Quantification of fMRI Artifact Reduction by a Novel Plaster Cast Head Holder

V. Edward¹, C. Windischberger^{2,3}, R. Cunnington¹, M. Erdler¹,
R. Lanzenberger¹, D. Mayer¹, W. Endl¹, R. Beisteiner^{1*}

¹Department of Neurology, General Hospital of Vienna, Vienna, Austria

²AGNMR, Institute for Medical Physics, Vienna, Austria

³NMR Group, University of Vienna, Vienna, Austria

Abstract: In light of artifact-induced high variability of activation in fMRI repeat studies, we developed and tested a clinically useful plaster cast head holder (PCH) with improved immobilization, repositioning, and comfort. With PCH, there were considerably lower levels of translational and rotational head motion components compared to head fixation with conventional restraining straps (CRS). Rotational components cannot be fully compensated by realignment and lead to “false activations.” In addition, task-correlated head motion, which highly increases the risk of artifacts, was considerably reduced with PCH, especially in a motion prone subject. Compared with PCH, head motion was 133% larger with CRS in a highly cooperative subject. With a motion prone subject, head motion range was increased by 769% (PCH: 0.9 mm, CRS: 7.8 mm), which may indicate the usefulness of PCH for restless patients. In functional activation maps, PCH alone yielded fewer residual motion artifacts than CRS + image registration. Subject tolerance of the head holder during the long measurement times of up to 2.5 hr was good, and slice orientation on different days confirmed the quality of repositioning. *Hum. Brain Mapping* 11:207–213, 2000.

© 2000 Wiley-Liss, Inc.

Key words: fMRI; fMRI time series; BOLD effect; plaster cast; motion artifacts; EPI; head fixation; automated image registration

INTRODUCTION

A main source of the high variability of BOLD-based activations in replication studies [Tegeler et al., 1999; Moser et al., 1996; Wexler et al., 1996, 1997; Rombouts et al., 1998; Crivello et al., 1998] are head motion artifacts [Hajnal et al., 1994, 1995] that can be

countered by movement correction algorithms [Woods et al., 1998; Friston et al., 1996; Jiang et al., 1995] and head fixation strategies. The former can introduce additional artifacts [Robson et al., 1997; Kwan et al., 1997; Ashburner et al., 1997; Grootenboer et al., 1997; Bullmore et al., 1997; Frouin et al., 1997] and interpolation errors. With rotational motion, there are changes in signal amplitude due to susceptibility effects that cannot be compensated by realignment and lead to “false activations” increasing in area with rotation [Wu et al., 1997].

Table I lists some of the current head fixation strategies with their advantages and disadvantages. Head motion restriction depends on the degree of coupling between head and fixation device, which in turn de-

Contract grant sponsor: Austrian Science Foundation (FWF); Contract grant number: P12451 MED.

*Correspondence to: R. Beisteiner, MD, MA, Department of Clinical Neurology, General Hospital and University of Vienna, Waehringer Guertel 18-20, A-1090 Wien, Austria.

E-mail: roland.beisteiner@akh-wien.ac.at

Received for publication 12 April 2000; accepted 11 July 2000

TABLE I. Current fixation strategies

Fixation strategy	Advantages	Disadvantages
Conventional restraining straps	Easy to apply	Low immobilization, no repositioning.
Bite bars [Bettinardi et al., 1991; Greitz et al., 1980; Tootell et al., 1995; Singh et al., 1997].	Direct coupling through the upper teeth to the cranium.	Subjects must bite the bar. Leads to fatigue, less stabilization and limited measurement times. Unacceptable to some subjects. Can provoke additional swallowing movements. Impaired communication, potential interference with breathing.
Vacuum cushions and Bean bags	Easy to apply.	Limited head motion restriction and repositioning capability.
Orthotic (poly urethane) foam padding in sealed sack [Kearfott et al., 1984].	Easy to apply.	Limited head motion restriction and repositioning capability.
Bony fixation [Debus et al., 1996].	Guarantees immobilization and repositioning.	Invasive, low patient tolerance, and repeatability.
Thermoplastic face masks [Fox et al., 1985; Kaiser et al., 1994].	Quick application (2 min), provides some degree of immobilization and repositioning.	Restricted areas of contact between thermoplastic material and head/neck, limited surface adaptation.
Fixation devices made of lucite and cushioned plastic pads [Mazziotta et al., 1982].		Small contact surface area, uneven pressure distribution.
Light cast fibre glass casting tape (orthoplast) [Bergström et al., 1976, 1981; Greitz et al., 1980].	Improved shape adaptation. Provides some degree of immobilization and repositioning.	Calvarium not covered, suboptimal malleability of material when uncured, suboptimal rigidity when fully cured, shrinkage after curing may lead to areas of increased pressure and vertex oedemas.

