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Note: Magnetic noise from the inner wall of a magnetically shielded room

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We measured the thermal magnetic noise generated by the inner high-permeability wall of a magnetically shielded room. This room houses a magnetoencephalogram (MEG), which contains 102 "small" identical magnetometers. For the measurement, we created two large magnetometers by summing the outputs of 46 magnetometers equally on the helmet's left and right side, to look at the summed noise of the right and left vertical walls. From these summed outputs, we calculated the rms noise amplitude due to all six walls at the MEG location to be ∼0.5 f T/$\sqrt{\text{Hz}}$ at 100 Hz, only slowly rising with lower frequency. This is well below the system noise of each small MEG magnetometer, hence is negligible for the MEG. [http://dx.doi.org/10.1063/1.4802845]

The magnetically shielded room (MSR) plays an important role in the technology of brain imaging; every magnetoencephalogram (MEG) detection system[1,2] is now enclosed inside an MSR,[3] where the purpose is to exclude external magnetic fluctuating disturbances from the sensitive MEG detectors. The MSR is generally made up of alternate layers of metal with high permeability, such as moly-permalloy, and metal with high conductivity, usually aluminum. The high permeability layers shield equally against any frequency of external disturbance, as the induced poles counter the external field. In the high conductivity layers, eddy currents are induced which oppose the fluctuating external field, the effect rising with frequency. But the inner wall, nearly always chosen to be the high permeability metal, can itself be a source of magnetic noise[4] because of thermally generated electronic current (Johnson-noise) and magnetic domain motion (related to "magnetic viscosity"). If these two thermal noises are large enough, they could interfere with MEG measurements, hence it is important to know their magnitude. Although several groups have estimated this noise theoretically,[5–8] and performed measurements of noise from small simple shield geometries,[6,7] there have been no direct measurements from the inner wall of an actual, full-size room. We here present such direct data.

An actual, direct measurement is necessary because the theoretical estimates for small, simple geometries when extrapolated to a full-size room can lead to considerable error. These estimates were performed by two groups. First, a Helsinki (Finland) group calculated the magnetic noise from simple high-permeability metal shapes due to Johnson noise,[5,6] but did not include the thermal domain noise, hence the estimates may have been too low. They also performed noise measurements from simple shapes of high-permeability metal,[6] but in their case the extrapolation to a large room is mathematically very cumbersome. Second, a Princeton (U.S.) group calculated the noise from simple high- permeability shapes and included domain noise,[7] but the extrapolation to a large room is again difficult. However, they also measured the noise in a small ferrite shield,[8] which indeed allowed some extrapolation to a large room. This yielded ∼0.7 f T/$\sqrt{\text{Hz}}$ as the three-dimensional noise amplitude at low frequencies, say >10 Hz; but Johnson noise was neglected here. Concerning the frequency (f) dependence, the various theoretical calculations show a variety of complex dependencies, almost all in the range of f^0 to $f^{-\frac{1}{2}}$, that is, they all show only a slow rise with decreasing frequency.[7] All in all, a direct noise measurement would therefore be valuable.

We performed the measurement by using most of the 102 magnetometers in our MEG system, a VectorView made by Elekta Neuromag Oy. These magnetometers are oriented approximately parallel to the scalp thereby sensing the component of magnetic field approximately normal to the scalp. From these "small" magnetometers, we created two extra-sensitive large-area magnetometers by summing the output amplitudes of 46 identical magnetometers equally on the right (*r*) and left (*l*) sides of the MEG helmet, with *r* and *l* as seen from an imaginary MEG subject's point of view. The output was a weighted amplitude sum of 46 small magnetometers on each side. That is, we have twice "tied together" 46 small magnetometers to make two large magnetometers, with higher signal/noise ratio (S/N) than each of the small ones. This was necessary because the estimates suggest the wall noise should be well below the system noise of each MEG small magnetometer, hence would not be directly measurable with these small units.

