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Preliminary Clinical Results with Low Flip Angle Spin-Echo MR Imaging of the Head and Neck

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A new approach for producing primarily T2- and proton-density-weighted MR images in less time than the conventional long TR, long TE imaging is to reduce the TR of a double spin-echo pulse sequence and to also reduce the RF excitation flip angle to minimize the resulting T1 sensitivity. In preliminary studies with a human volunteer and five patients with various diseases of the head and neck, conventional long TR, long TE and short TR, short TE images were compared with short TR, long TE images with reduced flip angles (45°, 30°), which required only 40% of the imaging time of the long TR images. The latter images showed a similar contrast pattern to the conventional T2-weighted image, and contrast-to-noise measurements indicated an increase in contrast between the lesion and nearby tissue when the flip angle was reduced. Furthermore, the maximum contrast/noise per unit imaging time on the short TR, long TE image was comparable to that on the long TR, long TE image.

Optimization of the flip angle with short TR allows a substantial reduction in imaging time but with a reduction in multislice capability. This technique will be most useful in areas of complex anatomy where two or more orthogonal imaging planes are required, such as the head and neck.

The head and neck region is characterized by a wealth of anatomic structures, among them many muscles. For the surgeon or the radiotherapist it is vital to know the location and extent of a lesion, and this generally requires imaging in at least two orthogonal planes. For some areas, such as the base of the skull and the nasopharynx, three orthogonal planes may be required to determine more precisely a therapeutic regimen [1]. Although MR imaging with short TR and short TE, which is strongly sensitive to differences in T1, often allows differentiation between muscle and malignant soft-tissue tumors or enlarged lymph nodes mainly on the basis of their mass effect, strongly T2-weighted images (long TE), by providing additional image contrast, can be helpful for confirming the existence of the disease and delineating its extent [2, 3]. However, for the image contrast to reflect differences in T2, the sensitivity to T1 differences must be reduced, and this is usually done by using a long TR. T2-weighted images are therefore the most time-consuming part of an MR examination. Whenever two or more sets of these images in orthogonal planes are required, an MR study becomes significantly longer. For many patients with head and neck disease a long imaging session may be intolerable, so that in practice T2-weighted images, while very desirable, may be collected for only one plane, or may not even be collected at all.

This study shows that it is possible to obtain strongly T2-weighted multislice imaging of the head and neck with a significant reduction in acquisition time by using a double spin-echo (SE) pulse sequence. In this approach the TR is reduced, and the resulting sensitivity to T1 differences is then minimized by reducing the RF pulse excitation flip angle. The use of a short TR with a long TE necessarily entails a reduction in the multislice imaging capability, so that this approach is likely to be most useful in those cases in which imaging time is limited and only a few slices are required.

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Theory

Images obtained with conventional SE pulse sequences and with moderate repetition times (TR<3000) always display a mixture of T1 and T2 effects in addition to the basic dependence on proton density. If there is no difference in T1 between two tissues, increasing TE without changing the 90° RF excitation flip angle will produce good T2-weighted contrast even with a short TR. However, when there is also a difference in T1 the normal T1 contrast due to short TR will usually conflict with the T2 contrast due to long TE. This sensitivity to T1 differences must be reduced to enhance the T2 contrast in the image, and this is usually done by using a long TR with the subsequent penalty in prolonged imaging time.

It has been shown that the T1 sensitivity of a gradient-echo (GRE) pulse sequence can be substantially reduced, even with short TR, by reducing the flip angle from the conventional 90° [4–6]. The same principle can be applied to reduce the T1 sensitivity of short TR SE pulse sequences. This principle is most easily perceived by considering a GRE pulse sequence consisting of α-degree pulses separated by a repetition time TR. The T1 sensitivity of the pulse sequence then depends on the amount of reduction, and subsequent regrowth, of the longitudinal component of the magnetization vector between RF pulses. When the flip angle is 90°, the longitudinal magnetization is reduced to zero. Tissues with a short T1 will then recover more than those with a long T1, producing the usual T1-weighted contrast. However, with a small flip angle (α<30°) the longitudinal magnetization is only slightly reduced, so that differences in the amount of regrowth for different T1s will have much less effect on the resulting signal intensity. The steady-state that is reached is thus one in which the longitudinal magnetization is nearly fully relaxed. With this reduction in T1 sensitivity, it then becomes possible to produce primarily T2- and proton-density-weighted images without the need for a long TR, and consequently in less time, by simply increasing TE.

