Physiology & Behavior 86 (2005) 379 – 389

PHYSIOLOGY & BEHAVIOR

Behavioral effects on rats of high strength magnetic fields generated by a resistive electromagnet

Thomas A. Houpt [a,*], David W. Pittman [b], Christina Riccardi [b], Jennifer A. Cassell [a], Denesa R. Lockwood [a], Jan M. Barranco [a], Bumsup Kwon [a], James C. Smith [b]

[a] *Department of Biological Science, BRF 252 MC 4340, The Florida State University, Tallahassee, FL, 32306-4340, United States*
[b] *Department of Psychology, Program in Neuroscience, The Florida State University, Tallahassee, FL, 32306-4340, United States*

Abstract

It has been reported previously that exposure to static high magnetic fields of 7 T or above in superconducting magnets has behavioral effects on rats. In particular, magnetic field exposure acutely but transiently suppressed rearing and induced walking in tight circles; the direction of circular locomotion was dependent on the rats' orientation within the magnet. Furthermore, when magnet exposure was paired with consumption of a palatable, novel solution, rats acquired a persistent taste aversion. In order to confirm these results under more controlled conditions, we exposed rats to static magnetic fields of 4 to 19.4 T in a 189 mm bore, 20 T resistive magnet. By using a resistive magnet, field strengths could be arbitrary varied from − 19.4 to 19.4 T within the same bore. Rearing was suppressed after exposure to 4 T and above; circling was observed after 7 T and above. Conditioned taste aversion was acquired after 14 T and above. The effects of the magnetic fields were dependent on orientation. Exposure to + 14 T induced counter-clockwise circling, while exposure to − 14 T induced clockwise circling. Exposure with the rostral–caudal axis of the rat perpendicular to the magnetic field produced an attenuated behavioral response compared to exposure with the rostral–caudal axis parallel to the field. These results in a single resistive magnet confirm and extend our earlier findings using multiple superconducting magnets. They demonstrate that the behavioral effects of exposure within large magnets are dependent on the magnetic field, and not on non-magnetic properties of the machinery. Finally, the effects of exposure to 4 T are clinically relevant, as 4 T magnetic fields are commonly used in functional MRI assays.

Keywords: High magnetic fields; Superconducting magnets; Taste aversion

1. Introduction

Magnetic resonance imaging (MRI) machines that are in typical clinical use generate high strength static magnetic fields of 1 to 2 Tesla (T). However, the theoretical capacity for MRI to resolve images down to 0.5 μm^3 is driving the production of MRI machines with higher magnetic fields [1]. Experimental MRI machines with field strengths of up to 8 T are used on humans [2], and 11.4 T MRI is used on animal models [3].

While static high magnetic fields are generally considered to be benign and undetectable to mammals, the physiological effects of very high magnetic fields are unknown. There is, however, some evidence suggesting that high fields can affect humans. A survey of engineers and workers developing 4 T MRI machines reported a significant incidence of vertigo and nausea [4]. Furthermore, there are anecdotal reports of vertigo and nausea associated with exposure to 8 T [2].

Using the large superconducting magnets of nuclear magnetic resonance (NMR) machines at the US National High Magnetic Field laboratory (NHMFL), we have found that exposure to high fields has behavioral and neural effects in rats. Specifically, four pieces of evidence have been gathered: 1) immediately after 30-min exposure to 7, 9.4, or 14 T, rats walk in tight circles for up to 2 min [5]. The direction of these circles is dependent on the orientation of the rat within the magnet, such that rats walked counter-clockwise after facing + 14 T but clockwise if upside down

---

* Corresponding author. Tel.: +1 850 644 4906; fax: +1 850 644 0989.
E-mail address: houpt@neuro.fsu.edu (T.A. Houpt).

0031-9384/$ - see front matter © 2005 Elsevier Inc. All rights reserved.
doi:10.1016/j.physbeh.2005.08.008

(i.e. facing −14 T). 2) If magnet exposure is paired with consumption of a novel sweet solution (glucose+saccharin), rats form a profound conditioned taste aversion such that they refuse to consume the sweet solution for many days after the exposure [6]. 3) When trained to climb towards a food reward at the top of a ladder, rats will refuse to climb the ladder if it traverses the bore of a 14 T magnet [7]. 4) At the neural level, 30-min exposure to high magnetic fields activates vestibular and visceral relays within the brainstem of the rat, as shown by the induction of c-Fos expression [8]. These results are consistent with an aversive or vestibular effect of the high magnetic fields. Also, they are similar to what might be seen after rotation or other vestibular stimuli leading to motion sickness in rodents and humans.

