

## Easy characterization of the radio-frequency field of $^{13}\text{C}$ NMR coils with aluminium-27 NMR

P. Jehenson\*

*Service Hospitalier Frédéric Joliot, CEA, 91406 Orsay, France*

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\* Correspondence and reprints.

### RÉSUMÉ

La détermination de la distribution du champ radio-fréquence de sondes de Résonance Magnétique Nucléaire (RMN) est difficile et prend du temps dans le cas du carbone 13 qui a une faible sensibilité et est utilisé, par exemple, dans les études *in vivo*. Nous montrons ici que cela peut être fait plus simplement et rapidement en utilisant la RMN de l'Aluminium 27 (bien meilleur rapport signal/bruit et temps d'acquisition plus court pour les spectres et les images, même distribution de champ mesurée, échantillons/fantômes beaucoup moins chers).

**Mots-clés:** RMN, sondes Radio-Fréquence, distribution champ Radio-Fréquence, Aluminium 27, Carbone 13.

### ABSTRACT

Determining the Radio-Frequency field distribution of Nuclear Magnetic Resonance (NMR) coils is difficult and time-consuming for the low sensitivity carbon 13. We show that this can conveniently be done using Aluminium-27 NMR (much larger signal/noise ratio and shorter acquisition time for both spectra and images, same measured field distribution, much cheaper samples/phantoms).

**Keywords:** Nuclear Magnetic Resonance (NMR), Radio-Frequency coil, Radio-Frequency field distribution, Aluminium 27, Carbon 13.

It is often essential to dispose of the Radio-Frequency (RF) field distribution of NMR RF-coils and several methods can be used (such as calibrating a pulse at various positions or qualitative or quantitative imaging) [1-3]. However, obtaining a good signal-to-noise ratio (SNR) remains difficult and time-consuming for nuclei such as carbon 13 ( $^{13}\text{C}$ ), which has low sensitivity and only 1.1% natural abundance (even concentrated substances like pure oil, mainly -CH<sub>2</sub>- chains, yield poor SNR). Furthermore,  $^{13}\text{C}$ -enriched compounds are expensive, particularly for large concentrated phantoms covering the sensitive region of in vivo coils (typically ten thousand dollars for a 2 Molar 1 liter phantom).

We here suggest to use aluminium 27 (Al) to overcome these difficulties and characterize the RF field of  $^{13}\text{C}$  coils.

$^{27}\text{Al}$  resonates close to  $^{13}\text{C}$  (only 3.6% higher resonance frequency), is 100% naturally abundant and has a sensitivity of about 0.2 times that of the proton for an equal number of nuclei, as compared to 0.016 for  $^{13}\text{C}$  ( $1.76 \times 10^{-4}$  when accounting for natural abundance) [4]. The much larger sensitivity of  $^{27}\text{Al}$  than  $^{13}\text{C}$  (spin 1/2) is due to its spin  $I=5/2$ . Indeed, magnetization and hence signal is proportional to  $I(I+1)$ , i.e. a factor of 35/3 in favour of Al (differences in gamma are here negligible) [4, 5]. A typical gain in sensitivity of at least 10 with respect to  $^{13}\text{C}$  is therefore expected, for an equal number of nuclei, even when considering  $^{13}\text{C}$ -enriched compounds (for instance, factor 13 for identical concentrations of  $^{13}\text{C}$ -enriched formate and Al-nitrate, or factor 40 between pure unenriched oil and a 2 molar (M) solution of Al-nitrate). Also, a compound like Al-nitrate is cheap and soluble in water. Another potential candidate, sodium, resonates further from  $^{13}\text{C}$  and is twice less sensitive than Al.

The adequacy and advantages of using Al-NMR were experimentally confirmed as follows.

Experiments were performed on a 3 Tesla 1 meter diameter NMR system. The same commercial 10 cm diameter " $^{13}\text{C}$ " surface coil was either tuned to  $^{13}\text{C}$  or  $^{27}\text{Al}$ .

Two equivalent 1.8 cm diameter spheres, one with 4.2M 99%- $^{13}\text{C}$ -enriched formate, the other with 2M Al-nitrate, were used to compare the RF field (B1) distribution for Al and  $^{13}\text{C}$ , as determined from pulse angle calibrations at various positions in space. In practice, the 180° pulse length was determined (at constant amplifier output power).

