Motion Artifact Suppression Technique (MAST) for Cranial MR Imaging: Superiority over Cardiac Gating for Reducing Phase-Shift Artifacts

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A motion artifact suppression technique (MAST) has recently been developed that significantly reduces motion artifacts in conventional 2DFT imaging. The technique utilizes modifications of slice-select and read gradient waveforms to eliminate velocity, acceleration, and pulsatility phase shifts that occur between the 90° pulse and data collection. T2-weighted cranial MAST images were rated visually superior to cardiac-gated images by two experienced neuroradiologists in 13 of 15 cases and in 14 of 15 cases, respectively ($p < 0.001$). Quantitative signal-to-noise comparisons for six brain regions in each patient confirmed the visually apparent superiority of MAST, especially for imaging the brainstem and subarachnoid cisterns ($p = 0.02$).

Improvements in signal-to-noise ratios of up to 43% were obtained when using MAST instead of cardiac gating. MAST or a similar technique has the potential to render cardiac gating obsolete as a method for reducing flow-related artifacts in cranial MR imaging.

Recent literature has given considerable attention to flow-related artifacts in cranial and spinal MR imaging [1–3]. Pulsatile motion of CSF and blood creates phase-shift artifacts with conventional 2DFT reconstruction techniques. These artifacts may obscure lesions or mimic pathology. Critical anatomic interfaces (such as brain-CSF) may lose edge definition. Other nonpulsatile motions (ocular, swallowing) may also create phase-shift artifacts that impede accurate diagnosis of intracranial disease.

Cardiac gating to the EKG or peripheral pulse has been shown to be effective in reducing flow-related artifacts and in improving the image quality of cranial MR [1]. However, cardiac gating has several disadvantages, including increased set-up time, limited choice of TR, and inability to reduce motion artifacts not in synchrony with the pulse.

Pattany et al. [4] have recently described an innovative motion artifact suppression technique (MAST) that appears quite effective in cranial MR. Several MR manufacturers are now offering similar (but not identical) software for motion suppression. This study was undertaken to determine whether MAST could replace cardiac gating as a method for reducing motion artifacts in cranial MR.

Materials and Methods

All scans were acquired on Picker Vista superconducting MR scanners operating at 0.5 or 1.5 T. Subjects were 15 patients and normal volunteers ranging in age from 29–64 years. Ten patients were studied at 0.5 T and five at 1.5 T. All scans were obtained using multisection techniques and the following parameters: TR = 1700–2200, TE = 80 or 100, field of view (FOV) = 23–30 cm, number of excitations = two, image acquisition matrix = 192 × 512 (for studies at 1.5 T) or 256 × 512 (for studies at 0.5 T), and slice thickness = 10 mm. Cardiac gating was performed by using an EKG trigger, with gating alternating every third beat so as to produce a TR in the specified range (1700–2200). No subjects had arrhythmias that might interfere with cardiac gating. A second scan was then obtained using MAST and setting TR to within 100 msec of the effective TR from the gated study.

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Two neuroradiologists who were blind to the study parameters analyzed the images for general image quality, visually apparent motion artifacts, and signal-to-noise ratio in selected brain regions. Comparison between gated and MAST studies in each patient was then possible at the same levels using nearly identical scan parameters. Signal-to-noise measurements were made using commercially available software for five selected brain regions (Table 1). Circular regions of interest (area = 1.0 cm^2) were placed over identical brain locations for gated and MAST images. Mean signal intensity in the brain region was then divided by standard deviation of the noise at a specified region in free space along the same coordinates in the phase-encoding direction. This method provided highly consistent and reproducible measurements of brain signal and noise in both gated and MAST images.

Results

The first observer rated the MAST images superior to cardiac-gated ones in 13 of 15 cases and equal in two of 15 cases; the second observer rated MAST images superior in 14 of 15 cases and equal in one of 15. In no instance was a set of MAST images judged inferior to the cardiac-gated set. Representative comparison images at four levels are shown in Figures 1–4.

Above the level of the lateral ventricles (where CSF and vascular motions are minimal) MAST offered no advantage over gated or nongated studies. At the level of the third ventricle CSF-brain interfaces seemed more sharply defined and the signals from the basal ganglia and caudate nuclei were more homogeneous on MAST images compared with cardiac-gated ones (Fig. 1).

TABLE 1: Improvement in Signal-to-Noise Ratio by MAST over Cardiac Gating in Selected Brain Regions

Region	Improvement in SNR (%)	p Value[a]
Centrum semiovale	3	NS
Temporal lobe	18	NS
Thalamus	28	0.02
Cerebral peduncle	33	0.07
Pons	40	0.04
Medulla	43	0.02

Note.—NS = not significant; i.e., $p > 0.10$.
[a] Calculated by paired two-sided t test, 14 df.

