Nonlinear Amplitude Compression In Magnetic Resonance Imaging: Quantization Noise Reduction and Data Memory Saving

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ABSTRACT

Dynamic range improvement in magnetic resonance imaging by nonlinear amplitude compression is proposed and the quantization noise reduction by a factor of 10 to 20 is confirmed by a numerical simulation. The implementation of the amplitude compression requires no additional hardware in a usual MRI system if the low spatial frequency lines of the MR signal are selectively prescanned through an attenuator. This method will be particularly effective in 3D imaging of large objects, MR angiography and imaging of solids.

INTRODUCTION

A typical time domain NMR signal is particularly large only near the zero spatial frequency point, thus any actual A-D converter cannot sample the higher frequency components exactly, this dynamic range problem in magnetic resonance imaging becomes very serious in high spatial resolution proton imaging of large objects. [1] This typical property of MRI signal is mainly due to the fact that density and relaxation times of protons in human soft tissue vary slowly relative to the pixel size of the MR image.

Recently several authors have reported various methods for the dynamic range improvement, such as nonlinear spatial phase modulation [2-4], estimation of low frequency components [5], and oversampling. [6] Our approach presented here is a simple and practical method for decreasing quantization error with a nonlinear amplitude compression of MRI signal

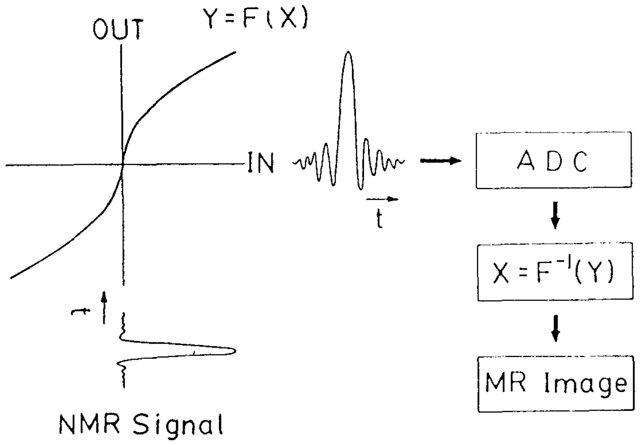

Fig. 1.

METHODS

Figure 1 shows the principle of the method presented in this paper. Amplitude of NMR signal is compressed with a nonlinear circuit and sampled with an analog to digital converter (ADC). The sampled value is then inversely transformed by computation so that the stored data should be proportional to the actual NMR signal. The resulting set of signal values is then used for the image reconstruction.

We made numerical calculations to simulate the data acquisition process in magnetic resonance imaging in the following way. Human head spin echo MR images (256 × 256 image matrix) obtained with an 1.5 T MR system were used as the numerical phantoms. Figure 2 shows one of the images used in the calculation. These images were taken with a multislice spin echo sequence in which the repetition time TR and the spin echo times TE were 2000 msec and 30 msec respectively. The pixel values ranged from 0 to 249 in the image in Figure 2.

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Fig. 2.

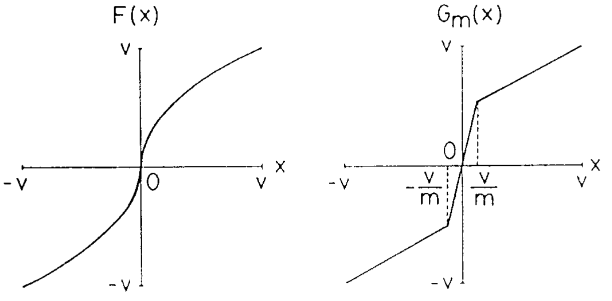


Fig. 3.

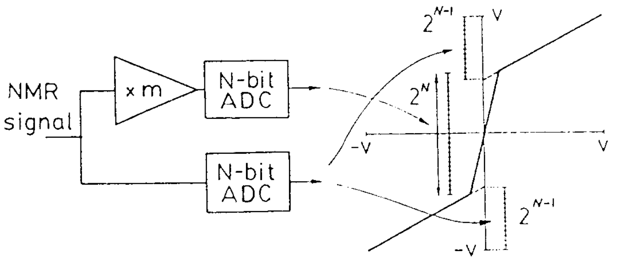


Fig. 4.

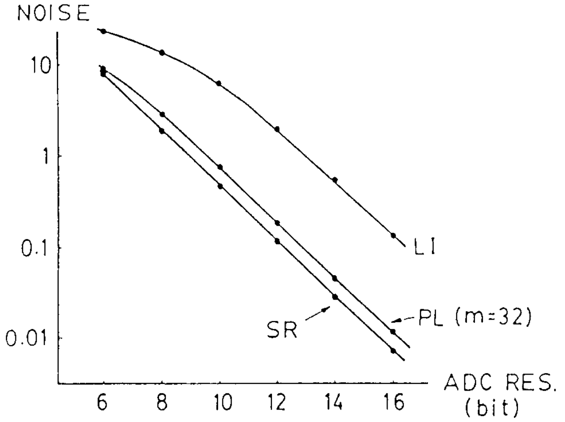


Fig. 5.