A significant operational problem with our earlier studies on rats was the use of superconducting NMR magnets. The advantages of the NMR machines are that they operate on the same principle as MRI machines, they produce extremely homogeneous fields, and they are available in a variety of field strengths (from 7 to 20 T at the NHMFL). They have several disadvantages, however, when used to provide sensory stimuli to rats in behavioral studies. Because they are superconducting and remain energized for months while drawing little outside current, it is very inconvenient to turn the magnetic field off and on again. Thus, a "sham–magnet" must be used for the 0 T controls (e.g. a PVC tube outside the magnetic field); this sham–magnet, of course, lacks many of the potential non-magnetic characteristics of the NMR machine such as odor, sounds, etc. Furthermore, the superconducting magnets are designed to be energized only to a set field strength, so that different strengths of magnetic field can only be applied within superconducting magnets in different physical locations. Finally, the NMR machines, being used primarily for biochemical studies, have relatively small, vertical bores (89 mm diameter), so that rats can be exposed only one at a time with their rostral–caudal axis perpendicular to the ground.

Resistive magnets do not have these disadvantages of superconducting magnets. Both superconducting and resistive magnets are electromagnets. The electric current in resistive magnets circles the bore through regular copper wiring (which has some resistance), and not through superconductors (without resistance) as in the NMR magnets. The magnetic field generated in a resistive magnet is proportional to the current, and therefore can be varied by changing the applied current. The polarity of the field can easily be reversed by reversing the current. The magnetic field also disappears when the current is stopped. This contrasts with an NMR magnet, in which the current and magnetic field persist long after energizing the superconductor. While superconducting NMR and MRI magnets are fairly common, large resistive magnets are rare due to their size and cost of operation. The major limitations on resistive magnets are the availability of electrical power (up to 20 MW for hours at a time) and the capacity to dissipate heat from the copper wiring during operation.

In order to confirm our findings that used NMR magnets, we employed a resistive magnet at the NHMFL with a vertical bore of 189 mm diameter that can produce fields between 0 and 20 T [9]. In this study we repeated and extended our stimulus response curve derived on NMR magnets [5] across 6 field strengths from 0 to 19.4 T, all within the same physical magnet (Experiment 1). In particular, we explored the effects of a relatively low 4 T exposure that is clinically relevant (Experiment 2). Because the field orientation as well as strength can be varied by the direction of the magnet's current without changing the rat's position, we contrasted the effects of exposure to +14 or −14 T (Experiment 3). Finally, because the resistive magnet had a 189 mm diameter bore, we were able to expose rats with their rostral–caudal axis parallel to the ground (Experiment 4).

The dependent measures were the acute effects of exposure on locomotor circling and rearing, and the acquisition and extinction of conditioned taste aversion after pairing a sweet taste with exposure. We have reported elsewhere the effects of resistive magnet exposure on ladder-climbing and c-Fos induction [in preparation].

2. General methods

2.1. Animals

Male Sprague–Dawley rats (175–200 g; Charles River) were housed individually in plastic cages in a temperature-controlled colony room at the National High Magnetic Field Laboratory at The Florida State University. The light/dark cycle was 12:12 with lights on at 0800 h. All conditioning trials were conducted during the light cycle. The rats had free access to pelleted Purina Rat Chow 5001 and deionized-distilled water ad libitum except where specified otherwise.

2.2. 0–20 T resistive magnet

High strength static magnetic fields were generated in a 20 T magnet constructed and operated at the NHMFL (see Fig. 1A) [9]. The basic design of the magnet is 400 mm thick copper coils of 500 mm outer diameter and 600 mm height wrapped around a 189 mm bore. Direct current of up to 40 kA at 500 V (20 MW) is passed through the copper coils, resulting in static magnetic fields of up to 20 T in the core of the magnet. The field strength falls off rapidly with distance, so that the field is near 0 T at 2 m distance from the center of the magnet (see Fig. 1B). The magnet is cooled by a chilled water system (173 l/s). The current and hence magnetic field could be arbitrary set to any field strength up to 20 T by the experimenters at the magnet, or remotely by the NHMFL control room located approximately 100 m away. Several minutes were required to ramp up the field strength from 0 T to the desired intensity; the field was set and allowed to stabilize before exposing any rats within the magnet.