Slightly inferiorly, MAST images reliably demonstrated branches of the middle cerebral artery more clearly than did cardiac-gated images (Fig. 2). At the lower midbrain level, MAST images demonstrated improved visualization of structures in the perimesencephalic cisterns (Fig. 3). Artifacts in the medial temporal lobes were reduced as well. The pons and medullary regions also were better visualized on MAST images than on cardiac-gated ones (Fig. 4).

These visually apparent findings were confirmed by comparing signal-to-noise measurements for six selected brain regions (Table 1). While improvement in signal-to-noise ratio was not significant for the centrum semiovale or temporal lobe white matter, remarkable improvement by MAST was observed at other levels. In four critical brainstem regions, MAST produced a 28–43% improvement in signal-to-noise compared with the cardiac-gated studies.

In general, motion artifacts seemed a little more prominent in studies at 1.5 T than at 0.5 T, although this factor was not systematically studied. MAST seemed to do quite well at both field strengths, and its advantage over cardiac gating was consistently demonstrated. No appreciable differences between the studies performed with a 192 × 512 matrix and a 256 × 512 matrix could be detected, since equivalently smaller FOVs were used with the smaller matrix size.

Discussion

Rubin, Enzmann, and their colleagues [1, 2, 5] have recently directed considerable attention to flow-related motion artifacts in cranial and spinal MR. Such artifacts apparently account for a significant portion of the noise in cranial MR and can be partially suppressed by cardiac gating. Despite the tremendous enthusiasm of its proponents, cardiac gating has several significant limitations and disadvantages for reducing flow-related artifacts which should be recognized.

First, cardiac gating requires a small but definite set-up time as electrodes or peripheral pulse monitors are attached to the patient. Such probes will occasionally become detached from the patient during scanning, resulting in nongated or improperly gated studies. EKG-gated techniques are also frustrated by cardiac arrhythmias. Gating to the peripheral pulse may act as an "arrhythmia filter" and overcome this

A B

Fig. 1.—*A* and *B*, Cardiac-gated (*A*) and MAST (*B*) transverse images at level of third ventricle acquired at 1.5 T. Ventricular margins are more sharply defined in the MAST image. Signals from caudate nuclei and basal ganglia seem more homogeneous in *B*.

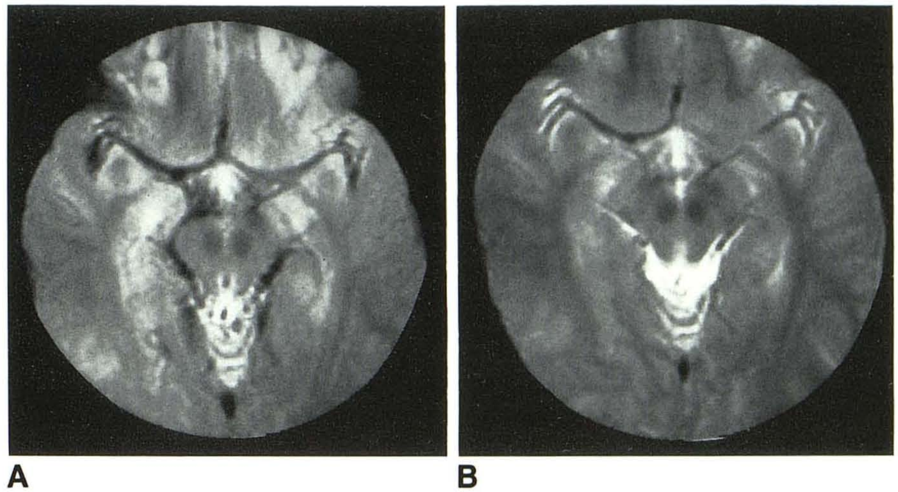

Fig. 2.—*A* and *B*, Cardiac-gated (*A*) and MAST (*B*) transverse images at midbrain level acquired at 1.5 T. Note better visualization of middle cerebral arteries and mamillary bodies in the MAST image.

