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COMMUNICATIONS

Artifacts Introduced by Zero Order Phase Correction in Proton NMR Spectroscopy and a Method of Elimination by Phase Filtering

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In *in-vivo* applications of proton NMR spectroscopic imaging, an oscillatory "ringing" artifact has been observed in some of the spectra. The source of this artifact was found to be the presence of a harmonic "beating" effect in the amplitude of the water reference free induction decay (FID) which was used for zero order phase correction for B_0 inhomogeneity and eddy current compensation. The source of the beats was found to be the presence of distinct populations of spins resonating at slightly different frequencies. When the common method of zero order phase correction was implemented using such an FID, the resulting phase-corrected, water-suppressed spectra displayed ringing. Examination of the unwrapped phase correction angle revealed unexpected jumps in phase at points in time corresponding to nodes in the amplitude of the FID. Low-pass filtering of the phase correction angle of the reference FID was found to smooth out these unanticipated phase jumps. When used as a reference for phase correction, the filtered phase information gave a phase-corrected, water-suppressed spectrum free from ringing.

Key Words: **NMR; phase correction; artifact; water reference; low-pass filter.**

INTRODUCTION

The presence of eddy currents induced by the switching of the localization and spoiling gradient currents in clinical MRI scanners results in distortions in the lineshapes of proton NMR spectra acquired *in vivo* and *in vitro.* Furthermore, the variation in the B_0 homogeneity across the magnet bore can cause further phase distortions due to the spatial variation in the Larmor frequency. Precise shimming can minimize the effect of B_0 inhomogeneity, however, in 2D and 3D spectroscopic imaging experiments a uniform magnetic field throughout the whole of the volume of interest (VOI) is difficult to attain. Automated shimming routines can help reduce B_0 inhomogeneity (*1, 2*), but isolated regions where shimming is poor will always persist where there is an abrupt change in chemical shift or susceptibility, such as at the skull and near the sinuses in the human brain.

Ordidge and Cresshull (*3*) proposed an effective method of correcting for these zero order spectral phase distortions of a metabolite spectrum by using a water reference FID collected from the same VOI. This correction method works on the assumption that the water and metabolite resonances are distorted in the same way by zero order phase effects. The algorithm proposed first calculates the water FID phase angle ϕ_w, as the arctangent of the quotient of the imaginary and real parts of the water FID. This phase angle is then subtracted from the corresponding phase angle of the water suppressed (metabolite) FID on a data point by data point basis. The phase distortions introduced by eddy currents and B_0 inhomogeneity are thereby removed from the water suppressed FID and its spectrum. This method has since had widespread use in *in vivo* proton NMR spectroscopy (*4, 5*). Using this method of zero order phase correction in a single slice point resolved (PRESS, *6*) localized spectroscopic imaging experiment (*7*), a "ringing" artifact was occasionally observed in some of the spectra (Fig. 1). In an attempt to isolate the source of the artifact, both the water suppressed and reference FIDs from the artifact ridden voxels were examined before and after the individual stages of the data processing sequence used to produce a spectroscopic image from a 2D phase encoded FID.

METHODS—EXPERIMENTAL

The methods of data processing used to produce the 2D spectroscopic images have been described in detail previously (*7*). In brief, both the reference and suppressed FIDs are spatially decoded using a 2D fast Fourier transform (FFT), the zero order phase correction angle is then calculated for all 1024 data points of the reference FID and used to phase correct the corresponding data points of the suppressed FID. The suppressed FID is then filtered using 4-Hz Gaussian line broadening prior to Hankel–Lancosz Singular Value Decomposition (HLSVD, *11*) water removal and the time to frequency domain