depends on shape and rigidity of the fixation material in its fully hardened state. In general terms, coupling is maximized by maximizing the contact surface area of the device and minimizing the residual space between device and bony skull. Due to overlaying nonrigid elastic layers of the bony skull (subcutis, dermis, epidermis, and hair), residual space can only be minimized by also increasing the pressure between bony skull and surface of the rigid device (e.g., bite bars that have to be actively bitten [Tootell et al., 1995; Singh et al., 1997]). This optimal shape adaptation is dependent on the malleability of the fixation material in its unhardened state and the force acting on fixation material and bony skull during the application and solidification time. Optimal shape adaptation ensures homogenous pressure distribution, which is crucial for good subject tolerance. Increased contact surface area also increases the degree of shape asymmetry of

the device and leads to improved rotational restriction. Further, it is highly desirable that the device be designed such that the subject can quickly free himself from the scanner in case of an emergency (nausea, aspiration, seizure, etc.).

In this article, we present and test a new plaster cast head holder with improved immobilization, repositioning, and comfort which may facilitate superior data quality and reliability for clinical applications.

MATERIALS AND METHODS

Subjects

Informed consent statements were obtained from the two male right-handed subjects aged 32 and 39 investigated.

MRI

A 3T whole-body imaging system (Bruker Medspec 3080) was used for obtaining anatomical images (FLASH) and performing fMRI (GE EPI; TE = 84.1ms, TR = 4s, voxel size $1.95 \times 1.95 \times 3$ mm). With the aid of localizer images, 13 transversal slices were positioned over the primary hand area for fMRI.

Paradigm

Subject 1, keeping the head as still as possible, performed two trials with the plaster cast head holder (condition PCH) and two trials with conventional restraining straps (condition CRS). The four trials consisted of 20s blocks of rest and right-hand finger tapping in the following order: rest, 5th, rest, 2nd, rest, 5th, rest, 2nd, rest, 5th, rest, 2nd, rest. To test repositioning, further EPI scans were obtained with PCH on 3 separate days. Subject 2 performed four trials with PCH and two trials with CRS. During the first two PCH trials, he was instructed to keep the head as still as possible (condition PCH), and during the remaining trials to imitate a highly restless subject with forceful head motion (FHM) during the measurement (conditions PCH+FHM and CRS+FHM).

Plaster cast helmet preparation

A thin plastic sack is placed over the head for protection. Then a latex cap is pulled over sack and head covering the nose. Cotton padding is inserted between latex cap and plastic sack over the auricular regions to create space in the PCH for the ears. A plastic tubing (1 cm $\times$ 40 cm) stuck on a copper strip (2.5 cm $\times$ 50 cm $\times$ 0.01 cm) is placed along a coronal plane through the preauricular points on top of the latex cap. Folded strips of wet plaster cast (Plastrona, Paul Hartmann AG) are molded immediately in front of and behind the rubber tubing. Sheets of wet cast are flatly positioned in the frontal and occipito-parietal regions. Then, wet plaster cast bandages are wound and molded around forehead, ears, calvarium (top of cranium), and occiput on top of the latex cap and tubing, going as caudal to the occipital protuberance and covering as much of the forehead, eyes, calvarium, and side of the face as possible. Care must be taken to keep the bandages circularly taught. Bandaging must be completed in 3 min in order to enable subsequent slitting of the semisolid cast along the protrusion caused by the rubber tube with a sharp knife (the scalp under-

Figure 1.

