Assessment of a gradient thermostat unit: Implications to field alterations at a 11.7 Tesla preclinical system

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Abstract— Modern high field preclinical MRI systems are built compact, with gradient coils that fit tightly in the magnet bore. Thus, heat generated during operation can be transferred directly from the gradient coil surface to the passive shims causing undesired field fluctuations that may affect data quality. The performance of a commercial thermostat unit that is designed to pre-heat the passive shims to limit these fluctuations is described for a preclinical 11.7 Tesla system. The main magnetic field is affected by changes in the cooling water of the gradient alone, indicating that a compact system design allows an efficient heat transfer from the gradient surface to the passive shims. Similar results are obtained when the gradients are pulsed. The thermostat unit that preheats the passive shims to 42.5 Celsius reduces the magnitude of the field variations by 90%. The *in vivo* experiments confirmed that the pre-heating of the passive shims is required, even for standard robust sequences.The thermostat unit reduces the field variation to a range that is acceptable for routine applications. However, any study that analyses spatio-temporal signal changes requires knowledge of the apparent irregular field variations created by the feed-back controlled thermostat unit.

Index Terms—drift compensation, field stability, gradient heating, gradient thermostat unit, high field, *in vivo* MRI, magnetic resonance imaging, magnetic resonance spectroscopy, passive shims, shim heaters, 11.7Tesla.

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1 INTRODUCTION

WHEN a magnetic resonance (MR) system is installed, magnetic field stability and homogeneity, shims and gradient inserts are assessed independently from each other to verify that the system is meeting the outlined specifications.

One could anticipate that during measurements the upper limit for resonance frequency alterations could be defined as specified for the magnet itself (e.g. 0.05ppm/ hour). However, larger frequency drifts that may affect data quality, especially in repeated acquisition schemes (e.g. magnetic resonance spectroscopy, thermography, functional MRI studies), can be observed if MR sequences are used that rely on extensive gradient switching [1], [2], [3]. It is thought that the frequency alterations are mainly due to direct heat transfer from the gradient insert to the passive shims [1] which are physically separated but closely located around the gradient insert. Alternatively, resistive parts of the magnet might heat up due to the mechanical vibrations that result from the Lorentz forces experienced by the gradient [2]. This heat will eventually reach passive shims located inside the magnet bore. In addition, the varying magnetic field created by the gradients can result in eddy currents in the passive shims, contributing to the temperature increase in these metal plates [1], [3].

These field drifts that result from scanner operation can be compensated to improve image and spectral quality. Navigator echoes or interleaved reference scans monitor the field during the scan and the compensation can follow either retrospectively or prospectively by updating the RF carrier frequency [4], [5]. Analogously, the reference signal acquired can also be used for correcting the field by a negative feedback applied on the Z0 shim coil current, after calculating the frequency shift from a reference signal [6]. Field locking by monitoring the resonance frequency of a reference sample placed in the magnet is another field compensating mechanism [7], albeit, this technique requires specific hardware which is not available in most horizontal bore MRI systems. In addition, it involves some technical difficulties such as positioning the deuterium probe and sample and dealing with the interference of the gradients in the deuterium signal [6].

Alternatively, the system design may allow stabilizing directly the temperature of the passive shims [3], [8] through feedback operated loops. Recently, a device that is designed to keep the temperature on the surface of the gradient insert at a preset temperature, well above room temperature, was installed by the manufacturer as black box add-on in the system studied here, to meet system specifications. Thus, in this work, we assessed the performance of a high field MR preclinical system under different operating conditions with and without making use of this temperature control mechanism. We demonstrate that the shim heaters are in reality an essential part of our MRI system to minimize field alterations during operation but they are introducing non linear, time dependent frequency alterations due to the feedback control. Thus, additional corrective measures may be required if experiments particularly sensitive to field variations are run interleaved or immediately after long gradient intensive acquisitions.