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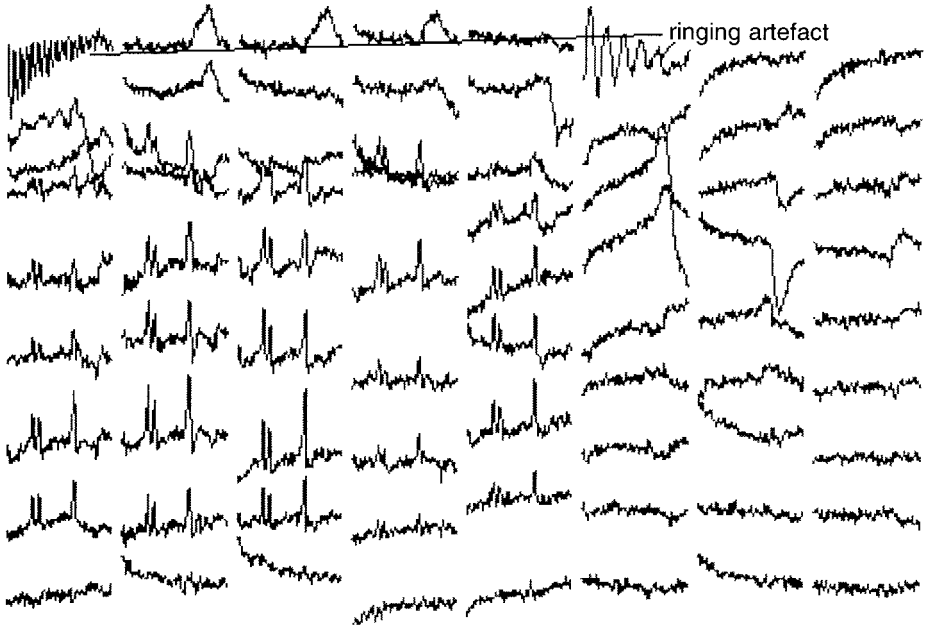

FIG. 1. An array of spectra collected from the human brain with a PRESS localized spectroscopic imaging sequence. Two of the spectra in the top row of the array from regions adjacent to the skull display a ringing artifact, which obscures any underlying resonances.

spectral FFT. All the data processing was carried out on a Sun Sparc 20 workstation using in house C and Matlab (The Math Works, Natick, MA) software.

In particular, the zero order correction method was implemented using an algorithm written in C which uses the *atan*2 function to calculate the water phase angle ϕ_w, as the arctangent of the quotient of the imaginary and real parts of the FID for all 1024 data points. This function returns an angle in the range $\pm\pi$, as such the phase angle of the water reference FID should evolve smoothly as a function of time, with abrupt steps of 2π at values of $\pm\pi$.

Experimental Results and Discussion

Examination of the phase correction angles of the water reference FIDs of offending spectra reveals unexpected abrupt jumps in phase of π (Fig. 2). To investigate the source of these phase flips, the magnitude of a water reference FID was plotted (Fig. 3). There is an obvious notch or "node" in the magnitude of the signal at the data point corresponding to the phase flip. If either the real or imaginary part of the FID approaches zero and change sign (at the node) the function could return the negative angle, i.e., $\phi_w + \pi$, and cause the flip. This node is reminiscent of the nodes observed in the beats effect of harmonic interference, produced by the interference of two sources whose frequencies differ by a small amount. This condition could arise in NMR in a region in which there is a rapid change in either chemical shift or susceptibility such as at a tissue/fat interface or near the sinuses. The spectra in the top row of the array in Fig.1 were indeed collected at the edge of a PRESS VOI, which is close to the skull and scalp, which contain significant amounts of lipids with a markedly different chemical shift from that of water. To investigate this possible explanation, Matlab simulations were then carried out using a synthetic FID, with two prominent resonant frequencies which differed slightly.

Computer Simulations

A synthetic water reference FID with two comparable populations of spins of slightly different Larmor frequency was created with a sampling interval of 1ms for 1024 data points. A zero frequency of 63.63 MHz (water at 1.5 T) was used, representing water *in vivo.* The two components (of equal size) had individual frequencies of 8 and 16 Hz offset from this zero frequency.

The beating modulation in the amplitude of the synthetic FID is illustrated in Fig. 4a. In Fig. 4b the unwrapped phase angle ϕ_w is plotted, and the unexpected flip of π in the phase at the positions in time of the nodes in Fig. 4a are indeed evident. A second simulated metabolite spectrum was then constructed with a water contribution diminished by a factor of 200 (to emulate the effect of CHESS water suppression) and contributions at 95, 108, and 172 Hz to represent the resonances of choline, creatine, and N-Acetyl Aspartate (NAA) at 1.5 T.