(a) Side view of plaster cast head holder; (b) Quarter view of plaster cast head holder; (c) Subject wearing plaster-cast head holder latched into the MR head rest.

neath is protected by the copper strip). With the slit helmet still on the subject, it is then molded with wet plaster cast bandages onto the head plate at a comfortable angle. A plastic cylinder (4 mm $\times$ 20 mm) is molded jutting out 2 mm out of the rear of the helmet and latches into a corresponding hole on the MR head-plate. The helmet is removed from the subject, and plastic screw fittings are molded with plaster cast onto the vertex and preauricular sites to enable attachment of the two parts to each other. The helmet borders are strengthened with additional layers of plaster cast bandages to guarantee stiffness, rigidity, and stability. Optionally, the eye areas of the helmet can be cut out for using video goggles, and Earlink Foam Eartips (Aero Company, Auditory Systems) can be used for acoustic stimulation. The final result of the described procedure is illustrated in Figure 1. Table II lists the different time intervals involved, which include 1hr 35min of preparatory time and 10 hr of drying time.

TABLE II. Time intervals associated with PCH preparation

Helmet preparation time	Preparation time without subject		15 min
	Time during which the subject is needed (24 min)	Preparatory time	5 min
		Bandaging	3 min
		Slitting	1 min
		Molding onto MR Headplate	15 min
	Postprocessing (35 min + 10 hr drying time)	Molding screw fittings onto helmet	30 min
		Optional eyehole cutting	5 min
		Drying time	10 hrs
fMRI	Application		5 min
	Removal		2 min

Data analysis

Fourier analysis of the translations in the X (medio-lateral), Y (anterior-posterior), Z (cranio-caudal) directions, and rotations around the X, Y, and Z axes (Pitch, Roll and Yaw) performed during 3D realignment [Woods et al., 1998] (AIR parameters: 3D rigid body 6 parameter alignment, least cost function, 3Dsinc interpolation with $3 \times 3 \times 3$ pixels Hanning window, smoothing: $4 \times 4 \times 4$ mm FWHM, image threshold: 2000) yielded the Fourier Coefficients (FC) of the base frequency of the block design ($\omega_{6,3}$) which was used to estimate the degree of task-correlated head motion. The root mean square (RMS) of the FCs of ω_1 , ω_2 , ω_3 , ω_4 and ω_5 was used as an estimate of low frequency components (drift). Head motion ranges, defined as the difference between maximum and minimum of the time courses of translations in the X, Y, and Z directions, as well as rotations around the X, Y, and Z axes were calculated. The average translational range per trial was found by averaging the ranges for X, Y, and Z translations. The corresponding average rotational range was found by averaging the ranges for Pitch, Roll, and Yaw rotations. These ranges were finally averaged across the two trials of each condition yielding the conditional motion ranges. In a similar manner, the corresponding conditional task-correlated and low-frequency FCs were also calculated. Further, the lengths of the 3D trajectories traversed by the head were calculated and averaged across the two trials per condition yielding the conditional 3D trajectory length. Finally, the percentage increase between conditions of conditional range, conditional drift, and conditional task-correlated FCs were calculated. Due to the possibility of off equilibrium magnetic effects (physiological and electronic), the first two time points in the time courses were excluded in all the calculations. Correlation analysis of unrealigned and realigned data was performed using a correlation threshold of 0.5 and a step function corresponding to the block design shifted by one time point as a reference function.

RESULTS

Figure 2 shows the head motion of Subject 1, which with CRS is visibly task correlated and of higher amplitude than in PCH. Tables III and IV show the conditional ranges, conditional task-correlated Fourier coefficients, conditional low-frequency Fourier coefficients, and conditional trajectory lengths, as well as the corresponding percentage increases between conditions. Good repositioning quality of the helmet was found as shown in Figure 3. PCH alone yielded fewer motion artifacts than image registration + CRS. Combined PCH and registration yielded highest artifact reduction, CRS alone yielded the highest artifact contamination (Fig. 4a,d).

DISCUSSION

Results show that higher levels of task-correlated motion can occur without the use of an optimized fixation device even though overall head motion may be low. Since fMRI activation detection algorithms are especially sensitive to task-correlated motion, such motion may

Figure 2.

Time plots showing the translations and rotations of the head with PCH (thick lines) and CRS (dotted lines). Positive X, Y, and Z displacements (red, green, blue) indicate left, nasal, and cranial shifts, respectively. Pitch, Roll, and Yaw (red, green, blue) are rotations around the X (medio-lateral), Y (anterior-posterior), and Z (cranio-caudal) axes, respectively.