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2 METHODS

2.1 Equipment/Materials

Measurements were made on an 11.7 Tesla horizontal bore Bruker Biospec 117/16 scanner (Bruker BioSpin, Ettlingen, Germany). The actively shielded BFG-150/90-S gradient insert (Resonance Research Inc. Billerica, MA, USA) has an inner diameter of 90 mm and an outer diameter of 160 mm, and as such fits tightly within the 160 mm magnet bore. The gradient coils are capable of switching 750 mT/m within 90 µs with gradient power amplifier operating at 300 V/ 200 A. Circulating cooling water is pumped through the gradient system at a rate of 5 l/min by a gradient chiller (Affinity Chillers, Lydall Industrial Thermal Solutions Inc., Ossipee, NH, USA)

The shim heaters installed in our system, aim at keeping the temperature of the shim iron constant at a preset target temperature (in our case 42.5 ºC). Hereby, 8 heating coils are integrated into the passive shims to control the temperature of the shim iron. The heating elements can be supplied with a constant current and thus can be switched "on" or "off" to reach the desired temperature. Hereby, pairs of the individual heating elements are monitored by one temperature sensor, so that the shim iron temperature can be adjusted via feedback control independently in 4 different sites. The shim heaters, temperature sensors as well as the preset values are controlled by the independent gradient control thermostat unit (GCTU) and its interface.

2.2 Data acquisition with phantoms

For the measurements with phantoms, a 3 mm NMR tube filled with 20 µl pure water mimicking a punctual source was used as phantom, if not otherwise described.

Prior to all the experiments, magnet stability was measured acquiring Free Induction Decays (FID) every 2 minutes over 15 hours to determine the magnet's natural drift's contribution to the measurements run here.

The performance of the system was assessed operating with and without GCTU that controls the shim heaters. After switching between these two operation modes, the field variation was measured for 12 hours and the rest of the measurements described here were run once the system was thermally stable. Room temperature shim field correction was disabled and the frequency variation was assessed by spectroscopic analysis of repeatedly acquired non- spatially selective FIDs. Except for the spatial dependency measurements, the phantom was placed in the centre of the magnet.

First, the NMR tube filled with pure water was placed inside the magnet and the temperature dependent field drift was quantified by varying the gradient chiller water temperature from 15.5 ºC to 20 ºC. The frequency variation was monitored for 32 minutes (64 FID acquisitions 30 seconds apart) in each temperature increment step. After the 3rd acquisition, the temperature was increased 0.5 ºC or 1 ºC for experiments with shim heaters "on" and "off", respectively. The temperature in the gradient cooling water reservoir would reach the new target temperature within few seconds. The current through the shim and gradient coils was nulled, to reduce any additional heat source in the system.

Second, the magnet drift was also measured by assessing the field variation for 4 hours pulsing gradients at different duty cycles and monitoring the field for 8 hours after gradient pulsing had stopped. All references to "duty cycle" in the document are expressed as a percentage of the allowed duty cycle recommended by the manufacturer (a percentage of all 3 channels on at 200, 195 and 245 mT/ m (in x, y and z, respectively) continuously would be normally regarded 100% duty cycle; the allowed duty cycle is much lower according to manufacturer's specifications: e.g. in single channel operation, the z-coil, 75mT/m gradient is allowed to be continuously on, whereas the x and y-coil are only allowed to handle 70mT/ m continuously). Spectra were acquired every 14 seconds throughout the measurement. During the gradient pulsing period, all three gradients were simultaneously switched on for 999 ms and off during 1 ms. This was repeated 13 times before an excitation pulse with a 10º flip angle was applied to acquire a FID. This block was repeated for 4 hours. An analogous sequence block setting gradients' amplitudes to zero was used to monitor the field drift for 8 hours. The gradient strengths used and achieved allowed duty cycles are given in Table 1.

TABLE 1

	Gradient Strength [mT/m]		
Duty cycle [%]	**X**	**Y**	**Z**
9.8	37.5	37.5	37.5
22.2	56.25	56.25	56.25
43.4	75	75	75
61.6	93.75	93.75	93.75
88.7	112.5	112.5	112.5

Table 1: Gradient strengths applied in each channel and achieved duty cycles

Third, field variation was followed at two different positions (z=0 cm and z= 2 cm) pulsing gradients for 4 hours at 88.7 % duty cycle and monitoring the field for 8 hours after pulsing with the shim heaters switched on. These measurements were performed to study spatial dependence.

