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Measurement of biomagnetic field in cell tissues utilizing pT resolution micro magnetic sensor based on magnetoimpedance element

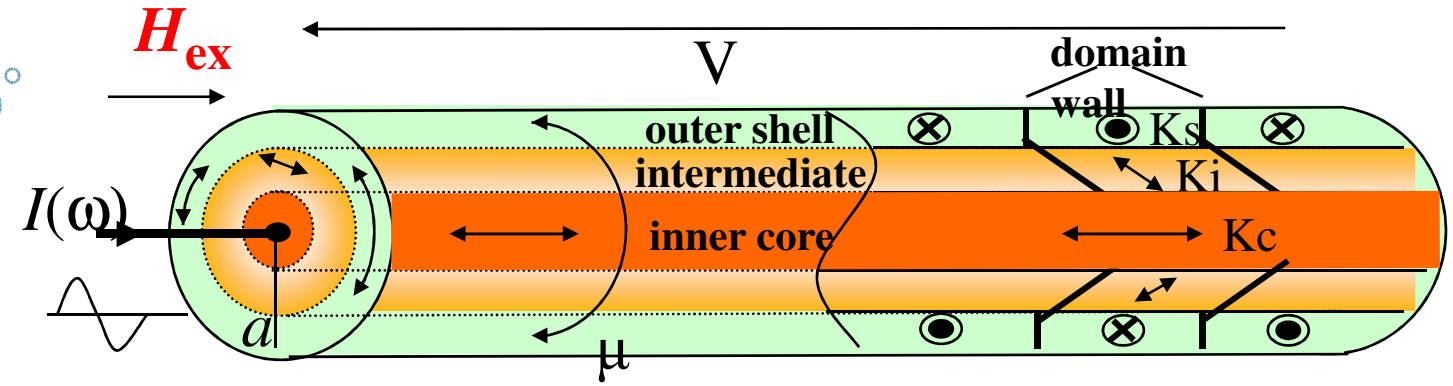
Tsuyoshi Uchiyama

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tutiyama@nuee.nagoya-u.ac.jp

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Domain Structure of Amorphous Wire and Current Magnetization Utilizing the Skin Effect



Skin depth $\delta = \sqrt{\dfrac{2\rho}{\omega\mu\,(H_{ex})}}$

ω : Angular frequency of a current
μ : Maximum differential permeability along the circumferential direction
ρ : Electric resistivity (130 $\mu\,\Omega$-cm)
H_{ex} : Applied dc magnetic field

$$Z = \tfrac{1}{2} R_{dc}\, k\, \alpha\, J_0(k\,a)\,/J_1(k\,a) \qquad k = (1\text{-}j)\,/\delta$$

$$\approx R_{dc} + j\omega L \qquad L = \mu l/8\pi \qquad \text{for } \delta >> \alpha$$

$$\approx \frac{\alpha}{2\sqrt{2\rho}} R_{dc}\,(1 + j)\sqrt{\omega\mu(H_{ex})} \qquad \text{for } \delta << \alpha$$

