

**STUDIES ON MAGNETISM AND BIOELECTROMAGNETICS FOR 45
YEARS: FROM MAGNETIC ANALOG MEMORY TO HUMAN BRAIN
STIMULATION AND IMAGING**

Shoogo Ueno

University of Tokyo/Kyushu University/Teikyo University

Emails: ueno@athena.ap.kyushu-u.ac.jp; ueno@fmt.teikyo-u.ac.jp

100-Word Short Summary

The studies on magnetism and bioelectromagnetics in our laboratory for 45 years are presented. The d'Arsonval award lecture includes magnetic analog memory, localized magnetic stimulation of the human brain by figure eight coils, parting of water by magnetic fields, bone growth acceleration by magnetic fields, cell destruction by pulsed magnetic force and magnetizable beads, control of iron ion release/uptake from/into ferritin by radio frequency magnetic fields, measurements of weak magnetic fields related to neuronal electrical activities by superconducting quantum interference device systems, and imaging of electrical impedance and currents in the brain by magnetic resonance imaging.

Key words: magnetic stimulation, brain imaging, TMS, MEG, parting of water, magnetic orientation, bone growth, ferritin, impedance MRI, current MRI

Correspondence to:

Shoogo Ueno, Professor Emeritus, the University of Tokyo, Department of Applied Quantum Physics, Graduate School of Engineering, Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka, 812-8581 Japan (Email: ueno@athena.ap.kyushu-u.ac.jp) or Faculty of Medical Technology, Teikyo University, Fukuoka, 4-3-124 Shinkattachi-machi, Omuta-shi, Fukuoka, 836-8505 Japan (Email: ueno@fmt.teikyo-u.ac.jp)

Studies on Magnetism and Bioelectromagnetics for 45 Years: From Magnetic Analog Memory to Human Brain Stimulation and Imaging

Shoogo Ueno (University of Tokyo/Kyushu University/Teilyo University)

The studies on magnetism and bioelectromagnetics in our laboratory for 45 years are presented. After a short introduction of our early work on magnetic analog memory, several topics on human brain stimulation/imaging and medical applications are reviewed and discussed: (1) Magnetic nerve stimulation and transcranial magnetic stimulation (TMS) of the human brain, (2) The magnetoencephalography (MEG) or measurements of weak magnetic fields generated from the brain by superconducting interference device (SQUID) systems, (3) Impedance magnetic resonance imaging (impedance MRI) and current magnetic resonance imaging (current MRI), (4) Cell destruction by pulsed magnetic force and magnetizable beads, (5) Magnetic control of cell orientation and cell growth, and (6) Control of iron ion release/uptake from/into ferritin, iron cage protein, by radio frequency magnetic fields. These bioelectromagnetics studies have opened new horizons in magnetism and medicine.

Prologue: Studies on Magnetic Analog Memory-----Entrance into Magnetism
The entrance into magnetism was to study partial switching properties of ferrite cores for magnetic analog memory devices. We explained the complex relationship between partial flux sets in magnetic cores and the memory characteristics of magnetic analog memories.

Magnetic Nerve Stimulation and Transcranial Magnetic Stimulation (TMS)
We measured the intracellular action potentials of lobster giant axons exposed to time-varying magnetic fields, and obtained that the macroscopic eddy currents which flow through the nerve tissues and the surrounding mostly contribute to the nerve excitation. We proposed a method to stimulate nerves in the body without interlinkage between a magnetic core and the nerves. We also proposed a method to stimulate localized areas in the brain by TMS with a figure eight coil, and we succeeded in magnetic stimulation of the human cortex with a 5-mm resolution.

The Magnetoencephalography (MEG)

We developed a 7-channel MEG system and succeeded in detections of human auditory brainstem magnetic fields as well as slow DC components related to short-term memory and cognitive functions. We also developed a micro SQUID system to measure magnetic fields generated by the brain electrical activities in small animals.

Impedance MRI and Current MRI

We proposed three types of impedance imaging based on new principles of MRI: Impedance MRI by using large flip-angles, impedance MRI with an additional AC coil, and impedance MRI based on diffusion tensor MRI. We also studied theoretical limit for detection of neuronal currents by MRI, and obtained that a current dipole strength of $12 \text{ nA} \cdot \text{m}$ resulted in the maximum signal drop of 0.6%. We obtained current imaging of a rat brain related to somatosensory responses by a 4.7 T MRI system.

Cell Destruction by Pulsed Magnetic Force and Magnetizable Beads

We proposed a new type of cancer therapy to destruct targeted cancer cells physically by pulsed magnetic force and magnetizable beads. Using TCC-S leukemia cells, the usefulness of the new method was demonstrated.

Magnetic Control of Cell Orientation and Cell Growth

We observed the phenomenon, named "Moses effect", that water is parted when exposed to an 8-T magnetic field with a gradient of 50 T/m. The estimated magnetic force acting on 100 ml of water was 0.28 N, i.e., 1/3 of the earth gravity. We also observed the magnetic orientation of adherent cells such as osteoblasts, vascular endothelial cells, smooth muscle cells and Schwann cells under 8-T magnetic field exposures. We succeeded in acceleration of bone growth (BMP-2/collagen samples) by magnetic fields.

Control of Iron Ion Release/Uptake from/into Ferritin by RF Magnetic Fields

We observed that radio frequency (RF) magnetic fields interact with iron cage proteins (ferritins) and alter their functioning. The iron ion release/uptake from/into ferritin was affected by RF magnetic fields of 1 MHz and $30 \mu \text{T}$ for several hours. These effects have potential therapeutic applications for brain diseases such as Alzheimer's and Parkinson's.