This same argument can be applied to a double SE pulse sequence consisting of an excitation pulse followed by two 180° refocusing pulses. Ignoring longitudinal relaxation between pulses, the net effect of the two 180° pulses is to rotate the longitudinal magnetization through 360°, approximately returning it to its state just after the initial α pulse. As with the GRE pulse sequence, if α is small the T1 sensitivity will be reduced.

Mathematically, the measured signal at the second echo of a double SE experiment with perfect 180° pulses is [5]:

$$S = S_0 \sin\alpha\, e^{-2TE/T2} \quad \frac{1 - e^{-TR/T1} + 2e^{-(TR-0.5TE)/T1} - 2e^{-(TR-1.5TE)/T1}}{1 - e^{-TR/T1}\cos\alpha} \tag{1}$$

where S_0 is proportional to the local proton density. If TE $\ll$ TR, then:

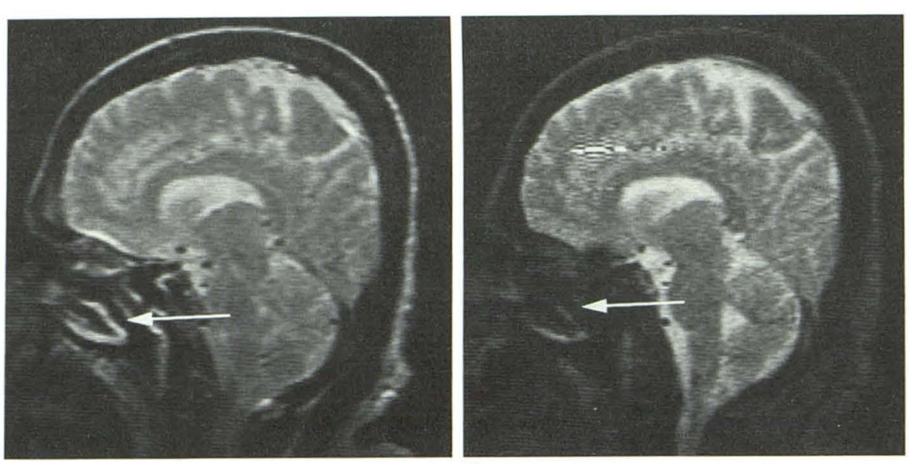
$$S = S_0 \sin\alpha\, e^{-2TE/T2}\, \frac{1 - e^{-TR/T1}}{1 - e^{-TR/T1}\cos\alpha}$$

And if $\alpha \ll 90°$, so that $\cos\alpha = 1$, then:

$$S = S_0 \sin\alpha\, e^{-2TE/T2}$$

Under these conditions the signal is only weakly dependent on T1 but strongly dependent on T2 and the proton density. In practice, the use of slice-selective 180° pulses will limit the accuracy of equation (1) [5], but the general conclusion is likely to remain valid: T2-weighted contrast can be increased by reducing the flip angle and thereby reducing the T1 sensitivity. Note that as the flip angle is reduced the signal is reduced by the factor sin α, so that there will be an optimum flip angle maximizing the T2-weighted contrast between two tissues. This optimum flip angle will reflect a balance between reducing the flip angle to minimize T1 sensitivity and increasing the flip angle to maximize the signal.

The initial results of our attempts to apply this theoretical result in the clinical setting are presented below. For this study we used reduced flip angle double SE rather than GRE pulse sequences in order to avoid signal loss due to magnetic susceptibility effects at air/bone and air/soft-tissue interfaces (e.g., nasal passages, paranasal sinuses, pharyngolaryngeal airway, temporal bone) to which GRE pulse sequences are more sensitive [4, 6, 7]. In an SE pulse sequence the 180°



A B

Fig. 1.—*A* and *B*, Fast T2-weighted MR images with low flip angle (30°). Spin-echo, 800/96 (*A*), and gradient-echo, 300/35 (*B*). Air/nasal mucosa interface (*arrows*) is clearly visible on spin-echo image, but because of magnetic-susceptibility-induced signal loss this region is not seen on gradient-echo image. Note also the little signal artifact obscuring gyrus rectus of frontal lobe, resulting from sinus air.

pulses serve to refocus field inhomogeneity effects such as these. An example of signal loss on a GRE image compared with a double SE reduced flip angle image is shown in Figure 1.