2.3 Data acquisition in-vivo

In vivo experiments were conducted in naïve Sprague Dawley rats (n=4, 280-400 g). Animals were anaesthetized with 2% isoflurane in O2 and placed in the scanner in a MR compatible cradle. The animals were covered by a warm water blanket to maintain their body temperature around 37 ºC throughout the experiment. A 72 mm resonator was used for signal transmission, and a dedicated rat brain surface coil for signal reception (Bruker Biospin, Germany). Following the initial acquisition of scout scans, either a baseline standard single voxel MR spectrum or multislice Rapid Acquisition Relaxation Enhanced (RARE) baseline images were followed by a sequence that utilized 88% of the allowed duty cycle for 25 minutes, followed by acquisition of a series of either MR spectra (every 5minutes) or multislice RARE acquisitions (every 90 seconds) to detect the signal differences following the use of gradients, with and without the shim heaters. MR spectra were acquired using a PRESS (Point Resolved Spectroscopy) sequence [9], [10], [11], [12] with the following parameters: TR= 2500 ms, TE= 20 ms, number of averages = 64, voxel size = 3x3x3 mm3; water suppression scheme (VAPOR [13] with Gaussian pulses and a 300 Hz bandwidth). Fastmap shimming [14] on a 4x4x4 mm3 voxel and the adjustment of the resonance frequency was only executed directly following the scout scan. No readjustments were performed thereafter. The multislice RARE protocol consisted of the following parameters: TR = 2812 ms, TE =24 ms, RARE factor 8, slice thickness 1mm, 8 slices with a 2mm interslice gap and a field of view of 32x32 mm2 with a 256x256 matrix. The read-out bandwidth was 12820 Hz, yielding 50Hz/ pixel in read-out direction to be able to visualize potential image shifts.

CIC biomaGUNE is an AAALAC accredited institution. Rats were held in groups in individually ventilated cages and manipulated in safety cabinets with HEPA filters. All the animal procedures were performed in accordance with the Spanish policy for animal protection (RD53/2013), which meets the requirements of the European Union directive 2010/63/UE regarding the protection of animals used in experimental procedures. The study was approved by the ethical committee of CIC biomaGUNE (AE-Biomagune-1413) and authorized by the regional government (PRO-AE-SS-041).

2.4 Data analysis

The repeatedly acquired non spatially selective FIDs were processed with Paravision 5.1. (Bruker Biospin GmbH, Ettlingen, Germany). The spectral processing software MNova v.7.1.1. (Mestrelab Research S.L., Spain) was used for automatically determining the frequency position of the peak to track it over time, determining in this way the field variation.

The time to reach thermal stability was calculated by fitting the monoexponential function $f(t) = A_0 + A_1 \exp(-t/t_{reco})$ to the acquired data using Matlab 7.5. (The Mathworks Inc., Natick, MA, USA). The recovery time, t_{reco}, is the time needed to reach or recover 69.3% of the total field variation whereas the time to reach thermal stability was defined as 5 times t_{reco}.

3 RESULTS

3.1 Phantom Studies

The magnet drift was measured with and without using the shim heaters. In both cases, the overnight drift was extremely small, below 1 Hz/h, well within the magnet specifications (25 Hz or 0.05 ppm/h). The transition of the field by switching the shim heaters on and off (and thus indirectly changing the temperature of the passive shims from 42.5 Celsius to room temperature) resulted in a frequency variation of 3900Hz (7.8ppm) over several hours. As expected, the time to reach thermal stability was almost 17% shorter when switching the shim heaters on (2h), compared to when it was switched off (2h20min).

An easy test to evaluate the sensitivity of potential frequency alterations due to gradients heating up during operation is to just alter the temperature of the cooling water that is constantly supplied to the gradient, thus, eliminating all confounding factors like vibrations and eddy current induced heating when pulsing gradients. We changed the chiller temperature setting between 15.5 and 20 ºC. With the shim heaters switched off, this resulted in changes of 0.3 ppm/ºC in the resonance frequency of water and the field varied approximately linearly (Figure 1). However, when the shim heaters were switched on, with the unit set to achieve a preset temperature of 42.5 ºC, the behaviour was different. Again, increasing the water temperature in the chiller from 15.5 to 20 ºC, resulted initially in a near linear drift of the resonance frequency of 0.17 ppm/ºC. Importantly, when water cooling temperature was set to values higher than 18.5ºC, heaters would switch off for the required amount of time and compensate in this manner for the extra heat arising from higher water temperatures. In this way, the temperature of the passive shims remained unchanged and thus, no further increase in the resonance frequency could be observed in the temperature ranges studied. Interestingly, upon installation, our system was set to reach 42.5 ºC surface temperature with a gradient chiller temperature of 18 ºC. As seen from this behaviour, an increase in chiller temperature reaching 18.5 ºC or above is causing a slight increase in resonance frequency, indicating that under the set working conditions the heaters are "on" all the time, but do not reach the preset temperature of 42.5 ºC in the temperature sensor. It is important to note that the variations seen here are not due to sample heating, as the temperature dependency of water protons is approximately 0.01 ppm/ºC (15).

