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Proton MRS and MRSI of the brain without water suppression

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ABSTRACT

Water suppression (WS) techniques have played a vital role in the commencement and development of in vivo proton magnetic resonance spectroscopy (MRS, including spectroscopic imaging – MRSI). WS not only made in vivo proton MRS functionally available but also made its applications conveniently accessible, and it has become an indispensable tool in most of the routine applications of in vivo proton MR spectroscopy. On the other hand, WS brought forth some challenges. Therefore, various techniques of proton MRS without WS have been developed since the pioneering work in the late 1990s. After more than one and a half decades of advances in both hardware and software, non-water-suppressed proton MRS is coming to the stage of maturity and seeing increasing application in biomedical research and clinical diagnosis. In this article, we will review progress in the technical development and applications of proton MRS without WS.

Contents

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1. Introduction

Water suppression (WS) techniques [1–12] have played a crucially important role in the development and applications of proton magnetic resonance spectroscopy (MRS) and spectroscopic imaging (MRSI). On average, water makes up more than 75% of the human brain by weight [13–15]. The proton MRS signal of water [16,17] is three to five orders of magnitude larger than those of the detectable metabolites in the brain [18,19]. The 12-bit or 16-bit analogue-to-digit converter (ADC) typically used on most MR scanners decades ago was unable to accurately digitize and resolve small metabolite signals in the presence of the huge water signal because digital noise can be larger than the signals of metabolites [19]. The need for water suppression was one of the reasons why the first and the majority of in vivo MRS studies in the early 1980s were performed on ^{31}P [20–24] and not on ^{1}H, despite the high natural abundance (99.9%) and MR signal sensitivity of protons. WS techniques [1–6], suppressing water signal prior to the acquisition of metabolite signal, greatly facilitated the development and applications of in vivo ^{1}H MRS [25–27]. They not only enable accurate digitization and resolution of weak metabolite signals but also avoid other problems associated with the dominant water signal, which extends far into the spectral region of interesting metabolites and distorts the baseline of the spectrum. WS has been routinely used ever since the inception of in vivo ^{1}H MRS, which is now widely used in research and clinical studies [27–34].

WS, however, has several disadvantages. (1) Signals with small chemical shift differences relative to the water resonance may be partially or completely suppressed by WS pulses and, therefore, cannot be accurately detected [18]. (2) Strong RF pulses used in some WS methods may cause magnetization transfer, which could in turn lead to systematic errors in metabolite quantification [35]. (3) RF pulses used for WS increase the total RF power deposition [36]. (4) Additional acquisition of non-water-suppressed MRSI data, which substantially increases scan time, is necessary if internal water is used in spectroscopic imaging studies as a reference for the quantification of metabolites [37,38]. (5) Strong gradient pulses for crushing the water signal increase the level of acoustic noise, possibly causing discomfort to some subjects [39–42]. And (6) WS pulses may introduce phase and lineshape distortions in the spectrum if the water signal is incompletely suppressed [43].

In vivo ^{1}H MRS without WS, on the other hand, can not only avoid the disadvantages associated with WS but also offer further advantages as evidenced by various publications in the past few years. (1) The water signal can be used as a reference to correct lineshape distortion caused both by eddy currents induced in the metal surface of the magnet due to the varying magnetic gradient field [44–46] and by inhomogeneity of the static magnetic field [47–49]. (2) The water signal can be used as an internal reference for quantification of metabolites [18,49–58]. (3) In MRSI, the water signal can be used to correct voxel-to-voxel frequency shifts caused by the inhomogeneity of the main magnetic field B_0 [49,59]. (4) In single voxel MRS with a large number (usually 64–256) of signal averaging to increase SNR, water signal can be used to correct lineshape distortions and to eliminate artifacts caused by subject motion [60]. (5) In MRSI using multichannel coils, the water signal can be used as a better reference than a metabolite signal for spectral alignment [59,61–63] and for optimal combination of multichannel spectra to increase the signal-to-noise ratio (SNR) [62–64].

The advantages of in vivo proton MRS without WS do not come without cost. The aforementioned problem of large dynamic signal range is only one minor difficulty that hindered the use of in vivo MRS without WS and has been overcome. In fact, modern MRI scanners equipped with 16-bit or 32-bit ADCs, and oversampling [19,65], which can greatly increase the effective dynamic range of the ADC, are able to acquire water and metabolite signals simultaneously in in vivo proton MRS, or even two-dimensional (2D) and three-dimensional (3D) MRSI, without introducing noticeable digital noise to or sacrificing intensities of metabolite signals. A major obstacle to proton MRS without WS is the troublesome sideband artifacts that appear in the proton MR spectra [66–68]. These artifacts are on both sides of the water peak (hence the name) and overlap with the metabolite peaks; they can be of the same order of magnitude as the metabolite signals. Spectral quantification or analysis would not be possible in the presence of these sideband artifacts. Effective techniques to eliminate sideband artifacts need to be developed so that the advantages of ^{1}H MRS without WS can be fully exploited.

Since the first publication of non-water-suppressed proton MRS in 1998 [68], numerous studies have been carried out on the methodology and on the applications of in vivo proton MRS or MRSI without WS. After more than 15 years of development, the techniques of non-water-suppressed proton MRS and MRSI are maturing, and their applications in biomedical research and clinical diagnosis are increasing [50,59,66–73]. The purpose of this article is to review the major technical developments in and the applications of proton MRS and MRSI without WS.

2. Sideband artifacts in proton MRS without WS

2.1. Origins of the sideband artifacts

Generally speaking, the sideband artifacts are caused by dynamic magnetic gradient fields, which are switched on and off for voxel localization in MRS, for slice selection and spatial encoding in MRSI, and especially for destroying undesirable signals from outside the regions of interest (ROI) defined by spatial localization methods, such as PRESS [26] and STEAM [25]. The detailed mechanisms underlying the correlations between the sideband artifacts and the dynamic magnetic fields may be complex and are still not fully understood [41,74]. However, the following may shed some light on the understanding and explanation: (1) The interaction of the magnetic field B_0 and the time-varying electrical current in the gradient coils will exert a magnetic force, called the Lorentz force, on the gradient coil windings, thus causing mechanical vibrations of coils as manifested by the acoustic noise during the MR scans. The current-carrying, vibrating gradient coils will in turn cause a fluctuating magnetic field. (2) The time-varying magnetic field generated by the vibrating gradient coils will induce eddy currents in the conducting surfaces of the MRI scanner; the eddy currents will in turn induce a time-varying magnetic field, which will exert a time-varying magnetic force on the gradient coils, thus contributing to the mechanical vibrations. In modern MR systems