This signal was then phase corrected with $\exp(-i\phi_w(t))$ for all 1024 data points. The FFT of the phase corrected metabolite FID (Fig. 4c) shows the "ringing" artifact observed *in vivo.*

Removing the Artifact

One possible method of removing this artifact is to filter the water reference FID so as to smooth out the abrupt nodes in

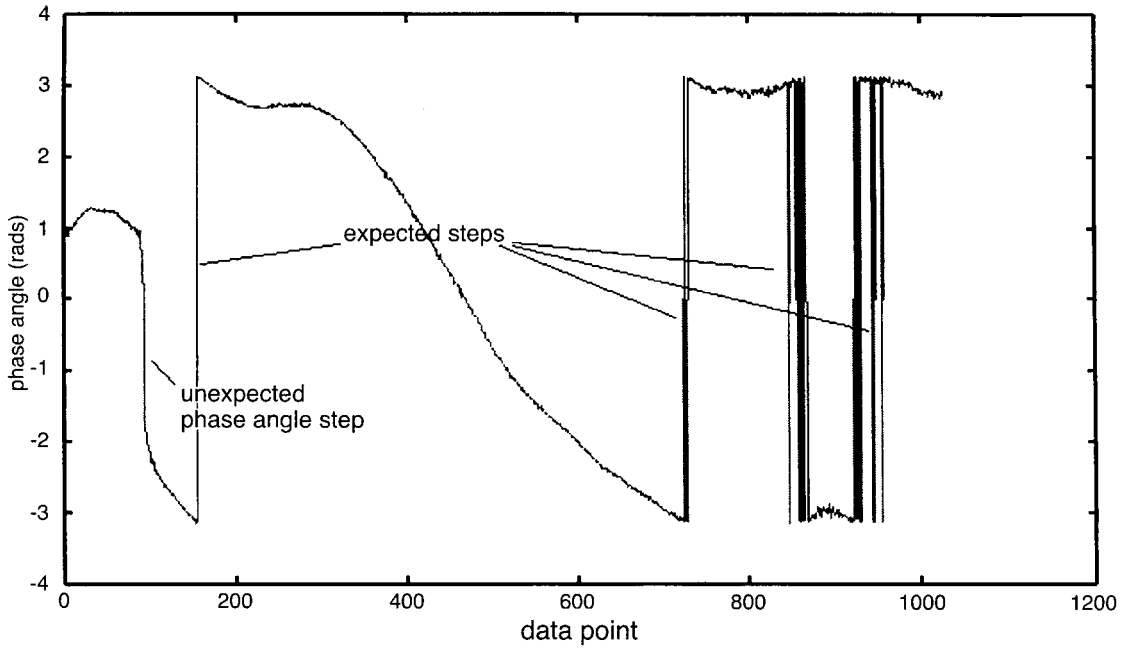

FIG. 2. The phase correction angle of the water-reference FID corresponding to the spectrum from the top row three from the right, which shows a marked ringing artifact. Note that the phase angle shows a distinct step of π (at data point 90) as well as the expected 2π steps which can be removed by phase unwrapping.

intensity. Low-pass filtering of a water reference signal has been reported before (*8, 9*). Webb *et al.* (*8*), low-pass filtered the water FID to attenuate the noise that is particularly dominant in the tail end of the signal. The fact that noise is more prominent in this region of a water signal than in a corresponding metabolite signal is a result of the typically shorter T_2 of water compared to metabolites *in vivo.* The phase correction angle as evaluated in this low signal-to-noise region could give an erroneous indication of the zero order phase perturbations experienced by metabolite resonances. As such, low-pass filtering is an effective way of removing this source of error without affecting the underlying phase pattern of the prominent water resonances.