The numerical phantom data were Fourier transformed to make a set of time domain NMR signal. This signal was compressed according to a nonlinear function, normalized so that the maximum value of the signal should be the full range value $(2^{N-1}-1)$ of an N-bit A-D converter and rounded off to a set of integer data. These quantized data were expanded according to the inverse function of the nonlinear function used before and inversely Fourier transformed to obtain the MR image. Above calculations were all carried out with 64-bit floating point precision. The digitization noise was evaluated by calculating the root-mean-square amplitude of the difference between the original and the final images.

The nonlinear functions used in the calculation are shown in Figure 3. In the figure the input and output signals range from -V to V and m is the amplifier gain when the nonlinear amplitude compression is realized by a combination of linear circuit components as described later. We call F(x) the square-root transform and $G_m(X)$ the piecewise-linear transform in this paper.

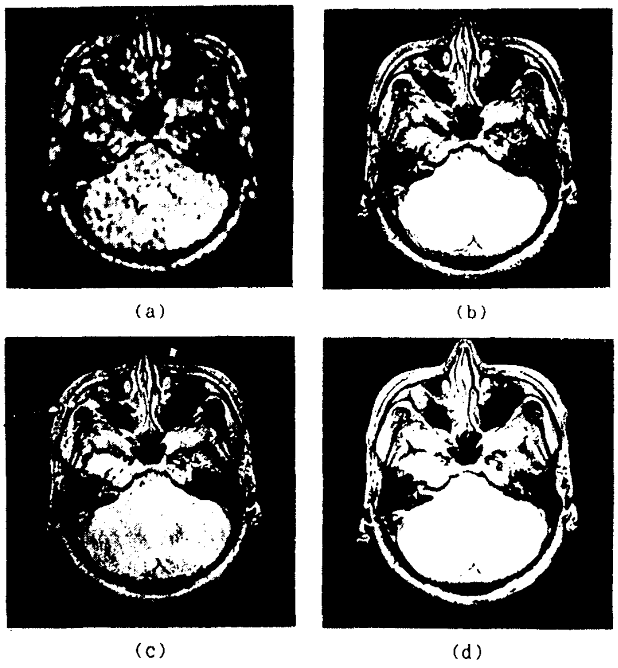
Figure 4 shows a a circuit which enables the piecewise-linear amplitude compression. In this circuits NMR signal is sampled with the ADCs both directly and through the amplifier at the same time. For spatial components with small amplitude, the output digits of the upper ADC in the figure are taken as the sampled values. On the other hand, for spatial components with large amplitude, those of the lower ADC are taken as the sampled values after the output values are multiplied by the gain m. If we plot the input-output relation so as to make the resolution constant throughout the input signal, the piecewise-linear transform is effectively realized as described in the figure. This circuit includes no nonlinear circuit unit, so that it has a high precision and stability.

The effects of thermal noise on the nonlinear transform were also evaluated as follows. Gaussian white noise simulating thermal noise whose rms amplitude was 1/8192 of the maximum amplitude of the time domain signal was added to the time domain NMR signal. This time domain signal was compressed, sampled, expanded and used for image reconstruction in the same way as mentioned before.

RESULTS AND DISCUSSION

Figure 5 shows the ADC resolution dependence of the quantization noise calculated with the image shown in Figure 2. The noise amplitude is plotted in the same scale as the pixel value of the image where that of the white matter is about 100. In Figures 7-8 the noise will be displayed in the same way. In Figure 5 LI, PL and SR are the functions used in the amplitude compression; LI, PL and SR represent the linear (no compression), the piecewise-linear ($m = 32$) and the square-root functions described in Figure 3, respectively. The quantization noise reduction by a factor of about 10 (PL) and about 20 (SR) is achieved in the nonlinear amplitude compression.

Figures 6 (a) and (b) are the reconstructed images whose spatial frequency components are sampled with an 8-bit and a 10-bit A-D converter without amplitude compression. Figures 6 (c) and (d) are those whose spatial frequency components are sampled with a 6-bit and an 8-bit A-D converter after the piecewise-linear amplitude compression ($m = 32$). The calculated quantization noise of Figure 6 (c) (nonlinear 6-bit) is


(a) (b)

(c) (d)

Fig. 6.

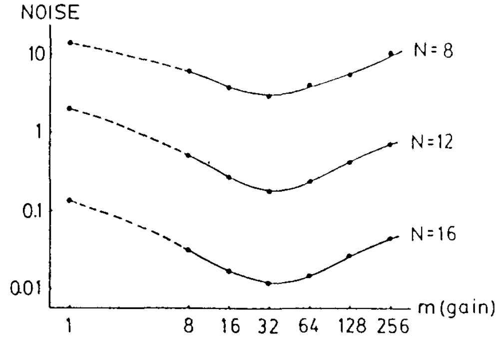


Fig. 7.