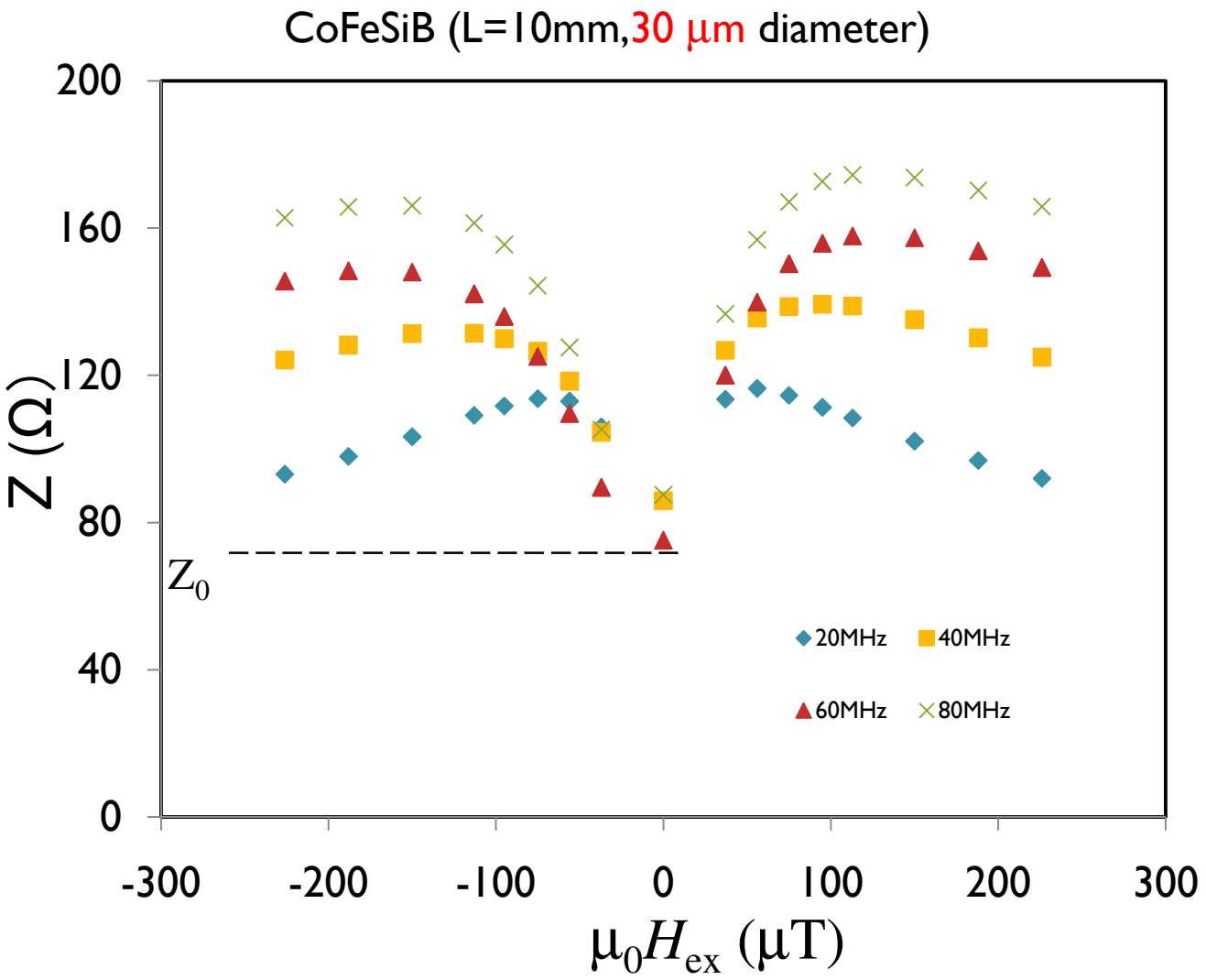
Skin effect

Magnetoimpedance (MI) effect

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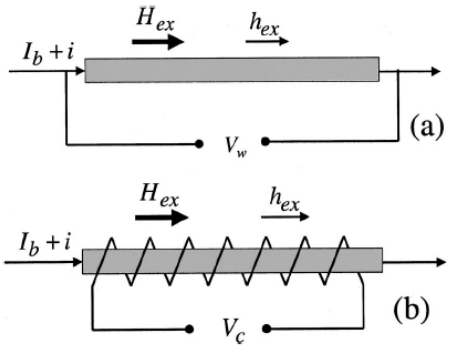
Magnetoimpedance Characteristics of Amorphous Wire



$\Delta Z/Z_0$ is more than100%

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Magnetic Field Response of MI Element