With reference to the artifact observed here, low-pass filter-

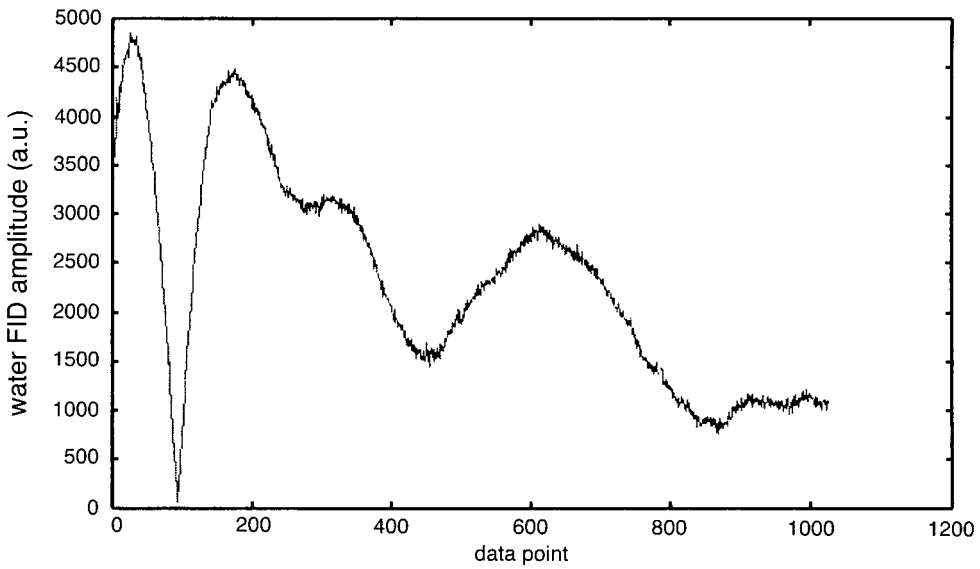

FIG. 3. The magnitude of the water reference FID used to calculate the phase evolution in Fig. 2. There is a distinct node or zero in intensity arising at the same point in time (data point 90) as the unexpected flip in phase shown in Fig. 2.