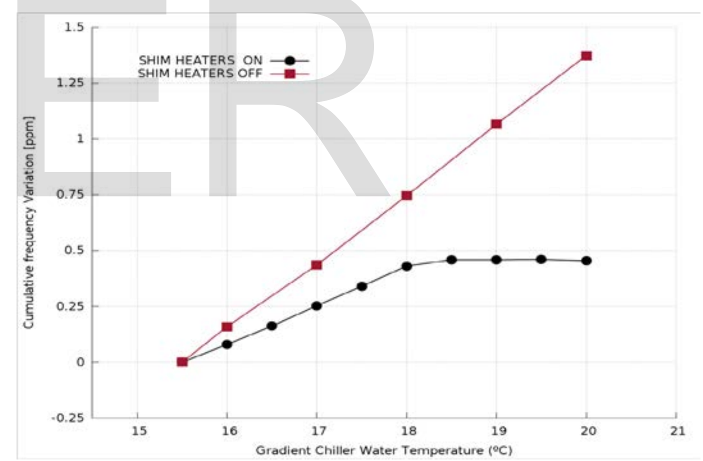

Figure 1: Cumulative frequency variation observed when the gradient cooling water temperature is changed manually in the gradient chiller with the shim heaters switched on and off. Results obtained using a 3 mm NMR tube filled with pure water.

Using the gradient under standard operating conditions at different duty cycles, with and without the use of the shim heaters, results in resonance frequency changes (Figure 2). The shim heaters considerably reduced the magnitude of the variation. Nevertheless, whereby the resonance frequency changed from one steady state condition to another in an exponential manner when the shim heaters were switched "off", the observed frequency alteration with the shim heaters "on" was completely different (Figure 2a and 2b, respectively). With the shim heaters "on", initially, within seconds, the resonance frequency increased (due to the heat generated by the pulsing gradients). As described above, this can be easily explained with our specific setting, as initially the heaters are "on" 100% of the time, without being capable of reaching the preset surface temperature of 42.5 ºC. Thereafter, as the gradient use constantly continues to dissipate more and more heat within the gradient insert, the individual temperature sensors might observe higher temperatures than pre-determined and desired. This in turn triggers that the individual heaters will be switched off as long as the temperature is equal or above the preset level (in our case 42.5 ºC). When the heaters switch off, locally the temperature drops, whereby the decrease in the resonance frequency implies that overall the temperature of the passive shims elements drops (see Figure 2b). The explanation for this is that heating elements are integrated adjacent to the passive shims within the magnet bore and thus have a strong influence on the temperature of these elements.