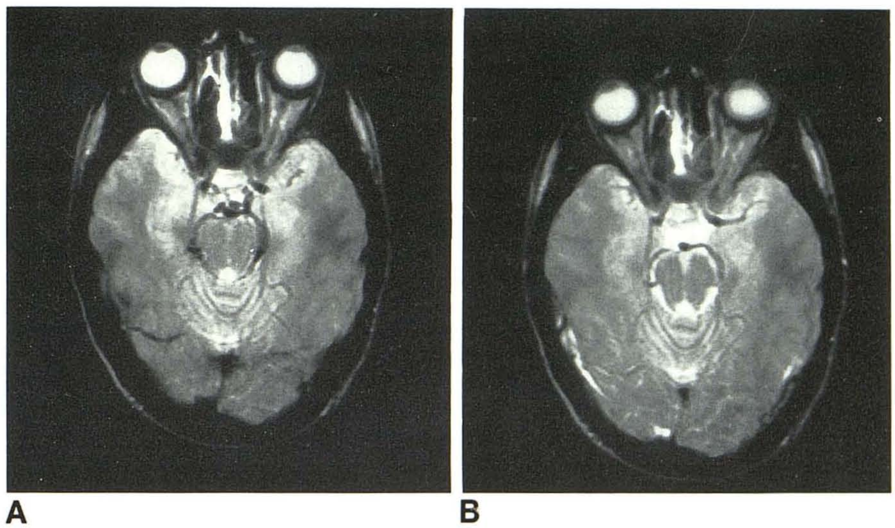

Fig. 3.—*A* and *B*, Cardiac-gated (*A*) and MAST (*B*) images in another patient acquired at 0.5 T. CSF signal is more uniform on the MAST image and the vessels more sharply defined. Medial temporal lobe artifactual high signal seen on cardiac-gated image is reduced by MAST.

problem; however, peripheral pulse gating requires specialized hardware and is not available to many users at present.

EKG or peripheral pulse gating also severely limits radiologists in their choice of TR. For T2-weighted images, TR must be chosen as a multiple of the cardiac cycle. For example, with a heart rate of 60, TR may only be specified to the nearest 1000 msec (i.e., 1000, 2000, 3000, etc.). This stringent constraint upon the choice of TR may affect one's ability to obtain optimum contrast between normal and pathologic tissues. Furthermore, if the patient's heart rate changes during the study, tissue contrast may vary unpredictably.

The most significant limitation of cardiac gating, however, lies in its inability to reduce motion artifacts out of synchrony with the pulse. Cardiac gating does appear relatively effective in reducing phase-shift artifacts from pulsating blood or CSF, but CSF motion varies with both the pulse and respiration [6, 7]. Furthermore, local hydraulic baffling effects around nerve roots and arachnoid septations create turbulence and phase-shift modulations of a complex nature not in synchrony with the pulse [2]. Random ocular and deglutitional movements that lie outside the realm of correction by cardiac gating can also create artifacts in cranial MR.

The use of rephasing gradients to reduce motion artifacts in MR was first proposed by Pattany and his colleagues in 1986 [8]. This technique was successfully modified and implemented as a patented software option available to Picker research sites (MAST®). The MAST technique has been used with great success at our institution for over 2 years in at least 3000 cranial and spinal MR examinations. For us, it has completely supplanted cardiac gating as a method for reducing motion artifacts in cranial MR imaging.

The mathematical formulation and preliminary clinical applications for MAST have recently been presented [4]. In conventional 2DFT MR imaging, physiologic motion occurring between the 90° and 180° pulses creates an unwanted phase-shift dispersion in the MR signal. By appropriately modifying read and slice-select gradient waveforms during the evolutionary phase of the MR signal, significant reduction in motion artifacts may be obtained (Fig. 5).

The general formulation for MAST involves a set of simultaneous equations that accounts for refocusing of moving material with constant velocity, acceleration, and pulsatility (jerk) [4]. Solution of these simultaneous equations determines the parameters of the gradient profile needed to eliminate unwanted phase-shift effects. MAST thus has the advantage of reducing all within-view phase dispersion artifacts, including, but not limited to, those in synchrony with the pulse. MAST modifications to eliminate higher-order deriva-