TABLE III. Dependence of head motion parameters on fixation technique and subject motion*

Subject	Condition	Conditional range		Conditional task correlated FC		Conditional drift		Conditional trajectory length (mm)
		X, Y, Z (mm)	ϕ, ρ, ψ (°)	X, Y, Z (mm)	ϕ, ρ, ψ (°)	X, Y, Z (mm)	ϕ, ρ, ψ (°)	
1	PCH	0,3	0,11	0,97	0,25	2,62	0,02	3.8
	CRS	0,7	0,23	2,43	0,81	6,38	0,04	5.6
2	PCH	0,3	0,15	0,46	0,33	2,66	0,02	5.9
	PCH+FHM	0,9	0,33	3,39	0,73	5,53	0,04	14.8
	CRS+FHM	7,8	2,64	26,07	8,31	79,48	0,43	100.0

* ϕ, ρ, ψ , FC = Pitch, Roll, Yaw, Fourier coefficient, X, Y, Z = medio-lateral, anterior-posterior, cranio-caudal axes.

TABLE IV. Percentage increase in head motion parameters depending on fixation technique and subject motion

Subject	Compared conditions	% Increase in conditional ranges		% Increase of task-correlated motion		% Increase of low frequency drifts		% Increase in average trajectory length
		X, Y, Z	ϕ, ρ, ψ	X, Y, Z	ϕ, ρ, ψ	X, Y, Z	ϕ, ρ, ψ	
1	PCH vs. CRS	133	109	151	224	144	100	47
2	PCH vs. PCH+FHM	200	120	637	121	108	100	151
	PCH+FHM vs. CRS+FHM	769	700	669	1038	1337	975	576

lead to serious mislocalizations, which are dangerous in clinical settings. With Subject 1/CRS, task-correlated head motion seems to be superimposed on top of a slow drift. Both task-correlated motion and head drift were highly suppressed by the PCH (Fig. 2, Table III). In terms of motion artifact reduction, we found PCH alone to be more effective than image registration + CRS (Fig. 4). This may be due to rotational head motion components [Wu et al., 1997]. While CRS increased head motion trajectory length by 47% compared to PCH with the highly trained cooperative Subject 1, trajectory length increased by 576% with the hyperkinetic Subject 2 in the CRS condition compared to PCH. Further, despite forceful attempts at head motion, the positional ranges in the X, Y, and Z directions were limited to only 0.6 mm, 0.6 mm and 1.4 mm with the PCH. This may indicate the usefulness of the PCH for restless hyperkinetic patients (e.g., motor disorders, etc). In terms of design considerations, our head fixation method has improved on some aspects of previously described head fixation techniques. Most important, as wet plaster-cast bandages are not only fully malleable but also tensile and slightly elastic, the bandages can be kept circularly taught during the bandaging, which creates a highly uniform distribution of pressure in the elastic layers between bony skull and device leading to minimization of residual space and

optimal shape adaptation on hardening. After solidifying, the plaster cast still exerts a slight pressure on the skull, which due to the excellent shape adaptation is homogenous. Due to this as well as the water permeable nature of plaster cast preventing sweat accumulation, subject tolerance is improved. Other materials such as light cast (fibre cast, orthoplast) [Bergström et al., 1976, 1981; Greitz et al., 1980], thermoplastics [Fox et al., 1985; Kaiser et al., 1994], orthotic foam, vacuum cushions, bean bags, and silicon rubber are not as rigid as plaster cast when fully hardened. Further, when solid, they are not as water permeable as plaster cast and may induce discomforting sweating. Additionally, they are not as malleable in their uncured states as wet plaster cast which facilitates encompassing more of the head compared to other methods where calvarium and neck are often left out. The initial windings of the cast were wound well caudal to the occipital protuberance, tightly reaching around the ears, eyes, and forehead, thereby not only increasing the contact surface area of the device but also increasing the shape asymmetry. In contrast to other methods, we incorporated a latching mechanism enabling the subject to free himself in case of an emergency. The knowledge of the subject that he can at any time free himself from the scanner may decrease the likelihood of panic attacks.

Figure 3.

Slice 7 of Subject 1 on three separate days. Despite the differences in signal intensity due to technical fluctuations, distortions due to the EPI sequence, as well as inaccuracies in MR bed repositioning a good repositioning in terms of slice orientation and offset is possible.