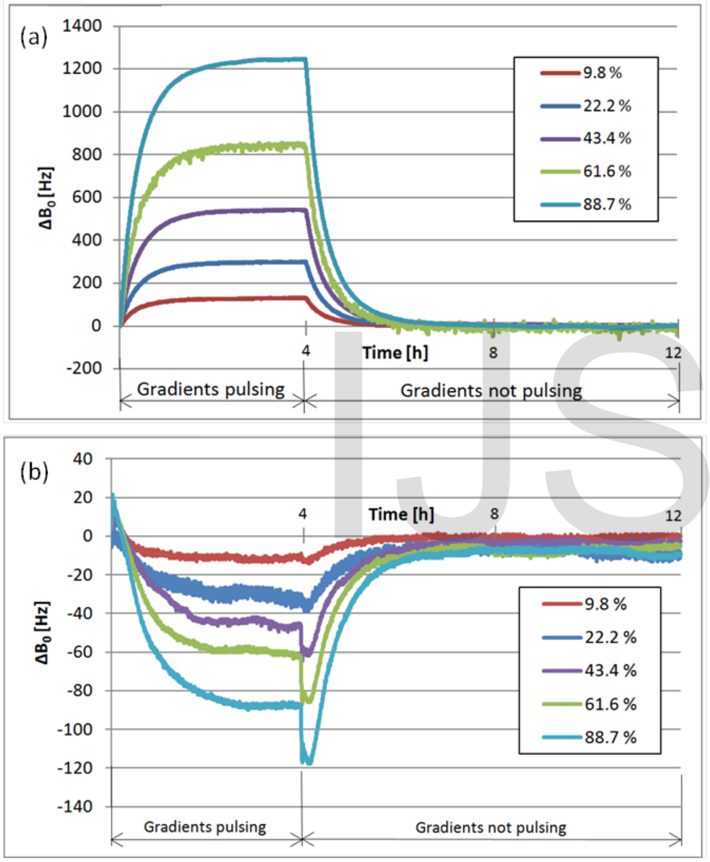

Figure 2: Frequency variation measurements during 4 hours of gradient use and the field variation for the following 8 hours for various duty cycles with (a) shim heaters off, (b) shim heaters on

When we stopped to pulse the gradients, we again observed totally different temporal behaviours with and without the shim heaters. Without the shim heaters, the return to baseline followed an exponential recovery trend. With the shim heaters switched "on", we observed a very fast initial drop in resonance frequency, indicating an additional sudden drop in temperature of the passive shims. Upon halting to pulse the gradients, the heat generating source is instantly zero. It appears that the heat is very efficiently taken away by the gradient water cooling and thus, results in an overall sudden drop of the temperature of the gradient insert and the passive shims. After roughly ten minutes, the trend changed and heaters heated up the gradient surface until baseline was reached.

Additionally, we explored the spatial dependence of the above observed field variation in one additionally point off-centre. The field variations observed for the same gradient duty cycle (88.7%) with the use of the GCTU at two different points varied considerably (Figure 3a), as the trend followed by the field at a given point lays on the combination of the geometry of the passive shims, their position in space and heat dissipation pathways.

3.2 In Vivo Studies

Standard in vivo measurements with the shim heaters on and off were performed in order to study magnet drift influences under real life experimental conditions. For this purpose, MR Spectroscopy as well as the RARE imaging method were selected to visualize frequency drift after the application of 88% duty cycle.

3.3 MR Spectroscopy Experiments

Spectroscopy was carried out in a representative voxel of the rat brain with the shim heaters on and off (see Figure 3b and 3c, respectively). These results reflect the effectiveness of the shim heaters since when they were switched on the maximum frequency drift was around 6 Hz. Albeit small, this frequency drift is much larger than the observed frequency drift per hour and is causing spatial dependent line broadening. For volume selective 1H MR spectroscopy, navigator echoes might be acquired to improve the quality of the spectra; especially heteronuclear experiments that require signal averaging, like 31P or 13C MRS or chemical shift imaging (CSI), may suffer from the resonance frequency oscillations. Having said this, when the shim heaters were off, the maximum frequency drift was 612 Hz approximately moving extremely fast immediately after pulsing gradients and giving rise to a completely distorted water line peak as a consequence of fast field drifts and averaging. Figure 3c displays how such distortions of the water line peak remain for at least 50 minutes after pulsing gradients. This frequency drift is recovering slowly at the same time that water suppression is getting more and more effective. Importantly, water could be properly suppressed only after roughly 110 minutes (Figure 3c). The observed frequency drift and recovery times strongly depend on the duration and intensity of a previous, gradient intensive experiment (see Figure 2) and thus, field drifts might be larger or smaller than reported for the selective in vivo experiments.

3.4 MR Imaging Experiments

Axial images of the rat brain were acquired with the shim heaters on and off (see Figure 4, upper and lower row, respectively) to visualize image drifting. Images on the first column correspond to the images acquired before pulsing gradients with 88% duty cycle, whereas the others are the subtracted images of the different time points with respect to the reference (before pulsing). These results reflect a much bigger difference between baseline and subsequent images when the shim heaters were off confirming in this way the results obtained by spectroscopy (Figure 3b and 3c).