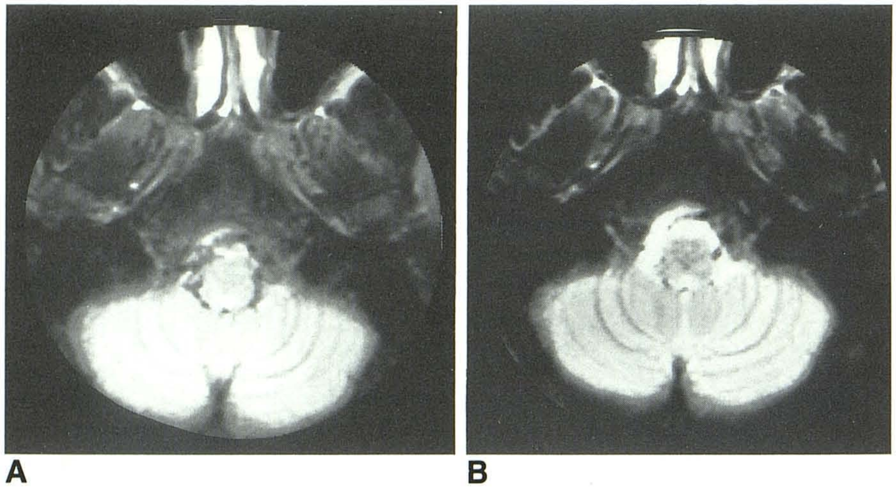

Fig. 4.—*A* and *B*, Cardiac-gated (*A*) and MAST (*B*) images at level of medulla acquired at 0.5 T. Interfaces of CSF with adjacent structures are much clearer on MAST images. Compared with cardiac gating, MAST improved signal-to-noise ratio by 43% in the medulla.

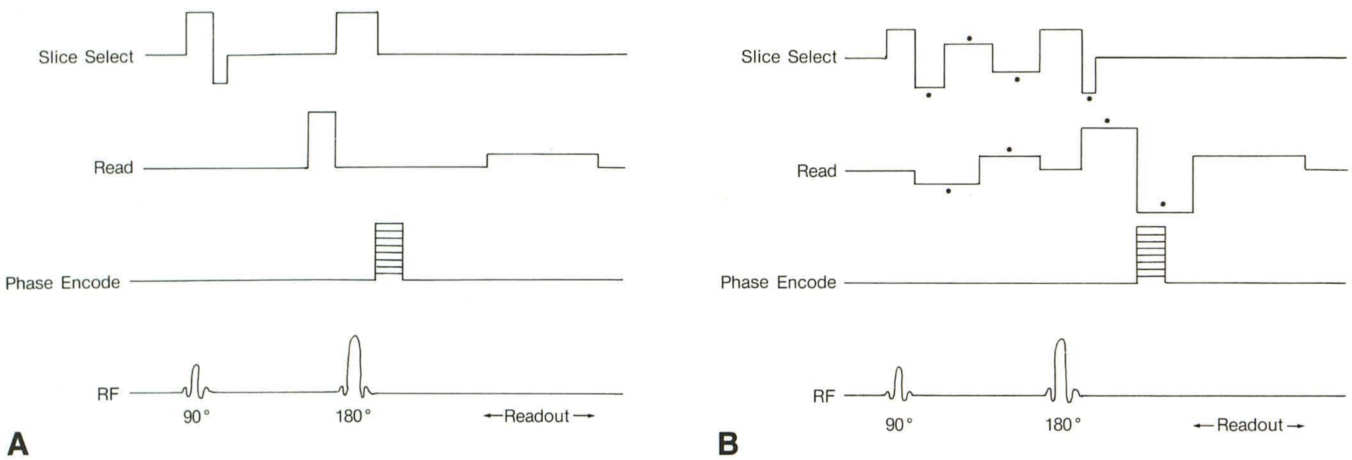

Fig. 5.—*A*, Gradient waveforms used in a conventional spin-echo pulse sequence.
***B*, Modifications of slice-select and readout gradient waveforms used in MAST. This sequence, with four extra lobes (*asterisks*) on each gradient, corrects for three orders of within-view motion (velocity, acceleration, and pulsatility). In general, *n* + 1 additional lobes are needed to correct for *n* orders (time derivatives) of motion.**

tives of acceleration are also available and are now being tested. MAST sequences using asymmetric multiple echoes, gradient echoes, and spin echoes with TE as short as 26 msec have also been developed and are used by us on a daily basis.

The only significant disadvantage of MAST seems to be the added stress it places on gradient power supplies. The rapid switching of read and slice-select gradients may cause peak current surges that exceed the amplifier's specifications. For routine cranial imaging (with FOV > 20 cm) the use of MAST requires about a 10–15% reduction in the total number of allowed slices during multislice acquisition in order to accommodate gradient power limitations. With very small FOVs (10–15 cm) the penalty is considerably greater, requiring a 25–40% reduction in total number of allowed slices. Software modifications of MAST sequences are currently being developed to overcome these modest limitations.

In summary, MAST has been shown to be visually and quantitatively superior to cardiac gating in reducing motion artifacts in cranial MR imaging. The advantage of MAST seems to be that it reduces all within-view phase dispersion artifacts, not merely those in synchrony with the cardiac cycle. The dramatic improvement in image quality with MAST and similar gradient modification techniques is becoming more widely enjoyed, and several MR manufacturers are now offering similar software. In the near future, techniques such as MAST may render cardiac gating an obsolete method for reducing flow-related artifacts in cranial MR.

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