Subjects and Methods

Imaging was done with a Technicare 0.6-T clinical whole body system using a head coil. Preliminary studies were done with a human volunteer to compare conventional long TR, long TE and short TR, short TE images with short TR, long TE, reduced flip angle images. A subset of these images was then made in five patients who manifested a range of diseases.

On the volunteer, the following images were made: (1) a conventional short TR, short TE (T1-weighted) SE image, 450/22 (TR/TE), (2) a conventional long TR, long TE (T2-weighted) SE image, 2000/48,96, and (3) short TR, long TE images with the same TE but reduced TR (800) and a range of flip angles (10°, 20°, 30°, 45°, 60°, 70°, and 90°). The reduction of TR from 2000 to 800 reduced the imaging time by 60%, but only five slices could be acquired simultaneously. For the short TR, long TE images the slice separation was equal to one slice thickness (4 or 5 mm) to avoid overlap between the Gaussian-shaped slice profiles and the resulting degradation of the image. With other pulse profiles it should be possible to reduce the gap. Because Gaussian selective pulses were used, the pulse angle was not uniform across the slice. To characterize the pulse amplitude, we defined a 90° pulse as the pulse that gave the maximum signal, and the other pulse angles were obtained by modifying the transmitter attenuation accordingly. For example, the attenuation was increased by a factor of 2 (+6 dB) for a 45° flip angle.

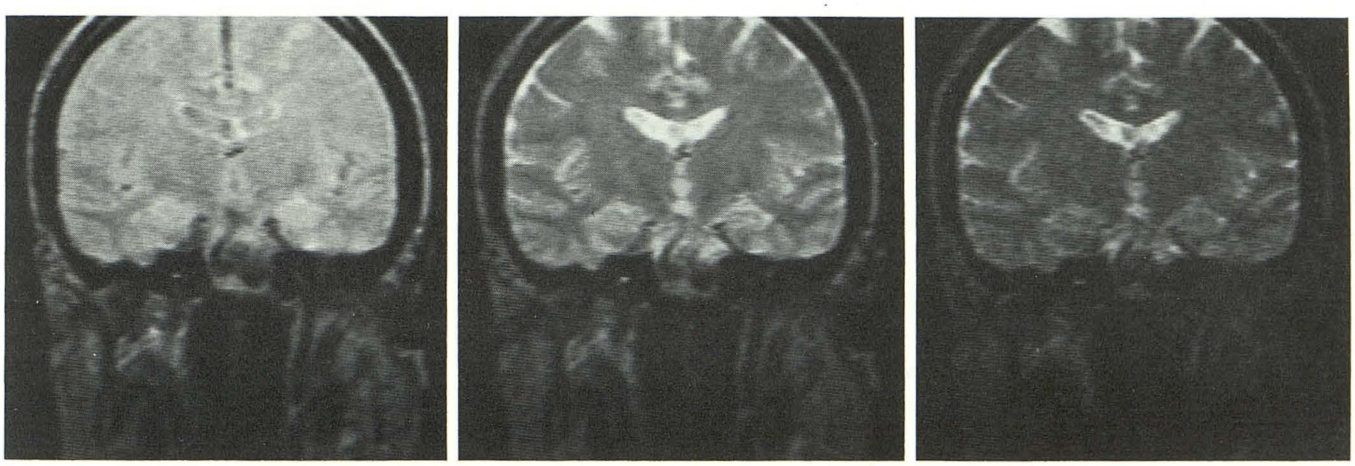
We then conducted a pilot study of the effectiveness of these short TR, long TE pulse sequences in five patients with diseases of the head and neck, including one benign and three malignant tumors and one case of infection. The fast T2-weighted images were acquired in addition to sets of conventional T1- and T2-weighted images to allow direct comparison of tissue contrast. In one study the conventional T2-weighted long TR, long TE image could not be obtained because of imaging time limitations. For the short TR, long TE images three flip angles were used on each patient: 90°, 45°, and 30°. These images were compared with the conventional images by choosing regions of interest on the diseased tissue and on an adjacent normal tissue (e.g., muscle, vitreous body, white matter) and by calculating the contrast-to-noise (C/N) ratio on all images.