4 DISCUSSION

Experiments conducted here show that the field drifts due to the heat generated during MR scanning in the high field preclinical MR system studied. The contribution of the magnet drift to the observed field variations measured can effectively be neglected, as the drifts assessed were 0.001 ppm/h and 0 ppm/h with the shim heaters off and on, respectively. Moreover, the variations seen are not due to sample heating, as the temperature dependency of water protons is approximately 0.01 ppm/ºC [15]. Given that it takes at least 2 hours for the system to completely stabilize when the state of the shim heaters are switched (on/off), it is not advisable to switch the shim heaters off overnight if experiments are planned early morning.

By changing the gradient water cooling temperature the temperature dependence of the field was qualitatively assessed. Results show that the magnetic field changes linearly with the temperature. This dependency was almost twice as high with the shim heaters off compared to when this device was switched on. Switching the shim heaters on, increases the overall temperature of the gradient insert, with cooling water supplying 5 l/minute at 32 psi at 18 ºC, and surface heaters trying to warm up the shim iron to 42.5 ºC. Thus, only altering the temperature of the cooling water of the gradients increases the overall heat dissipation to the passive shims differently, depending if the shim heaters are switched "on" or "off".

The system evaluated in this work has the shim heaters set to a target temperature of 42.5 ºC. Even with an increased chiller temperature (with flowing water at 18 ºC) and all heaters on 100% of the time, the target temperature could not be reached. To achieve this, the gradient cooling temperature would have to be increased even further. Increasing the temperature of the cooling water for the gradients is counterintuitive. Normally, the chiller temperature is set to a minimal value, low enough to carry away the heat generated by the gradients use as efficiently as possible, but high enough not to have condensation within the magnet bore. In practice, most MR systems operate at a chiller temperature between 12 and 15 ºC. However, when the gradient cooling water was set lower than 18 ºC, heaters would be on 100% of the time, and the overall temperature as well as the temperature of the surface would be substantially below 42.5 ºC. The use of gradients would result in large frequency changes. Thus, 18 ºC is a compromise to limit the maximum frequency variation. Users of systems with a temperature control unit, similar to the one described here, should be aware that the temperature of the gradient cooling water affects the performance of their system and that, lowering this temperature might not increase system performance.

As outlined, gradient use is the main source of heat generation within a MR scanner. When they were pulsed without any temperature control mechanism, the field drift observed on our system was considerable (Figure 2a). In fact, frequency variations of several hundreds of Hz (>1 ppm) were observed after only 1 hour gradient operation for higher as well as lower duty cycles. This variation, if left uncorrected, is unacceptable for many practical MR applications. This order of magnitude of frequency variations has not been observed in older MR preclinical systems. A main difference is that at 11.7 T, a new, much more expensive superconducting material is being used with non pressurized Helium cryo-cooling. To minimize the costs, the bore size of the magnet is minimized, and thus, with an overall compact design, it appears that unfortunately the heat transfer from the gradients to the passive shims is getting more efficient when compared to systems with a larger bore size using smaller gradient inserts.

The use of the GCTU to control the shim heaters effectively reduces the magnitude of the field variation by over 90 %, as seen in Figure 1 and Figure 2. Nevertheless, depending on the gradient use, the magnitude and trend of the remaining field changes displayed in Figure 2b cannot be neglected. Navigator echoes will compensate for the field drift as it will update the RF frequency either prospectively or retrospectively [4], [5], [8]. In the magnet studied here, however, the field presents some spatial dependencies, especially along the longitudinal axis of the magnet (Figure 3a). Hence, the correction will not be equally effective in all points in space. In this case, computing field maps and approximating the field with an adequate function, similar to [2], seems to be more effective to solve the field instability problem if required.