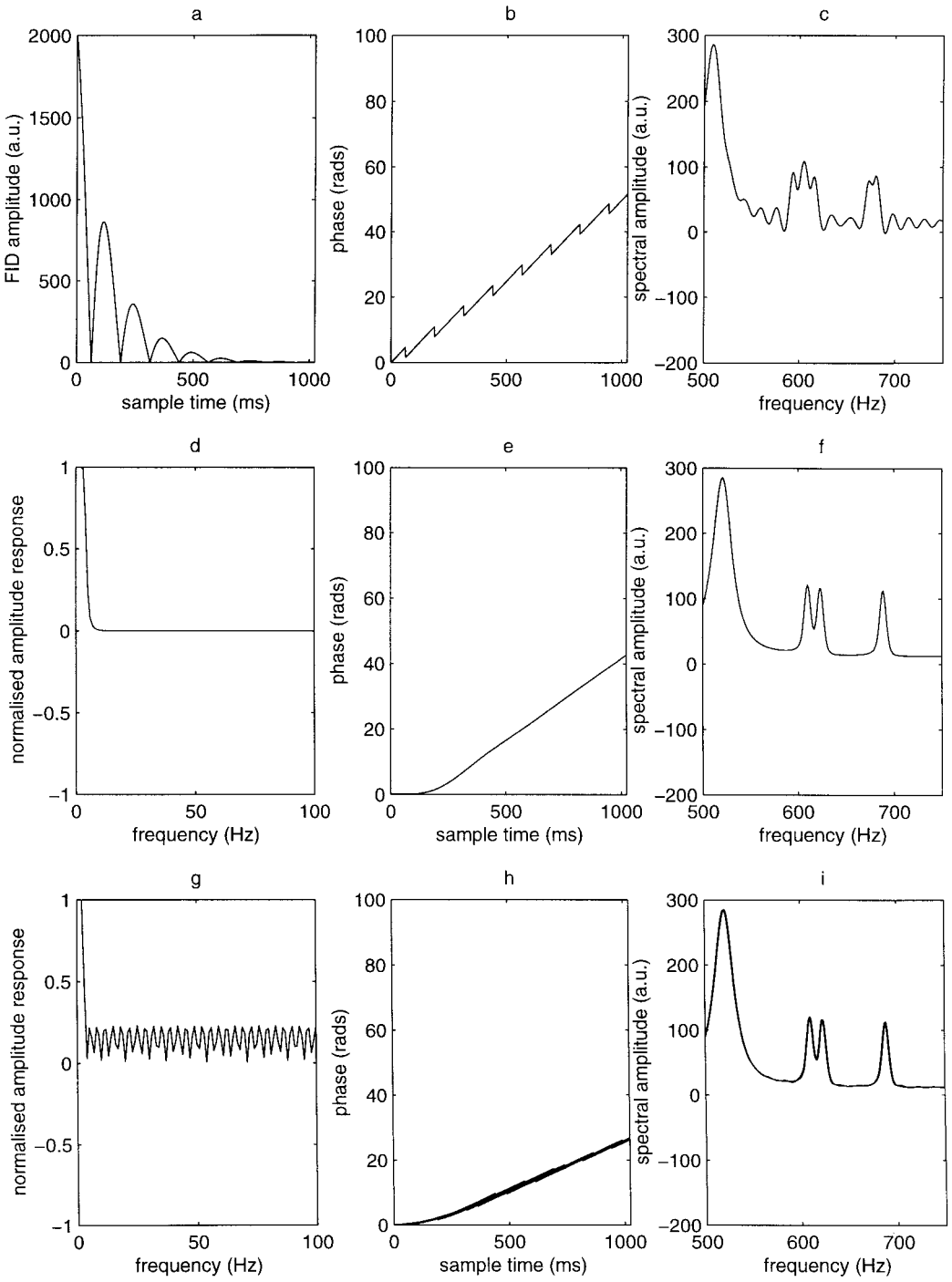

FIG. 4. Matlab simulations of the cause of the ringing artifact and the effect of low-pass filtering of the phase correction angle in removing the artifact. (a) The magnitude of the simulated water reference FID, which has two prominent resonances at frequencies 8 and 16 Hz offset from the zero frequency representing the transmitter frequency (66.63 MHz at 1.5 T). The beats due to harmonic interference of the two frequencies are well defined. (b) The phase angle of the FID of Fig. 4a after 2π unwrapping. Note the residual steps of height π corresponding to the nodes in the FID amplitude. (c) The simulated metabolite spectrum following phase correction with the phase angle of Fig. 4b. Note the marked ringing artifact, which masks the delineation of the simulated choline and creatine peaks. (d) The normalized low-pass transfer characteristics of the Butterworth filter. The pass band is 0–3 Hz. (e) The phase angle of the FID of Fig. 4a following low-pass filtering with a Butterworth filter. The steps have been smoothed out effectively, although a delay of around 100 ms has been introduced by the filter. (f) The simulated metabolite spectrum phase corrected with the IIR filtered phase angle of Fig. 4e. The ringing artifact has been completely removed but all four peaks have experienced a constant shift of approximately 40 Hz corresponding to the phase delay of the filter. (g) The normalized transfer characteristics of the Parks–Mclellan low-pass FIR filter used. The pass band is 0–3 Hz and the transition band is 3–5 Hz. (h) The phase angle of the FID of Fig. 4a following low-pass filtering with a FIR filter. The steps have been smoothed out effectively, the phase delay of the filter is less than that of the IIR filter. (i) The simulated metabolite spectrum phase corrected with the FIR filtered phase angle of Fig. 4h. The ringing artifact has been completely removed but all four peaks have experienced a constant shift of approximately 35 Hz corresponding to the phase delay of the filter.