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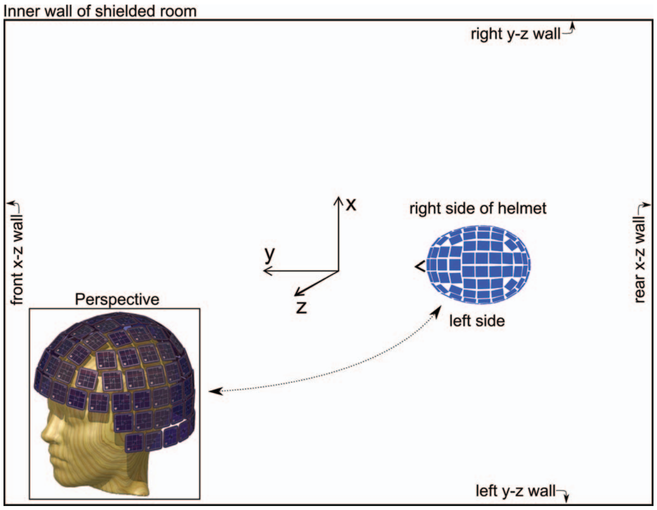

FIG. 1. Looking down on the inner layer of the MSR, with inside dimensions of 3.0 m (in x), 4.0 m (in y), and 2.4 m (in z). This layer consists of four sheets of 1 mm moly-permalloy, mounted on a high-conductivity aluminum layer of 10 mm thickness. The MSR contains the MEG helmet with 102 magnetometers (small squares), of which 46 on each side are summed separately, to make two large magnetometers. These measure the magnetic noise in the x-direction, generated thermally in the left and right walls. The nose of an imagined MEG subject is seen at the left of the helmet. The inset is a perspective view of the same helmet.

The setup is shown in Fig. 1, where the purpose is to measure the magnetic noise in the x-direction due to the two vertical *y-z* walls, right and left. We used open-source MEG processing software Brainstorm[9] to compute these geometrical properties of the magnetometers. We assign different weights to each small magnetometer, equal to the cosine of its angle to the *x*-axis, as implied in Fig. 2. The effective area of each large magnetometer is thus calculated to be 28 times the small area, or 56 times when both are summed or subtracted, hence increasing the S/N by a factor of $\sqrt{56} = 7.5$. We have, here, assumed uncorrelated noise in each small magnetometer. However, it is known that some of the MEG system noise is due to the Johnson noise in the r-f shield of the dewar,[10] which would correlate some of the noise in neighboring small magnetometers; the net effect would be to increase the system noise of each large magnetometer, hence somewhat reduce the factor of 7.5 for both, as we shall see. It should also be noted, by examining the inset of Fig. 1, that the *x*-signals in the large magnetometers will be contaminated by some *y* and z magnetic noise signal. For example *z*-noise will couple with small magnetometers that are tilted both in the *x* and *z* directions. However, this contamination is calculated to be negligible due to the relatively small *y* and *z* magnetometers areas. These areas are relatively 3.1/56 and 7.2/56, respectively, and assuming the *y* and z-noise is the same as x-noise, to first order. That is, assuming the *x, y,* and *z*-noise are uncorrelated and add in quadrature, the quadratic sum of *x*-noise + y-noise +z-noise is <1% greater than the x-noise by itself; hence this contamination can be neglected.

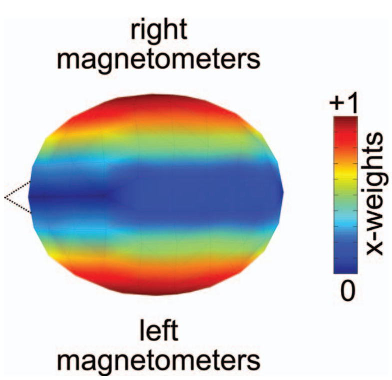

FIG. 2. Each magnetometer is assigned a weight from 0 to 1, depending on its angle to the *x*-direction. Taking all weights into account, the total effective area on each side is 28 times the area of each small square. Extreme left-right magnetometers have a weight of 1.0 and they are about 22 cm apart, resulting in incomplete cancellation of wall noise due to its x-gradient.