As seen in Figure 3a, when the shim heaters are on, the field variation follows a pattern that is not possible to characterize with a continuous polynomial function after gradients start or stop pulsing. If this is ignored and the field variation is approximated to a linear or exponential pattern, the correction will be suboptimal. When deciding on possible ways to work around this problem, two scenarios can be distinguished: (i) the field needs to be corrected during the gradient intensive sequence such as a long fMRI measurement, for example; (ii) the gradient intensive sequence has finished and a sequence sensitive to field inhomogeneities and stability needs to be run, for instance single volume spectroscopy or chemical shift imaging following a high resolution anatomical scan. In the first scenario, dummy scans can be introduced in the beginning of the acquisition until the system is driven to a condition in which the field variation can be modelled by a polynomial function. In the second scenario, waiting until the field changes its trend and starts drifting back to baseline before the field sensitive sequence begins with the corresponding corrective measure would be the most convenient strategy. As seen in the in vivo experiments, studies without heating of the passive shims will make even simple standard MR protocols difficult to interpret, and thus, it is recommended to leave the GCTU on.

5 CONCLUSION

Although the magnet and the gradient insert performed better than their specifications when measured independently, the overall performance was questionable under standard scanning conditions. Observed field drifts can be mainly attributed to the heating of passive shims so the commercial, feedback-controlled, gradient coil thermostat unit described here becomes effectively an essential part of the system. Given that it takes at least 2 hours for the system to completely stabilize when the state of the shim heaters are switched (on/off), it is not advisable to switch the shim heaters off overnight if experiments are planned early morning.

The thermostat unit is effective to reduce field instability issues caused by gradient heating to a great extent. Remaining field variations observed will not affect most regular anatomical imaging methods, as the Hz/pixel is usually large enough for the variations observed, Applications like fMRI, resting state fMRI, MR thermography and MR spectroscopy, might require additional temporal field correction approaches such as navigator echoes, dummy scans or a waiting period between acquisitions.

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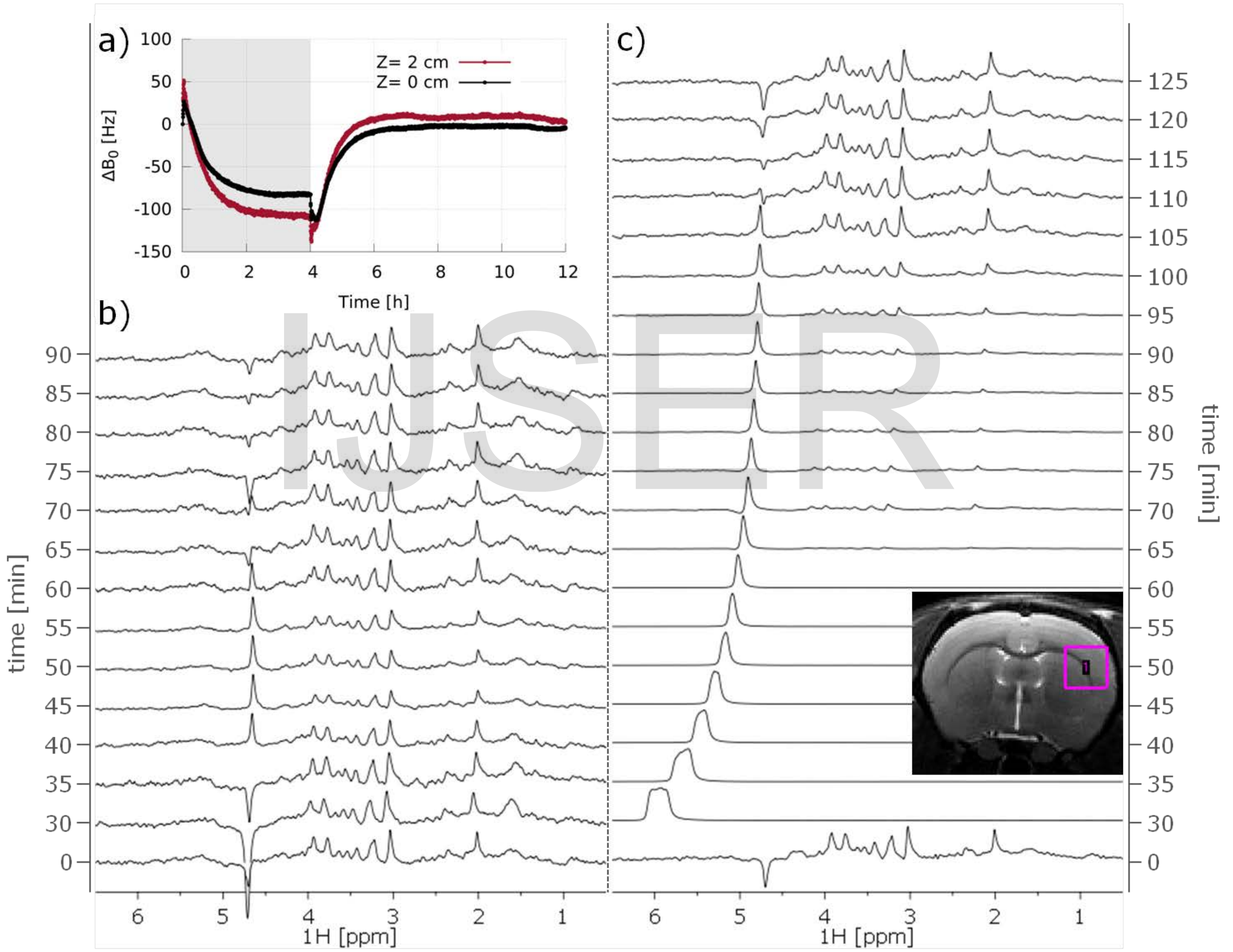