In each subject the long TE images were all acquired with the same spatial resolution (matrix of 128 × 256 or 96 × 256) and the same number of excitations (two or four). The short TE images were acquired with a matrix of 128 × 256 and four excitations. On our imager the signal intensity is scaled to account for differences in matrix size and number of excitations, so that the image signal (and contrast) stays the same as these parameters are changed, but the noise level varies. For these C/N comparisons, we therefore took the measured contrast on each image and divided it by the mean background noise measured on the long TE images. The C/N ratios given below are thus for equal resolution and number of excitations. We also calculated the C/N per unit imaging time by scaling the measured C/N values by the square root of the ratio of the imaging times, normalized to the imaging time of the long TR (2000) image.

Results

Three of the images of the volunteer are shown in Figure 2. The C/N measurements of two tissue pairs are plotted as a function of the flip angle in Figure 3, demonstrating improved contrast with reduced flip angles: 20–30° for CSF-white matter and 30–70° for gray matter-white matter.

The results of the C/N measurements on the five patients are listed in Table 1. In each case the C/N on the short TR, long TE images improved when the angle was reduced to less than 90°. The images shown in Figure 4 illustrate the effect of reducing the flip angle on patient 5. In all patients the pathology was demonstrated on the conventional and fast T2-weighted images with a similar contrast pattern. The first-echo images had only slight T1 and T2 sensitivity and showed less contrast but provided some anatomic information.



A B C

Fig. 2.—*A–C*, Coronal T2-weighted MR images obtained in a human volunteer with fast spin-echo pulse sequences (800/96). The excitation flip angles are 90° (*A*), 30° (*B*), and 10° (*C*). The optimum CSF-white matter contrast is obtained with a flip angle of 30°, as shown by the plot in Fig. 3. CSF regions of interest were not taken from the lateral ventricles, where there is significant CSF motion artifact, but from other areas of relatively static CSF (interhemispheric fissure, third ventricle, or interpeduncular fossa).

Discussion

The idea of reducing the flip angle in order to reduce T1 sensitivity and to improve contrast in T2-weighted type (T2*) images have been successfully applied to GRE pulse sequences [4–9]. However, magnetic susceptibility effects, particularly at higher fields, have limited the use of GRE imaging in areas such as the head and neck. Because there are no 180° refocusing pulses, any field variations within a voxel will lead to signal loss on the image. Recently, the application of altered flip angles to SE imaging has been discussed [10–13]. In this study we tested the ability of short TR, long TE small flip angle images to provide diagnostically useful T2-weighted images in less time than conventional long TR T2-weighted images.

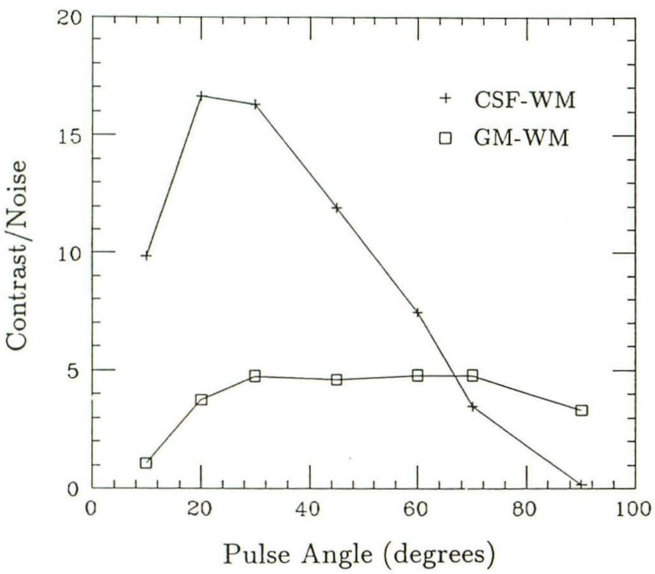


Fig. 3.—Measured contrast-to-noise ratios of two tissue pairs (CSF-white matter [CSF-WM]; gray matter-white matter [GM-WM]) as a function of flip angle for a double spin-echo pulse sequence (800/96) from images obtained in a human volunteer. Image contrast is best with intermediate flip angles; with large flip angles (90°) the T1-sensitivity conflicts with the T2-sensitivity, and with very small flip angles (10°) the overall signal/noise is substantially reduced.