In measuring the *x*-noise, our basic idea here is to use the two large magnetometers in both the $l + r$ summing mode and in the $l - r$ subtraction mode, and then subtract the latter from the former output. This leaves approximately twice the total wall noise, because it has been included twice, one from each large magnetometer. Stated otherwise, in the summing mode, the grand output is equal to the summed internal noise plus twice the noise of both right and left walls. In the subtraction mode, the grand output is again due to the summed internal noise, but the wall noise will be largely cancelled because the left and right magnetometers are quite close together in the *x*-direction, although not completely so, because wall noise will have some gradient in the *x*-direction. The summed minus the subtracted mode then approximately yields twice the total x-noise, which is what we first seek.

The measured data is shown in Fig. 3, in the form of a frequency analysis. The data were recorded at 04 AM when mechanical wall vibrations are least. It is seen, nevertheless, that there are large magnetic artifacts due to vibrations, which render the curves <50 Hz to be mostly unusable here. Large artifacts are also produced by 60 Hz and its harmonics. Both these types of artifacts are present in almost all MSRs and can only be reduced with great difficulty. However, there are also seen to be two frequency regions, which are almost clear of artifacts and readily usable for our purposes. In one of these regions we arbitrarily choose 100 Hz as our main frequency of interest.

In extracting numbers, we first look at the upper, 1-curve, due to a single small magnetometer. We see, at 100 Hz, a mean noise of 2.6 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$, in agreement with Elekta's commercial specifications. We compare this to the 3-curve (summed noise of only 92 small magnetometers), with a value at 100 Hz of 0.51 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$, resulting in a sensitivity improvement of 2.6/0.51 = 5.1. This is not the ideal factor of 7.5 we would have liked, where the degradation is here due to the correlated thermal-shield noise, as mentioned earlier. However, a noise reduction of 5.1 is adequate enough to allow our wall measurement. Next, we note that the summed value (2-curve in Fig. 3) is 0.78. The total x-direction wall noise, added in twice, is then the difference between these two values, in quadrature, i.e.,

$$(2\,x\ total\ wall\ noise)^2 = (0.78)^2 - (0.51)^2,$$

from which we calculate that the total x-noise of both *l* and *r* walls, at the location of the MEG helmet, is 0.30 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$.

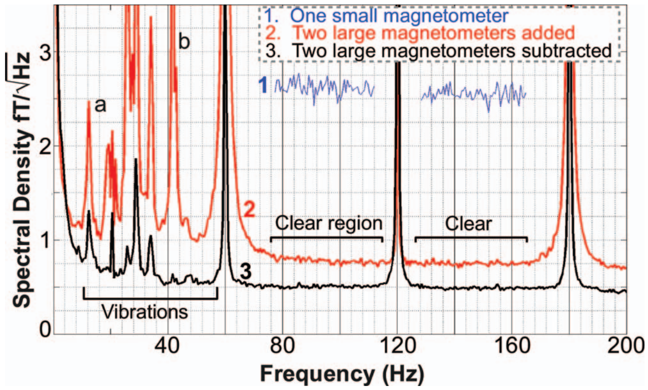

FIG. 3. Frequency analysis of a wall-noise measurement, for 30 min recording. The MEG bandwidth was 0.1 to 200 Hz, the sampling rate was 600 Hz, at 24 bits. Three sets of data are shown: (1) A single channel chosen which directly faces *x*-ward. (2) The two large magnetometers, added together. (3) The same but in the subtracted mode. Only two "clear" sections of the 1-curve are shown, to avoid crowding. The complete lower two curves are dominated by usual MSR artifacts: wall vibrations below 50 Hz, and 60 Hz and its harmonics. However, two regions are indicated which are almost clear of artifacts, hence due only to broad-band noise. Two vibration peaks are labeled "**a**" and "**b**."

