

# Magnetic field strength and reproducibility of neodymium magnets useful for transcranial static magnetic field stimulation of the human cortex

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## Abstract

*Objective.* The application of transcranial static magnetic field stimulation (tSMS) in humans reduces the excitability of the motor cortex for a few minutes after the end of stimulation. However, when tSMS is applied in humans, the cortex is at least 2 cm away, so most of the strength of the magnetic field will not reach the target. The main objective of the study was to measure the strength and reproducibility of static magnetic fields produced by commercial neodymium magnets.

*Methods.* We measured the strength and reproducibility of static magnetic fields produced by four different types of neodymium cylindrical magnets using a magnetic field-to-voltage transducer.

*Results.* Magnetic field strength depended on magnet size. At distances <1.5 cm, the magnetic field strength was affected by the presence of central holes (potentially useful for recording electroencephalograms). At distances >1.5 cm, the measurements made on the cylinder axis and 1.5 cm off the axis were comparable. The reproducibility of the results (i.e., the consistency of the field strength across magnets of the same size) was very high.

*Conclusions.* These measurements offer a quantitative empirical reference for developing devices useful for tSMS protocols in both humans and animals.

## Keywords:

Neuromodulation, rTMS, static magnetic fields, transcranial magnetic stimulation

## Introduction

Noninvasive neuromodulation techniques have gained a strategic position in cognitive neuroscience and have reshaped the way brain–behavior relations are investigated. Moreover, these techniques have been proposed as a treatment for neuropsychiatric disorders [1, 2]. Repetitive transcranial magnetic stimulation and transcranial direct current stimulation are commonly used as noninvasive neuromodulation techniques in humans and animals.

Recently we described that the application of transcranial static magnetic field stimulation (tSMS) in humans reduces the output of the motor cortex (tested using transcranial magnetic stimulation) for a few minutes after the end of stimulation [3]. Reduced motor output after tSMS can be explained by reduced motor cortex excitability. These data have been recently replicated by a different group [4].

Static magnetic fields, unlike time-varying magnetic fields, are not associated with induced electric currents and have been shown to influence a variety of biological systems [5]. A number of studies suggest that static magnetic fields act primarily at the synapse and alter the function of membrane ion channels [5, 6], and the application of static magnetic fields to different animal preparations seems to have an effect that outlasts the time of stimulation [7]. tSMS using small magnets may thus be a promising tool to modulate cerebral excitability in a noninvasive, painless, and reversible way. Moreover, tSMS possesses most of the characteristics of a good noninvasive neurostimulation technique: It seems to be effective; it has a reversible effect; it is easy to apply transcranially; it is not expensive; it has a convincing sham (at least in a laboratory environment); it is safe; and it does not require highly skilled professionals to apply it. All these characteristics may allow tSMS to be easily translated to the clinical (therapeutic) setting.

In tSMS the static magnetic field is obtained by using neodymium permanent magnets, which are rare-earth magnets made from an alloy of neodymium, iron, and boron with a tetragonal crystalline structure. This material is the strongest type of permanent magnet available on the market. However, when tSMS is applied in humans, the cortex is at least 2 cm away, so most of the strength of the magnetic

field will not reach the target. In order to properly design new tSMS protocols in human and animal studies, it would be practically helpful to know the actual strength of the magnetic field as a function of the distance from the magnet base surface. Moreover, it would be important to know the consistency (in terms of strength of the magnetic field) of the magnets that can be found on the market.

To address these issues, in the present experiments we measured the strength of the static magnetic field produced by four different types of neodymium cylindrical magnets using a magnetic field-to-voltage transducer. We verified the reproducibility of the results (i.e., the consistency of the field strength across magnets of the same size and type) by testing at least two magnets of each size and type.

