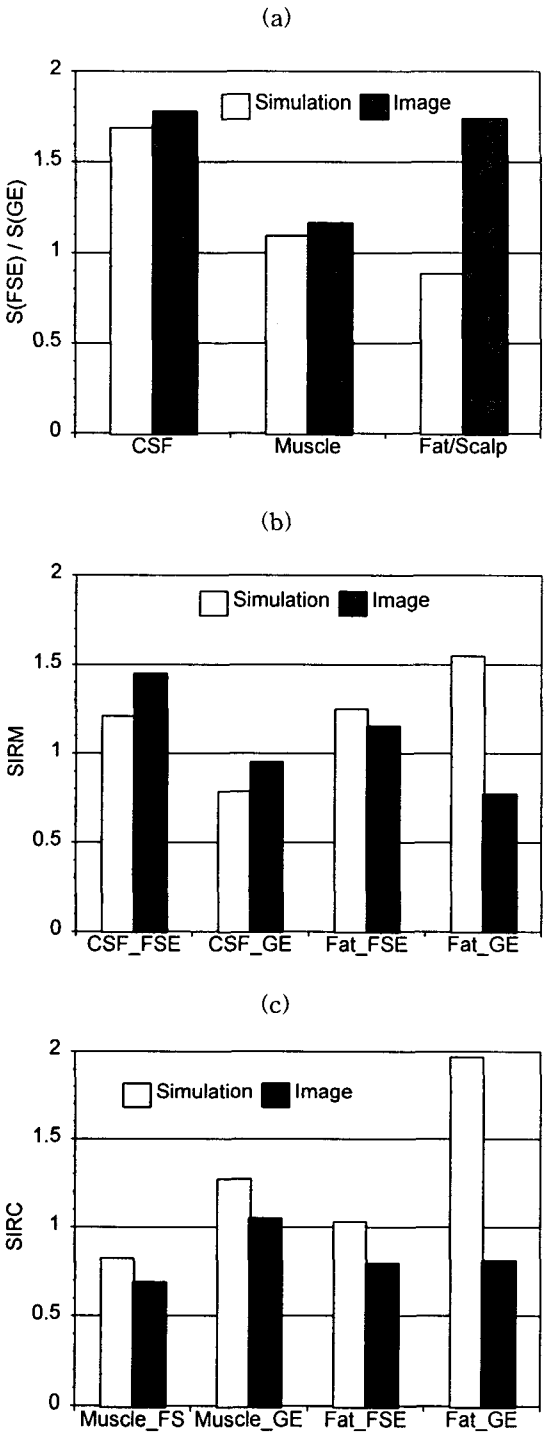

Fig 3. Comparison of signal intensities between simulation and 2D fast spin-echo and 3D gradient-echo images for CSF, muscle and scalp/fat: (a) Signal intensity ratio between FSE and GE (SIRB), (b) Signal intensity ratio relative to muscle (SIRM) and (c) Signal intensity ratio relative to CSF (SIRC).

those in the GE image and the skull edges appeared very clearly in the FSE image (see Fig 2) due to the edge enhancement effect in the FSE sequence[7,8]. Furthermore, the contrast between CSF, muscle and scalp in the 2D FSE image was significantly better than in the 3D GE image, due to the strong signal intensities (or SNR) from CSF, muscle and scalp (see Table 4) and enhanced edges of CSF. Since the scan time of the 3D GE sequence was approximately three times longer than that of the 2D FSE sequence (see Table 1), the 3D GE sequence was more susceptible to movement which causes blurring edges in the image. Although the near-isotropic nature (due to the thinner slice thickness) of the 3D data would be an advantage in terms of reducing the partial volume effect, SNR, image contrast and image quality of the 3D data were not good enough for accurate skull contour based on the analysis of the intensity measurements in the simulations and images, and visual inspection, which is a powerful tool for picking up small changes in the shape and intensity in the image. This is partly because the GE sequence in general has poorer SNR than the FSE sequence since the echo is formed by an α° pulse rather than a 180° pulse.