Currently, fMRI measurement times are limited due to cumulation of head movements and low subject tolerance of fixation devices. As our fixation method is well tolerated and suppresses both task-correlated head motion as well as drifts, prolonged stimulation for difficult clinical investigations and investigations of time-consuming sophisticated tasks—currently not feasible with fMRI due to its motion sensitivity are now possible. Successful measurements lasting up to 2.5 hrs have been

performed in our laboratory. Further, with our fixation method, good repositioning for repeat scans aimed at improving data reliability is facilitated. Since plaster cast is cheap, nontoxic, nonallergenic, and readily available in a clinical setting where also specific technical know-how exists, the fixation technique may be of interest for a broad range of clinicians and neurophysiologists.

In conclusion, the suggested method achieved improved immobilization, repositioning and subject tol-

Figure 4.

Close-up of activation results for Subject 1 (comparable slices) (a) PCH + image registration, (b) PCH alone, (c) CRS + image registration, and (d) CRS alone are contrasted against each other. Interestingly, the apparent order of movement artifact contamination is (from highest to lowest) CRS, CRS + image registration, PCH alone, PCH + image registration. Note the slightly anteriorly rotated head position with CRS.

erance with our volunteers. With our volunteers, investigations of up to 2 or more hrs were well tolerated, which may indicate the feasibility of long measurements on restless patients, thereby paving the way for broad clinical usage of fMRI.

ACKNOWLEDGMENTS

Stimulating discussions and support by E. Moser, L. Deecke and H. Imhof (all from Vienna) as well as photography by M. Klarhoefer and W. Endl are gratefully acknowledged. We thank Prof. H.H. Bergmann for providing workstation time for computing the AIR image registration matrices.

