Measurement 77 (2016) 29–33

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Noise and interference in measured NMR images

Peter Andris *, Ivan Frollo

Institute of Measurement Science, Slovak Academy of Sciences, Dúbravská cesta 9, Sk-841 04 Bratislava, Slovakia

A R T I C L E I N F O

Article history:
Received 25 June 2015
Received in revised form 12 August 2015
Accepted 1 September 2015
Available online 5 September 2015

Keywords:
Noise
Interference
NMR
MRI
Image
Measurement

A B S T R A C T

This article describes the measurement and evaluation of noise and interference in experiments with nuclear magnetic resonance (NMR). Their presence in experimental results causes irreversible artefacts in measured images or errors in the calculated values of investigated quantities. Noise in the signal also reduces the sensitivity of the measuring instrument. From the point of view of results, there is no significant difference between noise and interference. Both signals are multi-frequency or have a changing frequency, meaning that they must be characterised using their power or root mean square (RMS) values of voltage or current. The RMS voltage at the output of the NMR receiver with a receive coil in its input was measured using an NMR console and compared to thermal noise voltages of known sources, e.g. resistors with known resistivity in the input of their receiver. The comparison indicates the possible inherence of interference. The noise measurement using the console was performed in two ways: using an acquisition only and using a complete measuring NMR sequence, which resulted in an image. The results served to test the quality of the hardware used for NMR experiments. It has been proven that the presented method is suitable for testing and improving the signal-to-noise ratio of NMR scanners without the need for the accumulation of seldom-used expensive instrumentation.

1. Introduction

The quality of the results of nuclear magnetic resonance (NMR) experiments depends on the resulting signal-to-noise ratio (SNR). A good SNR can be acquired in many ways: noise and interference can be reduced to a sufficiently low value, the number of averaged results can be increased, or dedicated tools for SNR improvement can be utilised. SNR is calculated as a ratio of the statistically determined values of signals both from the experiment and noise (including respective interference). The calculation nevertheless tells us nothing about whether the value of the noise is sufficiently low. In our experiments noise was measured using a calibrated NMR console and compared to the thermal noise value of the same receiver with a known value resistance in its input. Moreover, the theoretical thermal noise value for the resistance and receiver was calculated. The good agreement between the measured and calculated values indicates low interference in the experiment. The resulting noise and interference can be measured in many ways; in our experiments a calibrated NMR console was utilised as a measuring instrument. Firstly, the investigated noise signal was acquired and digitised and the root mean square (RMS) value was calculated [1,2]. Secondly, a suitable image was measured and a region of interest (ROI) was selected. From the ROI data the RMS voltage was calculated. Thanks to the calibration of the console in both cases the real voltages were measured, which can be compared to the theoretical values of thermal noise. A possible difference indicates interference in the experiment and its grade. Measurement with an image is similar to the conventional

* Corresponding author.
E-mail addresses: peter.andris@savba.sk (P. Andris), ivan.frollo@savba.sk (I. Frollo).

http://dx.doi.org/10.1016/j.measurement.2015.09.003

measurement of SNR in magnetic resonance imaging (MRI). The difference and novelty of the presented method is in the use of the calibrated NMR console receiver and the way in which the measured data are mathematical processed. The presented equations provide the results as a real voltage which can be easily compared to calculated results or to results from different experiments. As a verification of the presented formulae and method, several calculations and experiments have been performed. The noise voltage from the resistively matched preamplifier, recalculated into the input of the preamplifier, was calculated. Similarly, the noise of the preamplifier was measured with its input terminated by a matching resistor using the NMR console and the noise voltage was calculated. The experiment was repeated with the preamplifier input terminated by an empty matched receive coil. Further experiments were based on image measurements. A sample was measured with spin echo (SE) and with gradient-recalled echo (GRE) sequences. Two regions of interest were selected in each of the images for which noise was investigated. The acquired results were processed into figures and into a table. The numerical results are averages from at least three measurements. Some theoretical and experimental questions of signals and noise in NMR techniques are solved in Refs. [3–18]. Refs. [19–21] are focused on properly processing the measured data. The theory and results described in the presented article are useful for technical and experimental practice as well as a platform for future theoretical studies. Moreover, the article offers further utilisation of the NMR console, which is available in every NMR workspace.