## Methods

### *Magnets*

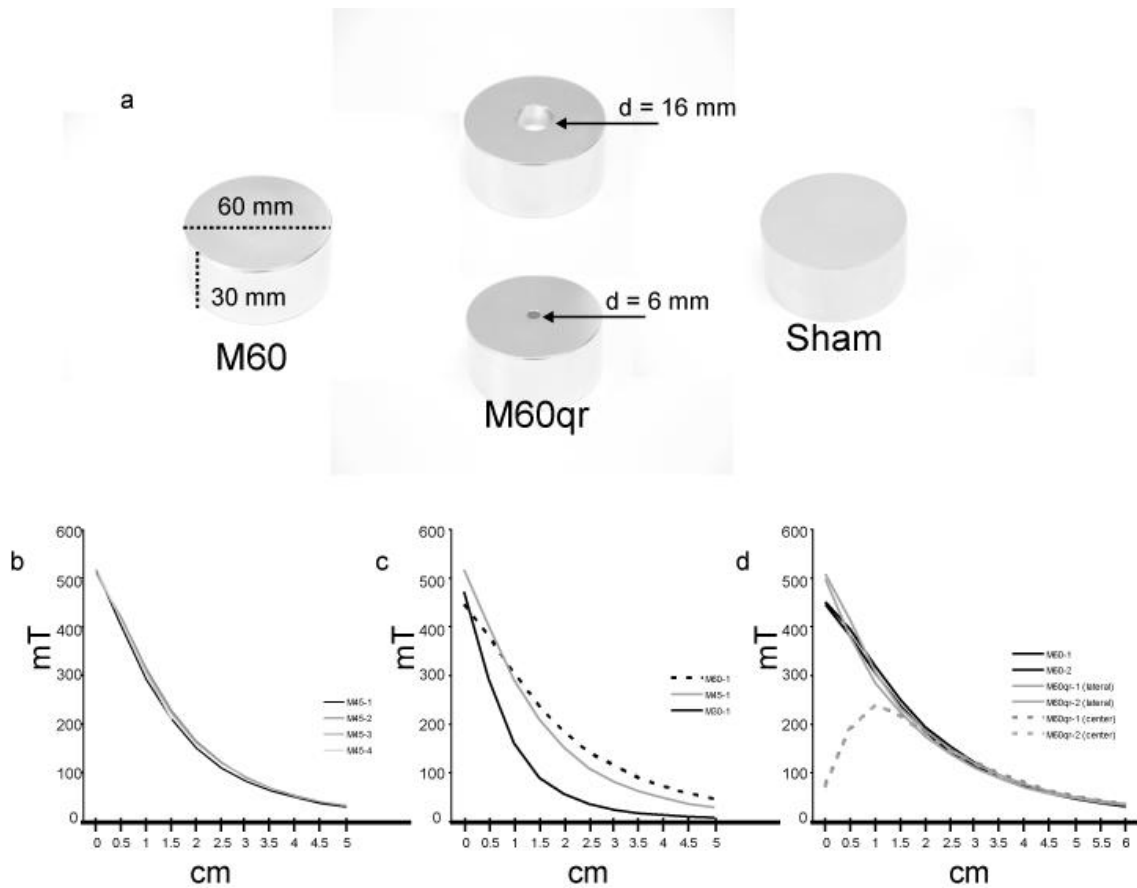
We measured the strength of the static magnetic field produced by 10 magnets and two inert steel cylinders (useful for sham stimulation). The characteristics of the magnets and of the steel cylinders are summarized in Table 1.

**Table 1.** Characteristics of the Magnets and of the Steel Cylinders (for Sham Stimulations)

Name	Type	Diameter, mm	Thickness, mm	Weight, g	Magnetic energy stored, MGOe	Nominal strength, N (kg)	Commercial name	Supplier
M30	Real	30	15	81	42	225 (23)	S-30-15-N	Supermagnete
M45	Real	45	30	360	45	765 (78)	S-45-30-N	Supermagnete
M60	Real	60	30	670	45	1220 (120)	MAG60r	Supermagnete via Neurek SL
M60qr	Real	60	30	638	45	1220 (120)	R-60-06-30-N	Supermagnete
MAG45s	Sham	45	30	368	0	0	MAG45s	Neurek SL
MAG60s	Sham	60	30	668	0	0	MAG60s	Neurek SL

Magnetic energy stored and nominal strength values are provided by the suppliers.