REFERENCES

- Ashburner H, Hutton C, Grootoink S, Turner R, Friston KJ (1997): Correction for movement-related effects arising from data interpolation in fMRI time-series. *Neuroimage* 5(4) Part 2, 3rd International Conference on Functional Mapping of the Human Brain. S453.
- Beisteiner R, Gomiscek G, Erdler M, Teichtmeister C, Moser E, Deecke L (1995): Comparing localization of conventional functional magnetic resonance imaging and magnetoencephalography. *Eur J Neurosci* 7:1121–1124.
- Beisteiner R, Erdler M, Teichtmeister C, Diemling M, Moser E, Edward V, Deecke L (1997): Magnetoencephalography may help to improve functional MRI brain mapping. *Eur J Neurosci* 9:1072–1077.
- Bergström M, Greitz T (1976): Stereotactic computed tomography. *Am J Roentgenol* 127:167–170.
- Bergström M, Boethius J, Eriksson L, Greitz T, Ribbe T, Widen L (1981): Head fixation device for reproducible position alignment in transmission CT and positron alignment emission tomography. *J Comput Assist Tomogr* 5:1136–1141.
- Bettinardi V, Scardaoni R, Gilardi MC, Rizzo G, Perani D, Paulesu E, Striano G, Triulzi F, Fazio F (1991): Head holder for PET, CT and MR studies. *J Comput Assist Tomogr* 15:886–892.
- Bullmore ET, Brammer M, Rabe-Hesketh S, Curtis VA, Williams SCR, Sharma T, Morris RG, McGuire PK (1997): Methods for diagnosis and treatment of stimulus correlated motion in generic activation studies using fMRI. *Neuroimage* 5(4) Part 2, 3rd International Conference on Functional Mapping of the Human Brain. S457.
- Debus J, Essig M, Schad LR, Wenz F, Baudendistel K, Knopp MV, Engenhart R, Lorenz WJ (1996): Functional magnetic resonance imaging in a stereotactic setup. *Magn Reson Imaging* 14:1007–1012.
- Fox PT, Perlmuter JS, Raichle ME (1985): A stereotactic method of anatomical localization for positron emission tomography. *J Comput Assist Tomogr* 9:141–153.
- Friston KJ, Williams S, Howard R, Frackowiak RS, Turner R (1996): Movement related effects in fMRI time-series. *Magn Reson Med* 35:346–355.
- Frouin V, Mességué E, Mangin JF (1997): Assessment of two fMRI motion correction algorithms. *Neuroimage* 5(4) Part 2, 3rd International Conference on Functional Mapping of the Human Brain. S458.
- Greitz T, Bergström M, Boethius J, Kingsley D, Ribbe T (1980): Head fixation system for integration of radiodiagnostic and therapeutic procedures. *Neuroradiology* 19:1–6.
- Grootoink S, Hutton C, Ashburner J, Howseman A, Josephs O, Rees GE, Friston KJ, Turner R (1997): Assessment of movement-related signal changes in fMRI. *Neuroimage* 5(4) Part 2, 3rd International Conference on Functional Mapping of the Human Brain. S454.
- Hajnal JV, Myers R, Oatridge A, Schwieso JE, Young JR, Bydder GM (1994): Artifacts due to stimulus correlated motion in functional imaging of the brain. *Magn Reson Med* 31:283–291.
- Hajnal JV, Bydder GM, Young JR (1995): fMRI: does correlation imply activation? *NMR-Biomed* 8:97–100.
- Jiang A, Kennedy DB, Weiskoff R, Tootell R, Woods R, Benson R, Kwong K, Brady T, Rosen B, Belliveau J (1995): Motion detection and correction in functional MR imaging. *Hum Brain Mapp* 3:224–235.
- Kaiser HJ, Sabri O, Wagenknecht G, Lege B, Hellwig D, Bull U (1994): A method of correlating and merging cerebral morphology and function by a special head holder. *Nuklearmedizin* 33:123–126.
- Kearfott KJ, Rottenberg DA, Knowles JR (1984): A new headholder for PET, CT, and NMR imaging. *J Comput Assist Tomogr* 8:1217–1220.
- Kwan RKS, Evans AC, Pike GB (1997): fMRI simulation for quantitative evaluation of analysis methods. *Neuroimage* 5(4) Part 2, 3rd International Conference on Functional Mapping of the Human Brain. S449.
- Mazziotta JC, Phelps ME, Meadors AK, Winter ARJ, Bentson JR (1982): Anatomical localization schemes for use in positron computed tomography using a specially designed headholder. *J Comput Assist Tomogr* 6:843–853.
- Moser E, Teichtmeister C, Diemling M (1996): Reproducibility and postprocessing of gradient-echo functional MRI to improve localization of brain activity in the human visual cortex. *Magn Reson Imaging* 14:567–579.
- Moser E, Baumgartner R, Barth M, Windischberger C (1999): Explorative signal processing in functional MR Imaging. *Int J Imaging Sci and Technol* 10:166–176.
- Robson MD, Gatenby JC, Anderson AW, Gore JC (1997): Practical considerations when correcting for movement-related effects present in fMRI time-series. *Proceedings of the ISMRM 5th Scientific Meeting and Exhibition*. p 1681.
- Rombouts SARB, Barkhof F, Hoogenraad FGC, Sprenger M, Scheltens P (1998): Within-subject reproducibility of visual activation patterns with functional magnetic resonance imaging using multislice echo planar imaging. *Magn Reson Imaging* 16:105–113.
- Singh KD, Holliday IE, Furlong PL, Harding GF (1997): Evaluation of MRI-MEG/EEG co-registration strategies using Monte Carlo simulation. *Electroencephalogr Clin Neurophysiol* 102:81–85.
- Tegeler C, Strother SC, Anderson JR, Kim SG (1999): Reproducibility of BOLD-based functional MRI obtained at 4T. *Hum Brain Mapp* 7:267–283.
- Tootell RB, Reppas JB, Kwong KK, Malach R, Born RT, Brady TJ, Rosen BR, Belliveau JW (1995): Functional analysis of human MT and related visual cortical areas using magnetic resonance imaging. *J Neuroscience* 15:3215–3230.
- Wexler BE, Fulbright RK, Lacadie CM, Skudlarski P, Kelz MB, Constable RT, Gore JC (1997): An fMRI study of the human cortical motor system response to increasing functional demands. *Magn Reson Imaging* 15:385–396.
- Woods RP, Grafton ST, Holmes CJ, Cherry SR, Mazziotta JC (1998): Automated image registration: I. General methods and intrasubject, intramodality validation. *J Comput Assist Tomogr* 22:139–152.
- Woods RP, Grafton ST, Watson JDG, Sicotte NL, Mazziotta JC (1998): Automated image registration: II. Intersubject validation of linear and nonlinear models. *J Comput Assist Tomogr* 22:153–165.
- Wu DH, Lewin JS, Duerk JL (1997): Inadequacy of motion correction algorithms in functional MRI: role of susceptibility-induced artifacts. *J Magn Reson Imaging* 7:365–370.