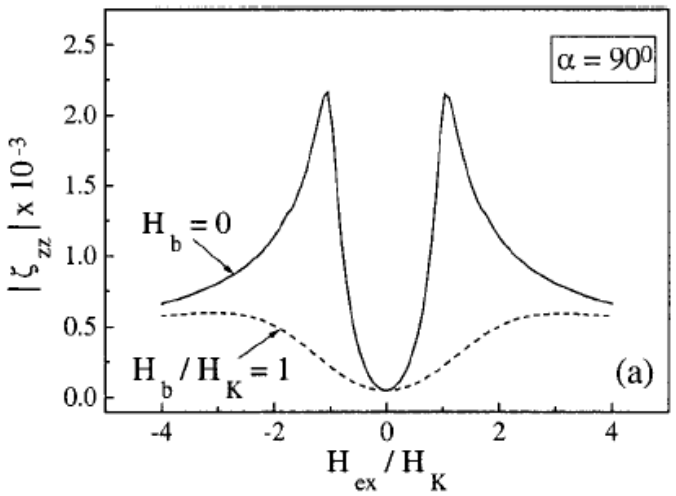
$$V_w = \bar{e}_z L = \left(\varsigma_{zz} \frac{2i}{ca} - \varsigma_{z\varphi} h_{ex} \right) L,$$

$$V_c = \bar{e}_\varphi 2\pi anL = \left(-\varsigma_{\varphi\varphi} h_{ex} + \varsigma_{\varphi z} \frac{2i}{ca} \right) 2\pi anL,$$

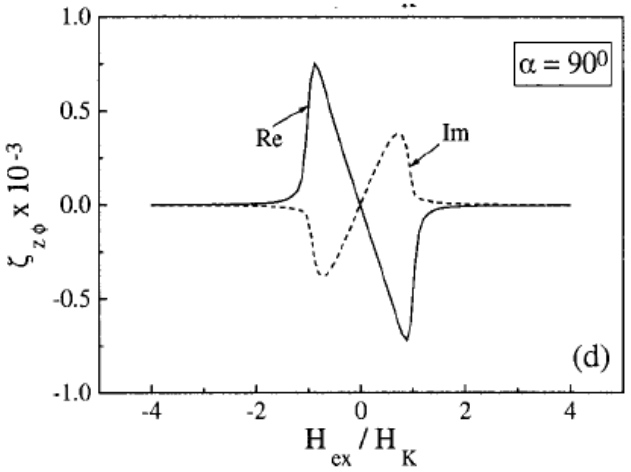
a: radius of the wire
n: number of turns per unit length