We used three different sizes of cylindrical magnets, which will be referred to as magnets 30, 45, and 60 (M30, M45 and M60). The number indicates the diameter (in millimeters). We also tested a 60-mm magnet with a quasi-ring shape. We will refer to this magnet as M60qr (see Fig. [1a](#)). For all magnets, the magnetization direction was parallel to the height axis. All the magnets were cylindrical nickel-plated (Ni-Cu-Ni) NdFeB magnets.



**Figure 1.** a. Pictures of the two different magnets with a main diameter of 60 mm (M60 and M60qr) and the sham. M60qr has a quasi-ring shape with internal hole diameters of 6 mm on one side and 16 mm on the other side ( $d$ , diameter). Sham is a nonmagnetic metal cylinder (nickel-coated steel) that has the same size and appearance as M60. b. The graph shows the magnetic field strength of four different M45 magnets tested at different distances from the magnet base surface. The reproducibility of the results (i.e., the consistency of the field strength across magnets of the same size and type) was very high (standard deviations  $<10$  mT). c. The graph shows the magnetic field strength of three different magnets (M30, M45, and M60) tested at different distances from the magnet base surface. Not surprisingly, at distances that are relevant for cortical stimulation in humans (i.e., 2–3 cm from the magnet base surface) the magnetic field strength was dependent on the magnet size. d. The graph shows the magnetic field strength of four different magnets (two M60 and two M60qr) tested at different distances from the magnet base surface. The reproducibility of the results was very high. At a distance smaller than 1.5 cm from the base surface, the magnetic field strength of M60qr was much smaller than M60, due to the central holes. Conversely, at a distance of at least 1.5 cm the results for M60qr were similar to M60. Interestingly, M60qr lateral measurements (i.e., parallel to the cylinder axis, 1.5 cm off the center) were comparable to the measurements performed with the M60 (along the cylinder axis) at all distances.

M30 was 30 mm in diameter and 15 mm thick, with a weight of 81 g (Model S-30-15-N, Supermagnete, Gottmadingen, Germany [<http://www.supermagnete.de>]). The maximum amount of magnetic energy that can be stored in this magnet is 42 MGOe (megagauss-oersteds), with a nominal strength of 225 N (23 kg).

M45 was 45 mm in diameter and 30 mm thick, with a weight of 360 g (Model S-45-30-N, Supermagnete). The maximum amount of magnetic energy that can be stored in this magnet is 45 MGOe, with a nominal strength of 765 N (78 kg).

M60qr was 60 mm in diameter and 30 mm thick, with a weight of 638 g (R-60-06-30-N, Supermagnete). The internal hole diameters are 6 mm on one side and 16 mm on the other side. The maximum amount of magnetic energy that can be stored in this magnet is 45 MGOe, with a nominal strength of 1220 N (120 kg). We considered this magnet shape useful for some brain stimulation applications, as it makes it possible to pass an electrode cable through the magnet and record from an electrode very close to the contact surface between the magnet and the scalp (e.g. to record electroencephalograms). All the data on M30, M45, and M60qr were provided by the manufacturer (Supermagnete). M60 was a customized cylindrical nickel-plated (Ni-Cu-Ni) NdFeB magnet of 60 mm in diameter and 30 mm in thickness (supplied by Supermagnete to Neurek SL, Toledo, Spain

[<http://www.neurek.com>]). The maximum amount of magnetic energy stored in this magnet and the nominal strength should be similar to the M60qr.

Nonmagnetic metal cylinders potentially useful for sham stimulation were also tested. These steel nickel-coated cylinders (MAG45s and MAG60s, Neurek SL) had the same size as and similar weight and appearance to M45 and M60.