Our results show that T2-weighted contrast with moderately short TR improves when the flip angle is reduced from 90°. In lesions with low contrast on the short TR, short TE image (patients 2 and 4 in Table 1), the contrast on the short TR, long TE images was improved by only 11–13% by reducing the flip angle. In those lesions with significant T1 contrast (patients 1, 3, and 5), however, the improvement in contrast on the short TR, long TE images ranged from 22% to nearly a factor of 3 with reduced flip angles. Furthermore, the flip angle that gave the best contrast was related to the amount of conflicting T1 contrast: the greater the T1-contrast the smaller the flip angle necessary to maximize the T2 contrast. For the lesions with low contrast on the T1-weighted images, a 45° flip angle was clearly better than a 30° flip angle. For those lesions with substantial T1 contrast, however, the contrast with 45° and 30° flip angles was similar, and for the lesions with the highest T1 contrast (patient 5, Fig. 4), the 30° flip angle produced better contrast.

In all the lesions studied, the measured C/N on the short TR, long TE images was less than that on the conventional long TR, long TE images. However, when the highest contrast, short TR values are normalized for equal imaging time (rather than equal number of excitations), the C/N per unit imaging time is comparable to, and in some cases (patients 1 and 4) better than, the conventional T2-weighted images. This suggests that TR is much less important for determining contrast when the flip angle is optimized than when it is fixed at 90°. The choice of TR for a particular application can thus be made on the basis of other considerations, such as available imaging time or the required number of slices. A similar result was found in analyzing the C/N per unit imaging time in GRE imaging [4].

The advantage of this faster T2-weighted SE technique over conventional SE sequences is the significant reduction in imaging time. A TR of 800 instead of 2000 reduces the acquisition time by 60% for images with the same resolution.

TABLE 1: Contrast/Noise Measurements

Patient No.	Disease	Compared Tissue	Contrast/Noise: SE (450/22) $\alpha = 90°$	Double SE[a] (2000/48, 96) $\alpha = 90°$	$\alpha = 90°$	Double SE[a] (800/48, 96) $\alpha = 45°$	$\alpha = 30°$
1	Lipoma	Vitreous body	+5.0[b] (+10.5)[c]	−10.0	−5.5 (−8.7)	−6.7 (−10.6)	−6.2 (−9.8)
2	Parotid tumor	Muscle	+0.3 (+0.6)	+11.9	+6.3 (+10.0)	+7.0 (+11.1)	+4.9 (+7.7)
3	Orbital metastasis (renal cell carcinoma)	White matter	−4.0 (−8.4)	+6.9	+2.5 (+4.0)	+4.0 (+6.3)	+3.6 (+5.7)
4	Carcinoma of base of tongue	Normal tongue	+0.2 (+0.4)	+7.3	+4.8 (+7.6)	+5.4 (+8.5)	+3.5 (+5.5)
5	Necrotizing external otitis	White matter	−5.3 (−11.2)	Not done	+2.3 (+3.6)	+5.6 (+8.9)	+6.7 (+10.6)

[a] Contrast/noise values are for the second echo.
[b] The first contrast/noise value listed is for equal excitations.
[c] The contrast/noise values in parentheses are for equal total imaging time, normalized to the time required for the TR = 2000 image.