Off diagonal component

Impedance



Off diagonal impedance



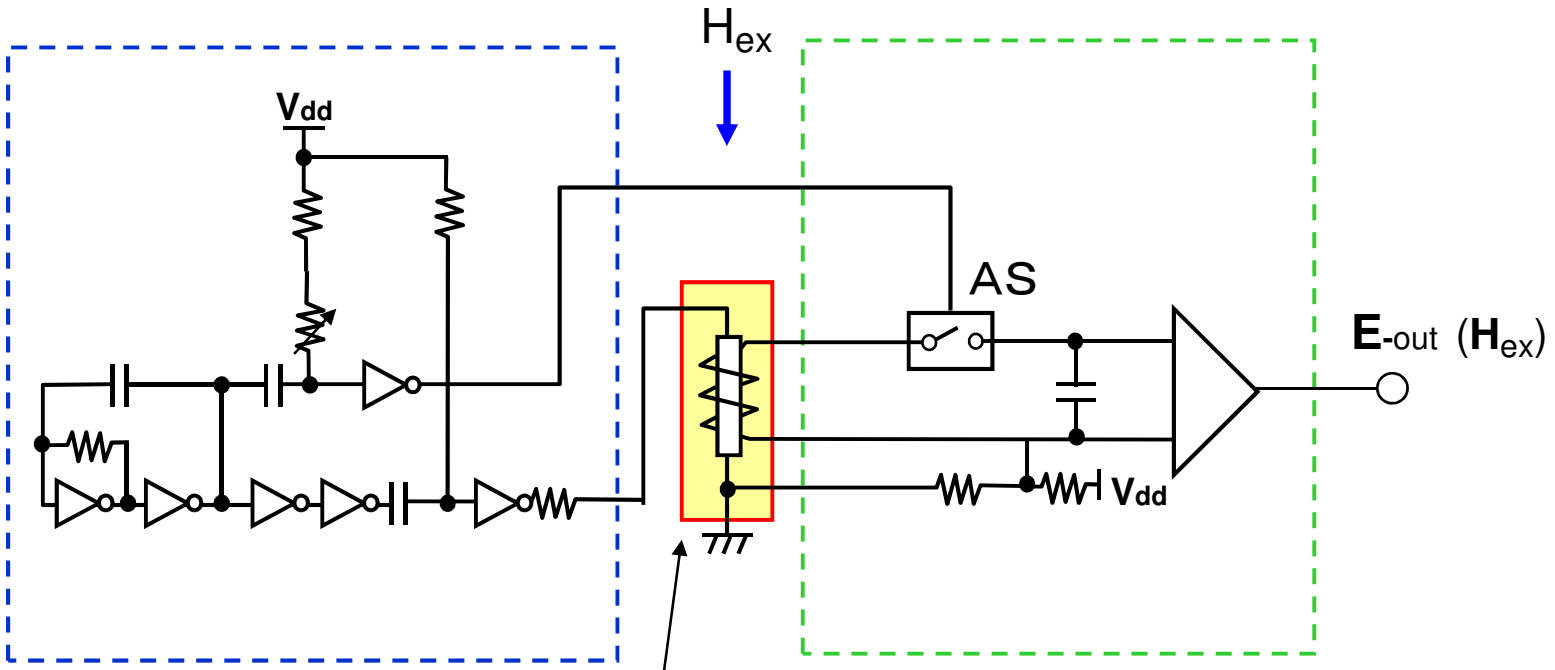
D. P. Makhnovskiy, L. V. Panina, and D. J. Mapps PHYSICAL REVIEW B, VOLUME 63, 144424

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PREVIOUS WORK
(Micro Magnetic wire & OFF diagonal MI sensor)

- S. Gudoshnikov, N. Usov, A. Nozdrin, M. Ipatov, A. Zhukov and V Zhukova, “Highly sensitive magnetometer based on the off-diagonal GMI effect in Co-rich glass-coated microwire,” Phys. Status Solidi A, DOI 10.1002/pssa.201300717 , 2014.
- B.Dufay, S. Saez, C. P. Dolabdjian, A. Yelon, and D.Menard,” Characterization of an Optimized Off-Diagonal GMI-Based Magnetometer,” IEEE Sensors Journal, vol. 13, No. 1, pp. 379- 388, 2013.
- T. Uchiyama, S. Nakayama, K. Mohri, and K. Bushida, “Biomagnetic field detection using very high sensitivity magneto-impedance sensors for medical applications, ”Phys. Status Solidi A 206, No.4, pp.639-643, 2009.
- V. Zhukova, M. Ipatov and A Zhukov, “Thin Magnetically Soft Wires for Magnetic Microsensors,” Sensors 9, 2009.
- S. Sandacci, D. Makhnovskiy, L. Panina, K. Mohri, and Y. Honkura, “Off-diagonal impedance in amorphous wires and its application to linear magnetic sensors,” IEEE Trans. Magn., vol. 40, no. 6, pp. 18–23, 2008.