### *Measurement procedures*

The magnetic field strength was measured using a magnetic field-to-voltage transducer with an integrated Hall probe. The sensor is a complementary metal-oxide semiconductor one-axis Hall probe (model I1A) integrated into a transducer (YM12-3-5-5T) (SENIS GmbH, Zurich, Switzerland). The Hall element in the probe occupies an area of  $150\ \mu\text{m} \times 150\ \mu\text{m}$ , providing a very high spatial resolution and angular precision. The Hall probe measures along a single axis perpendicular to its surface. All measurements represent the strength of the magnetic field vector (usually represented with the international symbol  $B$ ) along the axis perpendicular to the base surface of the cylinder. An integrated temperature sensor on the probe provides temperature compensation for better accuracy. The sensor is also protected against inductive currents that could disturb the measurement. The decay of the static magnetic field with distance was measured by increasing the distance between the Hall probe and the magnet surface, keeping the base of the sensor parallel to the surface of the magnet. For M60qr we performed measurements both on the cylinder axis and parallel to the cylinder axis. Note that because the magnetic field is normal to surface of the magnet only along the cylinder axis, our measurements parallel to the cylinder axis represent a lower bound of the actual strength of the magnetic field. The magnetic permeability of human tissues is similar to air or vacuum [8], so any differences in magnetic field strength between air and human tissues are negligible for the purpose of tSMS.

## **Results**

Figure 1 (b–d) shows the magnetic field strength of the different magnets tested at different distances from the magnet base surface. The reproducibility of the results was very high for all magnet sizes (Fig. 1b,d): Specifically, the standard deviation for all measurements performed on the four M45 magnets at different spatial points (Fig. 1b) was  $<10\ \text{mT}$ . As expected, at distances that are relevant for cortical stimulation in humans (i.e., 2–3 cm from the magnet surface), the magnetic field strength was dependent on the magnet size (Fig. 1b–d), and the nonmagnetic metal cylinder had a null magnetic field strength ( $<0.001\ \text{mT}$ ). At a distance smaller than 1.5 cm from the base surface, the magnetic field strength of M60qr was much smaller than M60, due to the central holes (Fig. 1a,d). Conversely, at a distance of at least 1.5 cm the results of M60qr were similar to M60, and both center measurements (i.e., on the cylinder axis) and lateral measurements (i.e., parallel to the cylinder axis, 1.5 cm off the center) were comparable (Fig. 1d).

## **Discussion**

We believe that tSMS can play a role in the development of future strategies for noninvasive neuromodulation. Herein, we measured the magnetic field strength of permanent magnets of different size and shape at different distances from the magnet base surface. The most important result is that there is good reproducibility of the magnetic field strength when similar magnets are compared. Furthermore, at 2–3 cm from the magnet surface the magnetic field strength is in a range between 120 and 200 mT. Therefore, tSMS using relatively small magnets produces a magnetic field that is strong enough to reach most of the cortical targets with strength between 120 and 200 mT. It seems that this range is enough to obtain biological effects [5].

For a magnetic cylinder, the magnetic flux is such that at the center of the base surface of the cylinder the magnetic flux lines are perpendicular to the surface. Moving toward the periphery of the surface, the flux lines come out at an angle that deviates from the cylinder axis, and they diverge at increasing distance from the surface. A simple strategy to increase the overall strength of the magnet—and thus to decrease the spatial decay of the magnetic flux density—is to increase the diameter of the magnet. The drawback of this strategy is a loss of focality. An alternative strategy to increase the overall strength of the magnet while maximizing focality is to increase its thickness. The optimal magnet in each specific clinical application would therefore depend on the desired tradeoff between overall strength and focality.

These results should also be considered when performing tSMS in animal laboratories, where tSMS could represent an alternative neuromodulatory tool to current available techniques. In animals (monkey,

cat, rat) the distance from the magnet to the cortex is shorter and the total cortical surface is smaller; hence, it is important to adjust both magnet size and distance in order to achieve the optimal stimulation parameters. The measurements presented here offer a quantitative empirical reference for the development of tSMS protocols in both human and animal studies.

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### **Authorship Statement**

Drs. Casto Rivadulla, Guglielmo Foffani, and Antonio Oliviero designed and conducted the study, including data collection and data analysis. Dr. Antonio Oliviero prepared the manuscript draft with important intellectual input from Drs. Casto Rivadulla and Guglielmo Foffani. All authors approved the final manuscript. The University of A Coruña and Hospital Nacional de Paraplégicos provided funding for the study; statistical support in analyzing the data, with input from Drs. Casto Rivadulla, Guglielmo Foffani, and Antonio Oliviero; and funding for editorial support. Drs. Casto Rivadulla, Guglielmo Foffani, and Antonio Oliviero had complete access to the study data.

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