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Decoding 3D search coil signals in a non-homogeneous magnetic field

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ABSTRACT

We present a method for recording eye–head movements with the magnetic search coil technique in a small external magnetic field. Since magnetic fields are typically non-linear, except in a relative small region in the center small field frames have not been used for head-unrestrained experiments in oculomotor studies.

Here we present a method for recording 3D eye movements by accounting for the magnetic non-linearities using the Biot-Savart law. We show that the recording errors can be significantly reduced by monitoring current head position and thereby taking the location of the eye in the external magnetic field into account.

1. Introduction

In vestibulo-oculomotor studies, rotating or translating devices are often used to stimulate the vestibular sensory organs of the inner ear while monitoring the eye movements. The preferred method for monitoring eye movements is the magnetic search coil technique, which is well established in humans, in non-human primates and other animals (Collewijn, van der Steen, Ferman, & Jansen, 1985; Fuchs & Robinson, 1966; Hess, 1990; Judge, Richmond, & Chu, 1980; Robinson, 1963). In recent years eye movement recording techniques based on video have gained popularity due to their lesser invasiveness (Houben, Goumans, & van der Steen, 2006; Imai et al., 2005). However, the search coil technique still remains the method of choice for many researchers, due to important advantages such as high spatial and temporal resolution, signal-to-noise ratio, stability, reproducibility and minimal sensitivity to blinking and pupil stability. The search coil technique offers particular and hitherto unmatched advantages in studies of three dimensional (3D) eye movements with or without the head moving.

When using the search coil technique in 3D eye movement studies, a dual search coil consisting of two, roughly, perpendicular coils in a single rigid construction (Collewijn et al., 1985; Hess, 1990) or simply a pair of independent coils (Tweed, Cadera, & Vilis, 1990) are used as sensors. In this study we deal solely with the rigid dual search coil, although the method applies in principle also for two independent coils. With the search coil firmly fixed to the eye, the subject is sitting inside a magnetic field that consists of two or three alternating magnetic fields (primary fields) generated by orthogonally arranged external field coils (frame coils). The primary fields induce currents in the two search coils depending on their orientation relative to the primary fields. From these currents the 3D orientation of the search coils (and thus the eye's orientation) can be determined. Since reliable measurements can only be obtained within the region, where the fields are homogeneous and mutually orthogonal, subjects are typically placed with the head fixed in the center. When measuring eye–head movements, large rectangular frame coils (e.g. 2 × 2 × 2 m) are typically used such that the subject can move its head without leaving the homogeneous part of the field (see e.g. Tweed, Glenn, & Vilis, 1995).

To minimize distortions of the primary field, e.g. by the metallic parts in the vicinity, the frame needs to be placed around the head of the subject within a motion device. This imposes considerable restrictions on the size of the frame coils such that eye movements are often not reliably recorded when the subject's head is free to move. Certain geometric frame configurations like the Helmholtz configuration or other configurations with a larger number of frame coils (Collewijn, 1977; Ditterich & Eggert, 2001; Rubens, 1945) provide better linearity than a simple cubic frame, yet at the cost of reducing the subject's field of view. Visuo-vestibular studies typically require the fixation of point targets in far-viewing as visual stimulus and a smaller field of view than the approximate 90° provided by the cube configuration would cause a significant restriction during combined eye–head movement studies.

Abbreviations: 3D, three dimensional; P, Position; E, orientation; STD, standard deviation.

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Here, we present a method for measuring eye movements with the search coil method by taking the non-linear spatial field characteristics into account using the Biot-Savart law. The recording technique was evaluated in two steps: (1) a simulation of eye movements made by an 'artificial eye' which was positioned in various orientations at different locations in the magnetic field and (2) an *in vivo* experiment, where rhesus monkeys were trained to fixate targets with their heads unrestrained. The head movements were measured with an ultrasonic system to locate the spatial eye position in the primary field.

2. Materials and methods

2.1. General experimental setup

For practical purposes, we used two different setups for these experiments. The simulation experiment, which required the manipulation of a three- axis gimbal protractor at different locations, was performed in a large magnetic field frame with side length of 75 cm (Angle-Meter NT, Primelec, Regensdorf, Switzerland). The *in vivo* experiment was done in a similar but much smaller system with side length of approximately 30 cm (Eye Position Meter 3000, Skalar Instruments, Delft, The Netherlands), fitted inside the inner frame of a motorized four-axis gimbaled motion device (Acutrol, Acutronic Schweiz AG, Bubikon, Switzerland). Although the Primelec system is a three-field system generating three primary magnetic fields in contrast to the Skalar system, we used only the output signals of two primary magnetic fields in both sets of experiments (for a three-field approach see Appendix A). One of these fields was directed vertically along the subject's rostro–caudal axis and the other was directed horizontally along the interaural axis of the subject. Physically, each field resulted in fact from superimposing the magnetic fields produced by two parallel-arranged square shaped coils at each side of the frame (Fig. 1). The two coil pairs generated two homogeneous magnetic fields in the center of the frame that were in space quadrature. The Primelec system used frequency encoding to enable separate detection of the fields whereas the Skalar system used phase encoding.