2. Theory and methods

Unlike noise, which is a random signal, interfering signals may be deterministic. When received by an NMR console, both signals are filtered and the power or RMS value of their voltage or current is of interest. If the noise figure F of the receiver and its input impedance are known, the influence of the interference on the resultant sensitivity can be estimated. Consider a receive coil connected to a receiver similarly to Fig. 1. Let the NMR signal equal 0. The only signals received by the receiver are noise and interference. Thermal noise is always present and can be easily calculated. A matched preamplifier with input resistance R_{in} produces an RMS voltage (recalculated into its input):

$$V_n = \sqrt{F} \cdot \sqrt{4kT0.5R_{in}2\Delta f}, \quad (1)$$

where $k = 1.38 \times 10^{-23}$ W s/K is the Boltzmann constant, T is the absolute temperature of both the resistances R_{in} and source resistance to it matched (therefore 0.5 R_{in}), and $2\Delta f$ is the frequency bandwidth of the console (the frequency interval between $f_0 - \Delta f$ and $f_0 + \Delta f$). An equivalent interfering RMS voltage $V_{\text{interfering}}$ (filtered to the frequency bandwidth of $2\Delta f$) completes the noise voltage (1) as:

$$V_{\text{resulting}} = \sqrt{V_n^2 + V_{\text{interfering}}^2}. \quad (2)$$

The revised noise figure of the interfered console receiver F_{rev} can be expressed as:

$$F_{\text{rev}} = \frac{V_{\text{resulting}}^2}{V_n^2} F = \frac{V_{\text{resulting}}^2}{4kT0.5R_{in}2\Delta f}. \quad (3)$$

In practice, the $V_{\text{resulting}}$ voltage can be measured using the NMR console [1] and compared to the theoretical value (1). The smaller the difference observed between both values, the less interference the receiver has. In an NMR experiment the matching resistance is replaced by a matched coil (Fig. 1) containing a measured sample. An interesting question is as to how accurately the matching resistance can be replaced by a matched coil. Fig. 2 depicts calculated RMS values of noise for matched coils and a matching resistance of 50 Ω. It is obvious that for technical practice and the fact that the frequency bandwidth is not too wide that the replacement is fully acceptable. The matching device values for the coils were calculated using the theory in [3]. The measurement using the console can be performed in two ways; each way requires calibration of the console. The console can only be utilised for acquisition of noise, and $V_{\text{resulting}}$ is possible to calculate using suitable or modified formulae, e.g. in [1]. Alternatively, a suitable image can be measured using the whole NMR hardware and the measured data can be utilised for the $V_{\text{resulting}}$ calculation.

Consider an array of n complex values representing time samples of noise or data for the image construction:

$$v = v_0, \ldots v_{n-1}. \quad (4)$$

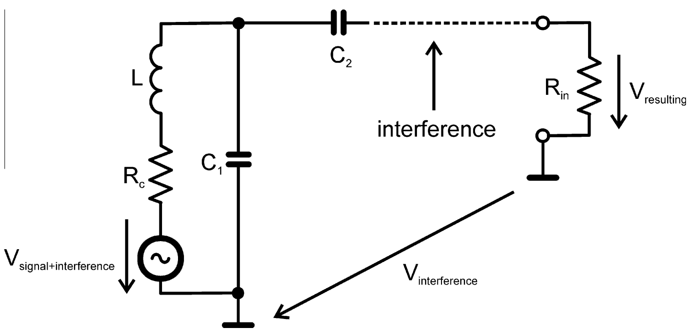

Fig. 1. A matched and tuned receive coil in an interfering environment.