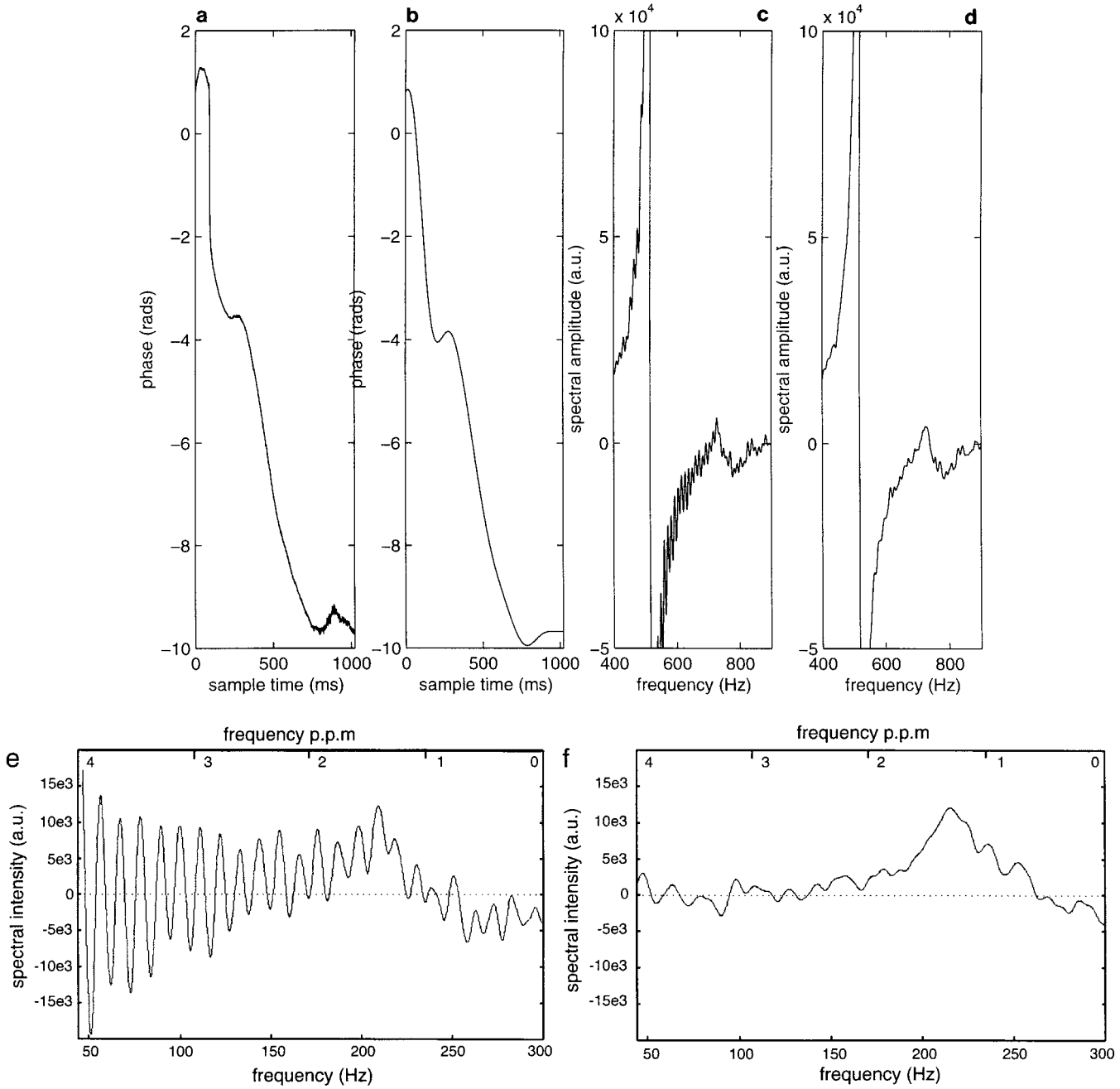

FIG. 5. *In vivo* application of low-pass phase filtering to an extreme case of the artifact. (a) The phase correction angle prior to filtering, with a step of π at about 50 ms. (b) The phase correction angle after filtering, the vertical step has been smoothed out. (c) The water suppressed spectrum phase corrected with the nonfiltered phase. The ringing artifact is marked even without HLSVD water removal. (d) The water-suppressed FID phase corrected with the filtered phase, the artifact is no longer evident. (e) The spectrum of Fig. 6c after HLSVD water removal. Any metabolite information is obscured by the ringing. (f) The spectrum of Fig. 6d after HLSVD water removal, the ringing is no longer evident leaving a broad lipid signal at around 220 Hz.

ing of the FID will not necessarily remove the beats as they are an effect of harmonic interference between prominent components of the FID. It is these components which indeed need to be preserved in order to gain an accurate representation of the zero order phase pattern. An alternative approach is to filter the unwrapped phase correction angle in an attempt to smooth out the residual glitches caused by instabilities in the *atan*2 function at data points corresponding to the nodes. Knight-Scott and Li (*9*), used a low-pass filter to extract phase data from the low signal-to-noise region described by Webb (*8*). The effect