In both sets of experiments, we used the same type of (implantable) dual search coil (Hess, 1990). In brief, the dual search coils consisted of one three-turn wire coil with a diameter of ca. 15 mm (direction coil) and two serially connected oval-shaped miniature wire coils of ca. 1.5 × 2.2 mm diameters and 150 turns each (torsion coil). The torsion coils were rigidly mounted at diametrically opposed positions on the circumference of the direction coil such that the direction of maximal sensitivity was roughly at 90° with respect to the sensitivity direction of the direction coil. The dual search coil was finally sealed with an electrically insulating Araldite (XD4510, Astorit, Switzerland) and surface coated with a bio-compatible plastic compound (Rilsan PA11, Arkema, France).

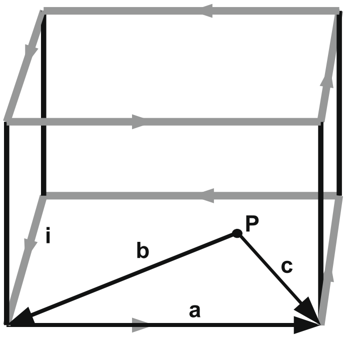

Fig. 1. The magnetic field H_{total} at point P is calculated by superposition of the eight sticks of the two primary coils. It is mainly directed in the vertical direction. The similar calculations are made for the other primary magnetic field which is mainly directed horizontally.

All search coil induction data were digitized at 833.33 Hz with a resolution of 12-bit. The data were analyzed offline using MATLAB (The Mathworks Inc., Natrick, MA, USA) and 3D eye orientations were expressed as rotation vectors in space-fixed x- (orthogonal to the y- and z-coordinates), y- (interaural axis), and z-coordinates (head vertical axis). The eye's orientation while looking straight-ahead was taken as reference position (Haustein, 1989; Hess, Van Opstal, Straumann, & Hepp, 1992).

2.2. Search coil signal demodulation using the Biot-Savart law

We used the Biot-Savart law to compute the direction and relative strength of the magnetic field at the position of the search coil (the eye). The rectangular frame coils consisting of straight aluminum bars were approximated by sticks of zero thickness. With this simplification the integration in the Biot-Savart law can be circumvented by using the more computer efficient vector calculations (Haus & Melcher, 1989).

$$H = \frac{i}{4\pi}\frac{c \times a}{|c \times a|^2}\left(\frac{a \bullet c}{|c|} - \frac{a \bullet b}{|b|}\right) \tag{1}$$

This equation describes the magnetic field vector "H" resulting from one of the eight sticks of the frame coils. Each stick is described by a vector, say "a" with base at one end of the stick and endpoint at the other end, pointing in the direction of the current flow, denoted by "i" (Fig. 1). To compute the magnetic field vector "H" at point P of the current "i" in stick "a", the equation further requires the vector "b" with base at point P and endpoint at the base of "a" and the vector "c" with base at P and endpoint at the endpoint of vector "a". The resulting magnetic field H_{total} can then be determined by the superposition principle of the eight sticks (or bars) in the frame for each of the coil pairs that generate a primary field. An estimation of the amount of current flow "i" is not important because the calculated field does not need to be in absolute values. The field should simply be calculated relative to the center of the frame coils i.e. no correction is made in the center.

The following describes how to demodulate the search coil signals using only two primary fields (Y and Z). The procedure for three primary fields (X, Y and Z) is shown in Appendix A.

We used a right-handed orthogonal coordinate system with positive x-direction pointing straight forward (parallel to the naso-occipital axis of the tested subject), positive y-direction pointing leftward (parallel to the subject's interaural axis) and the z-direction pointing upward (parallel to the subject's rostro-caudal axis). As seen from the subject, positive rotations about the x-, y- and z-axis are clockwise, downward and leftward.

To describe the geometry of the magnetic flow field, we denote the magnetic field vector of the primary Y-field at point P by $\vec{v}(P)$. It associates with each point P inside the frame coils a vector according to the relation (superscript "T" stands for transpose):

$$\vec{v}(P) = [v_1, v_2, v_3]^T \tag{2}$$

Similarly, we denote the magnetic field vectors of the primary Z-field at the point P by:

$$\vec{w}(P) = [w_1, w_2, w_3]^T \tag{3}$$

Consider now a search coil, which we will call *direction coil* due to its close alignment with the direction of the line of sight, with the sensitivity vector $\vec{d} = [d_1, d_2, d_3]^T$ (orthogonal to the plane spanned by the search coil) at position P in the external field (Fig. 2). The sensitivity vector carries information about the magnitude of the in-