The SNR was also compared, for a simple  $90^\circ$  pulse scan with the spheres placed at 2 cm from the coil center.

Gradient Echo images were obtained from a 1 liter phantom of 1M Al-nitrate for  $^{27}\text{Al}$  and pure unenriched oil for  $^{13}\text{C}$  (a  $^{13}\text{C}$ -enriched phantom of that size would be very expensive).

There was very good agreement between the B1 distribution as determined by Al and  $^{13}\text{C}$ , with a maximum difference of 6.7%.

The SNR (for a single  $90^\circ$  pulse, and a sphere at 2 cm from the coil center) was about 8 times larger for Al than for  $^{13}\text{C}$ , even though formate was fully  $^{13}\text{C}$ -enriched and more than twice as concentrated as Al nitrate (theoretical value = 6.3).

Fully relaxed Al images were very easily obtained in 2 minutes (repetition time TR 500ms, echo time TE 30ms,  $64 \times 64$  matrix, field of view (FOV) 20 cm, 10 mm slice thickness, pixel SNR of about 40). Acquisition of  $^{13}\text{C}$  images with a similar SNR and acquisition time needed 30 times larger pixels and non-fully relaxed conditions (TR 75 ms vs. T1 of oil of about 300 ms). Alternatively, many hours of acquisition were needed to get fully relaxed  $^{13}\text{C}$  images with pixel characteristics similar to those of Al images.

Relaxation times were estimated (not precisely measured). T1 estimates were about 300 to 500 ms for Al-nitrate and 8 to 13 s for  $^{13}\text{C}$ -formate (determined from signal saturation at various TRs). Linewidth were obtained after a simple automatic x, y, z shim. They were 7 to 8 Hz for Al-nitrate and 3 to 5 Hz for  $^{13}\text{C}$ -formate, giving  $T_2 > 42$  ms (and probably  $T_2 < 125$  ms) and  $T_2 > 64$  ms, respectively.

T1 relaxation times are thus further strongly in favour of Al-nitrate. Of course, they depend on magnetic field, compound, etc., however,  $^{13}\text{C}$ -formate is one of the cheapest and simplest carbon compounds (easy to manipulate, soluble in water and relatively cheap). Also, it is convenient, and needed for imaging, to have a single, or largely predominant, carbon peak. Carbon T1s can be shortened with relaxation agents, but defining the proper conditions is not always fast and easy.

As far as Al-nitrate is concerned, many other cheap compounds are little soluble in water and at least some have very broad lines.

The linewidth was only 7-8Hz for Al-nitrate (with a quick shim), and 3-5Hz for  $^{13}\text{C}$ -formate. The difference could be due to the effect of quadrupolar broadening for Al because of its spin  $> 1/2$ . The advantage for  $^{13}\text{C}$  sensitivity is, however, not very large for determination of pulse lengths on spectra or fid (unless much narrower linewidth can be obtained on formate and not on Al-nitrate, by shimming, but this, if at all possible, is time-consuming). The advantage would be small or inexistent for imaging, since signal-to-noise can only be gained if the smallest usable gradient strength is limited by the linewidth of a few Hz. In this unlikely case, being able to reduce the gradient strength by a factor of 2 for  $^{13}\text{C}$  (adjustments would be quite time-consuming), would yield a gain of square root 2, i.e. 1.4, in SNR.

The quadrupolar broadening for Al is, therefore, of little importance here (at most 7-8 Hz), in the present experimental conditions (3 Tesla and the "classical" sample solutions chosen).

So, the B1 distribution of  $^{13}\text{C}$  coils can be determined with  $^{27}\text{Al}$ . Experiment time is much shorter for Al than for  $^{13}\text{C}$  (minutes vs hours), because of the much higher SNR (typically over 10 times), as expected from theory, and of shorter relaxation times for usual substances. This includes easy and fast setup of proper experimental parameters, for both spectroscopy and imaging. Furthermore, Al-nitrate is over 2000 times cheaper than  $^{13}\text{C}$ -enriched formate (and yields 10 times better SNR), which allows large phantoms to be used and good B1 distribution images to be obtained.

In conclusion,  $^{27}\text{Al}$ -NMR is convenient to obtain  $^{13}\text{C}$  RF coil field distribution.

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