CMOS Circuit for MI Sensor



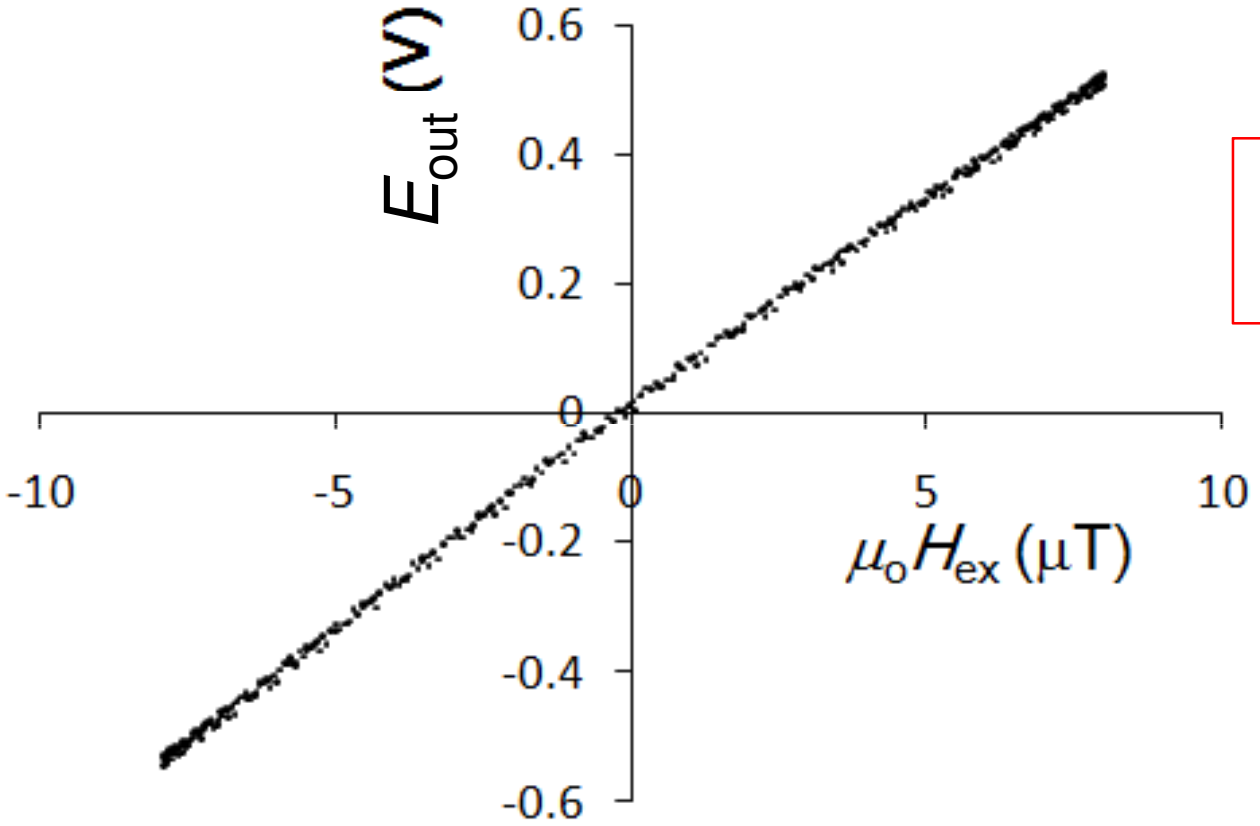
Pulse generation circuit (CMOS multi-vibrator)

Signal processing circuit

MI element with pick-up coil (Amorphous wire)

K. Mohri, Y. Honkura, Amorphous Wire and CMOS IC Based Magneto-Impedance Sensors – Origin, Topics, and Future, SENSOR LETTERS, Vol.5, pp.267-270, 2007.

Magnetic Field Detection Characteristics of CMOS MI Sensor



Sensitivity
70kV/T

Almost no hysteresis : It seems that single like domain structure is realized due to dc component (total amount) of pulse current passing through the a- wire.

Ultra Low Intrinsic Noise

It has been pointed out that magnetic field noise spectral density of the MI element within a simplified model for single domain structure is expressed as