Figure 3: Field variation observed at z=0 cm and z= 2 cm when pulsing gradients at 88.7% duty cycle for 4hours and acquiring the field variation for 8 hours thereafter with the shim heaters on **(**a). A time series of *in vivo* MR spectra acquired every 5 minutes with the shim heaters “on**”** **(**b) and “off**”** **(c**) following an experiment that utilized an 88% duty cycle for 25 minutes. At baseline, the spectrum was acquired following FastMap shimming. Directly following the gradient intensive experiment (30 minutes +), the field drift was so large that the water line appeared in a rectangular shape due to combination of very fast drifting fields and signal averaging when the shim heaters were switched “off”**.**

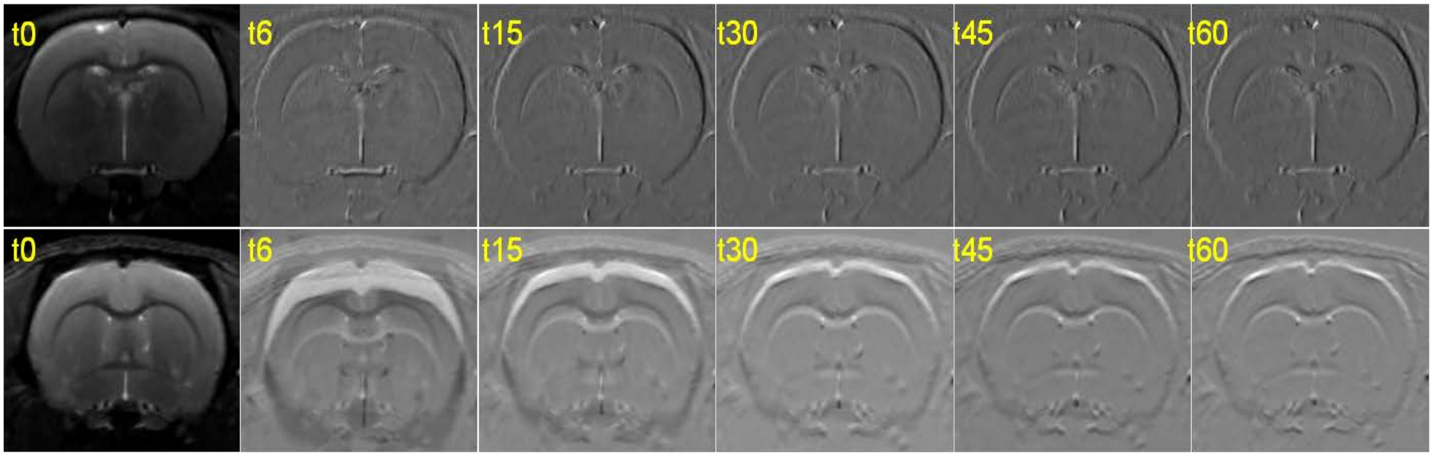

Figure 4: A time series *of in v*ivo image was acquired with a RARE sequence either the shim heaters “on” (upper row) or “off” (lower row) following the application of 88% duty cycle experiment for 25 minutes. The image on the left is the original image (t0) and subsequent images are difference images ranging from 6 to 60 minutes**.**