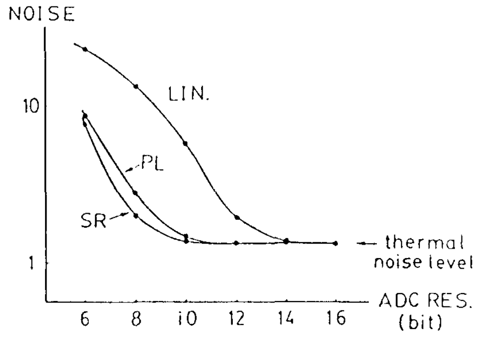


Fig. 8.

nearly equal to that of Figure 6 (b) (linear 10-bit), which is clearly seen in these images. This is because the amplitude resolution for the small signal with the piecewise-linear compression (m = 32) is about 16 times larger than that without the compression as shown in Figure 4.

Figure 7 shows the gain dependence of the quantization noise calculated with the image shown in Figure 2. In this figure, N is the number of digit of the A-D converter used in the calculation. The noise of the image makes a broad minimum around m = 32.

Figure 8 shows the ADC solution of the noise calculated with the image in Figure 2 when the Gaussian white noise is added to the time domain signal. The rms amplitude of the white noise which is 1/8192 of the peak amplitude of the time domain signal as mentioned before, is about 1.32 in the image. This figure clearly demonstrates that the noise in the MR image is limited by the thermal noise contained in the NMR signal as expected. The total noise, however, reaches to the lower limit much faster (by about 4 bits) when the signal is nonlinearly compressed. The above results show that the nonlinear amplitude compression can reduce the quantization noise drastically irrespective of the thermal noise though there is the lower limit of the noise determined by the thermal noise.

The circuit which realizes the square-root transform can be built but it is thought to be unstable in its operation because the gain becomes infinite when the input signal is zero. The piecewise-linear circuit, on the other hand, has a good stability and precision because it consists of linear components as mentioned before. This circuit has some complexity but the scanning technique described in Figure 9 enables the piecewise-linear amplitude compression without any additional hardware in most MRI systems. After only the low spatial frequency components are scanned with a low amplifier gain (unity gain), the whole spatial frequency components are scanned with a high gain (= m), which realizes the piecewise-linear transform $G_m(X)$ described in Figure 3 quite easily. Although the amplifier is set before the ADC in Figure 4, it is desirable that the amplifier or the attenuator should be connected after the preamplifier of the signal receiving system to avoid the effect of external noise and other miscellaneous noise generating in the system.

The nonlinear amplitude compression proposed in this paper will be applicable to other imaging methods such as (3D) MR angiography and imaging of solids in which a fast and high resolution ADC is not available. The combination of this method and the nonlinear phase modulation method [2-4] will be more effective in the quantization noise reduction in magnetic resonance imaging.

CONCLUSION

The numerical simulation has revealed that the nonlinear amplitude compression can reduce the quantization noise quite effectively if one chooses an appropriate nonlinear transform. The piecewise-linear transform is the best nonlinear transform as far as we have studied. The implementation of this method to a usual MRI system requires no supplementary hardware. The scanning technique in which after the low spatial frequency components have been prescanned with an attenuation, all the frequency components are measured without it, realizes the

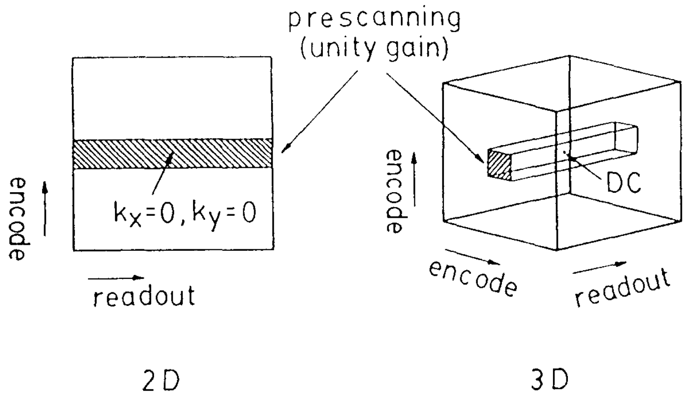


Fig. 9.

piecewise-linear amplitude compression quite easily. This technique can be applied to MR angiography, localized spectroscopy and imaging of solids as well as high spatial resolution proton imaging of large objects.

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Audience—R.T. Hill; *Radar Systems Panel Member,* **Michael Carpentier** *and his wife* **Francine**; **Mrs. Suzuki** *and* **Professor T. Suzuki**, the Conference Chairman

Later; **Professor Suzuki** *(center) chats with* **Mr. Hill** *and with Boston AESS Chapter President,* **Eli Brookner**.