We have, here, assumed that, in the subtracted value (3-curve), the wall noises cancel out exactly, but we know this cannot be true because of their x-gradients; however we justify this assumption as follows. We note that the vibration artifacts have a range of cancellation, because of variation in their gradients. For example, peak "**a**" at 12 Hz is only 2/3 cancelled, while peak "**b**" at 42 Hz is almost completely cancelled. Let us assume, conservatively about halfway, that the wall noise is 85–90% cancelled, leaving an uncancelled 0.03 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$. However, 0.03 added in quadrature to 0.51 makes only a negligible difference, and can here be ignored, therefore we retain our 0.30 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$ as the total wall noise in the *x*-direction, at 100 Hz.

Next, we try to extract wall-noise data at frequencies other than 100 Hz. Looking at higher frequencies in Fig. 3, we see no significant change in the difference between 2 and 3 curves for frequencies up to 165 Hz, as high as we go here. Going back lower than 100 Hz, we stop at, say, 80 Hz. The 2-curve is slightly elevated here, but this could well be a spillover from 60 Hz, hence we draw no conclusion. Going lower, we can first guess the shape of the 1-curve, if it were free of vibration artifact. At frequencies below about 10 Hz, it shows the rapid rise of the characteristic f^{-1} curve of these magnetometers, but before that, there are two frequencies which are almost artifact-free: 16 Hz and 10 Hz. There are 2-curve uncertainties, but using our previous logic, we calculate: at 16 Hz, total x-noise = $\sim$0.36 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$ and at 10 Hz it is = $\sim$0.41 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$, as only very approximate values. However there is clearly no rapid rise with lower frequencies, in agreement with the theoretical estimates (Table I of Ref. 7). That is, while curves 2 and 3 each show a rapid rise with decreasing frequency, the difference between these two curves does not rise in this way. In fact, the curves can be seen to cross at 4 Hz, which is an acceptable statistical fluctuation involving both curves.

Further, we can expand the x-noise value of 0.30, which is only one component of the wall-noise vector, to obtain the amplitude of the three-dimensional wall-noise vector, at the location of the MEG helmet in the MSR. This is the quantity finally needed, to be of general use, and allows comparison with the similar value extrapolated from the previously mentioned ferrite shield.[8] To do this, although the wall distances to the helmet are, here, different in *y* and *z* in comparison to *x*, we are, here, justified in assuming they are the same, allowing us to simply multiply 0.3 by $\sqrt{3}$, obtaining $\sim$0.5 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$ as the three-dimensional rms noise amplitude. We are justified because we are, here, only interested in first-order accuracy; the smaller z-spacing (than x-spacing) will give a larger z-value than 0.3, but the situation is reversed for *y*-spacing, partially canceling the *z*-value error, keeping our errors reasonably small. In comparison with the extrapolated value of $\sim$0.7 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$ from the small ferrite shield measurement,[8] our final value of $\sim$0.5 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$ is somewhat less, especially so when the ferrite value should be the low side because it ignores thermal currents. But our value, based on an actual MSR measurement, should perhaps be more valid because there are fewer uncertainties.

Finally, we point out that the noise measured here is specific to our particular MSR. Although most MSR's in use today have about the same internal dimensions, but the number of 1 mm sheets can vary from one to four, i.e., the inner-wall thickness can vary from 1 to 4 mm. The thicker this high-permeability wall, the better it will shield the Johnson noise from the aluminum layer on which it is mounted, this noise could be comparatively large, depending upon the aluminum-layer conductivity. We expect the 4 mm wall to almost completely block out the aluminum Johnson noise, while a 1 mm wall would allow a large fraction to get through to the magnetometers.

Therefore, all-in-all, thermal magnetic noise from the inner high-permeability wall of an MSR is negligible, in comparison with internal systematic noise for present-day MEG usage, especially if the inner wall is at least 3 mm thick. We conclude that this MEG systematic noise can be much reduced before thermal wall noise becomes a limiting factor.

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