Conclusions

The signal intensity of various tissues near bone interface in 2D and 3D neurological MR images has been simulated and measured. Both the simulation and imaging of the 2D SE and 3D GE sequences have CSF, fat and muscle with broadly similar image intensity and SNR's and have succeeded in getting all tissues about the same signal (see Tables 3 and 4). However, in the 2D FSE sequence, image contrast between CSF, muscle and scalp was good and SNR was relatively high, imaging time was relatively short.

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2차원과 3차원 신경계 자기공명영상에서 뼈 주위에 있는 여러 조직의 신호세기 계산 및 측정

305-350 대전광역시 유성구 가정동 161
한국전자통신연구원 원천기술연구본부 뇌파정보팀

유돈식

목적: 본 논문은 2차원과 3차원 신경계 자기공명영상에서 뼈 주위에 있는 여러 조직의 신호세기를 계산하고 측정값과 비교 분석하는 데 목적을 두었다.
대상 및 방법: 신경계 양성자 강조영상은 뼈를 제외한 뇌척수액과 근육 및 지방 등 모든 조직을 보여준다. 또한 자기공명영상을 이용하면 2차원이나 3차원 영상을 얻을 수 있다. 본 연구에서는 2차원 영상기법으로 2차원 고속스핀반향(Fast spin-echo) 영상법을 사용하였고 3차원 영상기법으로는 3차원 경사자계반향(Gradient-echo) 영상법을 사용하였다. 2차원 스핀반향(Spin-echo)과 3차원 경사자계반향 영상법에 나타난 뇌척수액과 근육 및 지방의 신호세기를 알아내기 위해 2차원 스핀반향과 3차원 경사자계반향의 신호세기의 이론값을 계산하였다. 2차원 고속스핀반향 영상법에서는 양성자 강조영상을 얻기 위해 긴 반복시간(4000 ms)과 짧은 반향시간(TE_{eff} =22 ms)을 적용하였다. 3차원 경사자계반향 영상법에서는 양성자 강조영상을 얻기 위해 작은 꺽임각(8°)과 짧은 반복시간(35 ms) 및 짧은 반향시간(3 ms)을 적용하였다.
결과: 2차원 고속스핀반향 영상법에서는 뇌척수액과 근육 및 지방의 영상 대조도가 우수하였고 신호 대 잡음비(SNR)값은 39 - 57 사이였다. 3차원 경사자계반향 영상법에 나타난 뇌척수액과 근육 및 지방의 영상 대조도는 2차원 고속스핀반향 영상법의 결과와 비슷하였지만 신호 대 잡음비(SNR) 값은 26 - 33 사이였다. 신호 대 잡음비는 2차원 고속스핀반향 영상법이 3차원 경사자계반향 영상법보다 높았고 가장자리 향상효과 때문에 2차원 고속스핀반향 영상에서 머리뼈의 가장자리를 쉽게 구별할 수 있었다. 덧붙여 2차원 고속스핀반향 영상에 나타난 뇌척수액과 근육 및 지방 사이의 대조도는 강한 신호세기와 향상된 뇌척수액의 가장자리 때문에 상당히 우수하였다.
결론: 2차원과 3차원 신경계 자기공명영상에서 머리뼈 주위에 있는 여러 조직의 신호세기를 계산하고 측정값과 비교 분석하였다. 뇌척수액과 근육 및 지방의 계산값과 측정값의 영상 대조도와 신호 대 잡음비 값이 2차원 고속스핀반향 영상법과 3차원 경사자계반향 영상법에서 대체로 일치하였다. 그렇지만 2차원 고속스핀반향 영상에서 뇌척수액과 근육 및 지방 사이의 대조도가 우수하였고 신호 대 잡음비는 상대적으로 높았으며 상대적으로 짧은 영상시간이 소요되었다.

중심단어: 자기공명영상, 신호세기, 뇌척수액, 지방, 근육