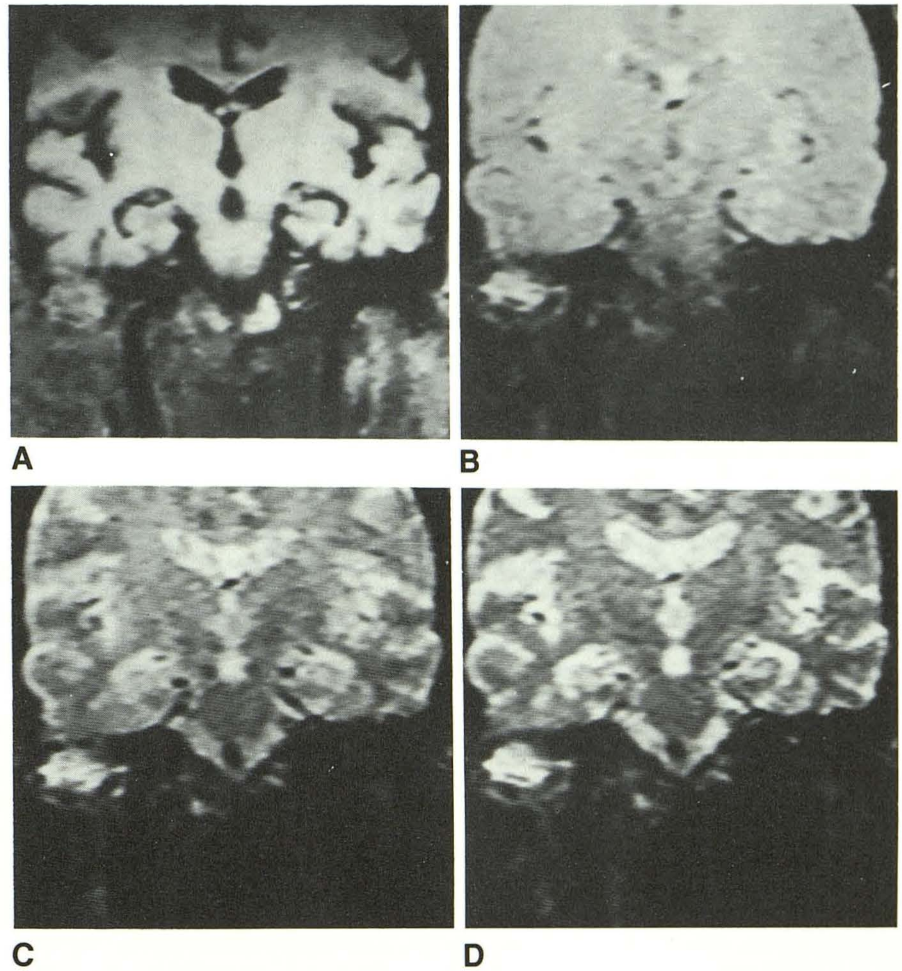


Fig. 4.—*A–D*, Coronal MR images obtained in a patient who has right necrotizing external otitis with subsequent disease in the mastoid air cells. Conventional T1-weighted spin-echo image, 450/22 (*A*). Fast T2-weighted second-echo images in the same patient acquired with different pulse angles: 90° (*B*), 45° (*C*), 30° (*D*). The best contrast was obtained with a 30° pulse angle. (See also Table 1 for contrast/noise figures.)

This in turn makes possible the acquisition of fast T2-weighted images in two orthogonal planes in about the same time required for one set of conventional T2-weighted images. Alternatively, images with higher spatial resolution could be obtained in the same amount of time. The imaging time could be further reduced by combining this approach with methods for shortening the data collection time, such as hybrid imaging [14] or half-Fourier imaging [15].

A drawback to this technique is that fewer slices can be acquired simultaneously than with a conventional long TR SE pulse sequence. However, a few slices judiciously chosen in relation to the disease often provide the necessary information. On our imager we could acquire five slices with TR = 800 and TE = 96. In patients with extensive nasopharyngeal carcinoma, for example, the most anterior extent of the tumor inside the nose can be better demonstrated on short TR, long TE images than on short TR, short TE images [16]. Another potential drawback of using reduced flip angles is the alteration of the slice profile [5, 17]. Further work is needed to analyze the conflicting demands of reduced imaging time, improved contrast, multislice capability, and a uniform slice profile to determine an optimum balance of TR and α for particular applications.

In conclusion, the T2-weighted contrast on a double SE image with short TR can be substantially improved by reducing the flip angle and thus reducing the sensitivity to T1 differences. Primarily T2- and proton-density-weighted images can be produced in 40% or less of the time required for conventional long TR T2-weighted images, but with a reduction in C/N and multislice capability. Therefore, as yet, this approach will not replace—at least in the present state of the art—conventional long TR, long TE studies in all applications. However, when imaging time is limited yet several orthogonal imaging planes and only a few slices are required, these short TR, long TE images can provide information that would otherwise not be available. Moreover, our initial work demonstrates the potential of this imaging strategy for anatomic regions, like the head and neck, where multiple orientation T2-weighted images of high quality are desired in a time-efficient manner.

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