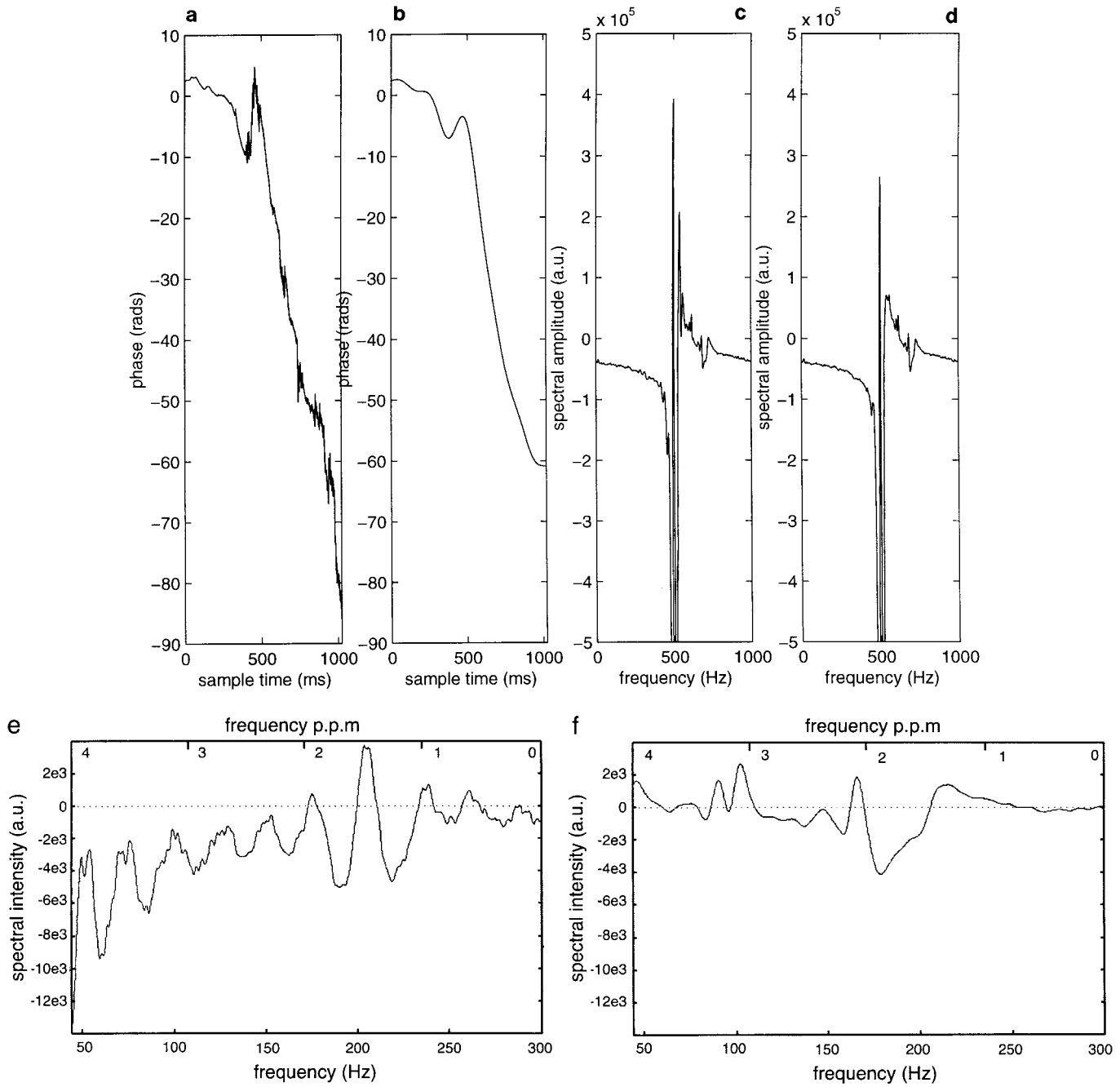

FIG. 6. *In vivo* application of low-pass phase filtering to a milder example of the artifact. (a) The phase correction angle prior to filtering, with several noisy steps of π distributed throughout. In the region corresponding to low signal-to-noise in the FID (the tail end of the phase evolution) the steps or "glitches" are particularly abundant. (b) The phase correction angle after filtering. Note how the smoothing is particularly pronounced in the tail end of the phase evolution. As the FID is line broadened with a 4-Hz Gaussian filter prior to the FFT, the phase information contained in this region has no significant influence on the phase of the resulting spectrum. (c) The water suppressed spectrum phase corrected with the nonfiltered phase. The ringing artifact is not marked before HLSVD water removal. (d) The water-suppressed FID phase corrected with the filtered phase, the artifact is still not obvious. (e) The spectrum of Fig. 6c after HLSVD water removal. Any metabolite information is obscured by the ringing which is now obvious. (f) The spectrum of Fig. 6d after HLSVD water removal, the ringing is no longer evident leaving well-resolved choline and creatine, with NAA requiring first order phasing and broad lipid resonances around 150 and 220 Hz.

of low-pass filtering of the unwrapped phase correction angle was therefore investigated, first using the simulated data of Fig. 4, and then with the *in vivo* data which displayed the spectral ringing artifact.

METHODS—FILTER DESIGN

The efficiency of two low-pass filters was investigated using the signal processing toolbox of Matlab (*10*). The first

was an infinite impulse response (IIR) Butterworth filter with a pass band defined as a fraction of the 500 Hz Nyquist frequency. A Butterworth filter has the feature that the transition from pass band to stop band is monotonic (Fig. 4d). The second filter that was investigated was a finite impulse response (FIR) filter designed using the Parks–McClellan algorithm. The advantage of FIR's is that the phase response in the pass band is linear; i.e., there is a constant phase and group delay of the filtered signal. The group delay of the filter is given by $n/2$ (where n is the order of the filter), the signal is therefore delayed by $n/2$ data points. This constant delay for all frequencies means that the FFT of the FIR filtered data has no phase distortion in the pass band, just a uniform frequency offset (Fig. 4i). The effects of pass bandwidth of both the IIR and FIR (in terms of a fraction of the Nyquist frequency of 500 Hz) and the order of the FIR upon the evolution of the phase correction angle were investigated. The optimization criteria used were first an accurate representation of the unwrapped phase angle minus the glitches caused by nodes in the FID. Second, minimum frequency dependent first order phase effects in the 50–250 Hz region of the phase corrected metabolite spectrum were sought.

RESULTS AND DISCUSSION

The Butterworth IIR filter of Figs 4d–4f, was found to be most effective with a low-pass region of 0–3 Hz and an order of 5 giving the normalized amplitude response of Fig. 4d in the 0–200 Hz region (0 Hz representing the frequency of water). The phase delay of the filter is apparent in Fig. 4e, which gives rise to the offset of around 40 Hz in the FFT of the data.

The FIR was found to be most effective with a pass band of 0–3 Hz and a transition band of 3–5 Hz (Fig. 4g). The order of this filter was set at 300 following the rule of thumb that a FIR filter should be of order at least 3 times less than the length of the data set (1024 points). With little to chose between the performance of these two low-pass phase filters when applied to simulated data, the Butterworth filter was chosen as it is less computationally intensive and has a constant frequency shift in the 50–200 Hz region (0 Hz set at water resonant frequency). The results of the application of this filter to the water reference phase angle of two sets of *in vivo* data are shown in Figs. 5 and 6. The zero order phase was retained by removing the offset between the filtered and nonfiltered phase information at the first data point (*8*). From these two examples it can be seen that the method is effective in the case of an extreme artifact visible in the spectrum without HLSVD (*11*) water removal (Fig. 5) and performs equally well in a more subtle case where the ringing is only obvious in the spectrum following HLSVD water removal (Fig. 6).

CONCLUSIONS

The source of a persistent spectral artifact has been pinpointed as the computer implementation of a popular zero order phase correction algorithm (*3*). To avoid this artifact the phase angle of a water reference FID (ϕ_w) should be protected against sudden sign changes induced by nodes in the water reference FID. Low-pass filtering of ϕ_w acts to smooth out glitches in the unwrapped phase angle while preserving the bulk of the phase information in the reference scan. When applied to artifact-prone, water-suppressed FIDs, the filtered phase correction angle was found to give a spectrum free from the ringing artifact. The filters used here were chosen for their effective low-pass filtering with minimum phase and frequency distortion in the frequency range of 50 to 250 Hz, which represents the metabolites of interest in brain spectroscopy at 1.5 T.

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