$$\beta = \sqrt{\frac{2\alpha k_B T}{\gamma M_0 \pi a^2 l}}$$

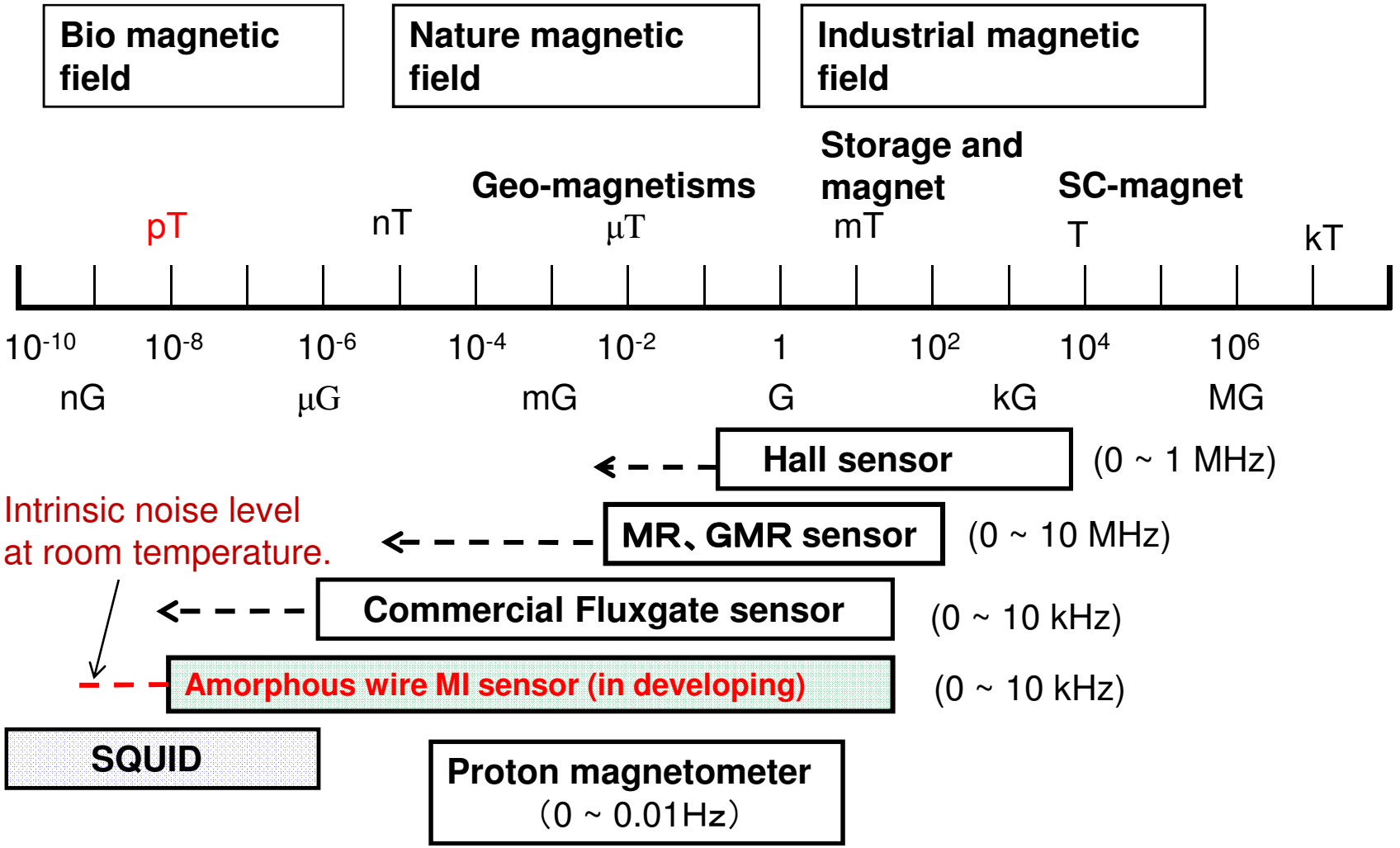
T : the temperature
α : the magnetic damping constant
k_B : is Boltzman constant
g : gyro magnetic ratio
M_0 : saturation magnetization
a : diameter
l : length of a wire element

Intrinsic magnetic noise is approximately 10 fT for 1cm Co- rich amorphous wire at room temperature.

L .G. C. Melo, D. Menard, A. Yelon, L. Ding, S. Saez, and C. Dolabdjian, "Optimization of the magnetic noise and sensitivity of giant magnetoimpedance sensors", *J. Appl. Phys.* vol. 103, pp. 033903-1-03303-6, 2008.

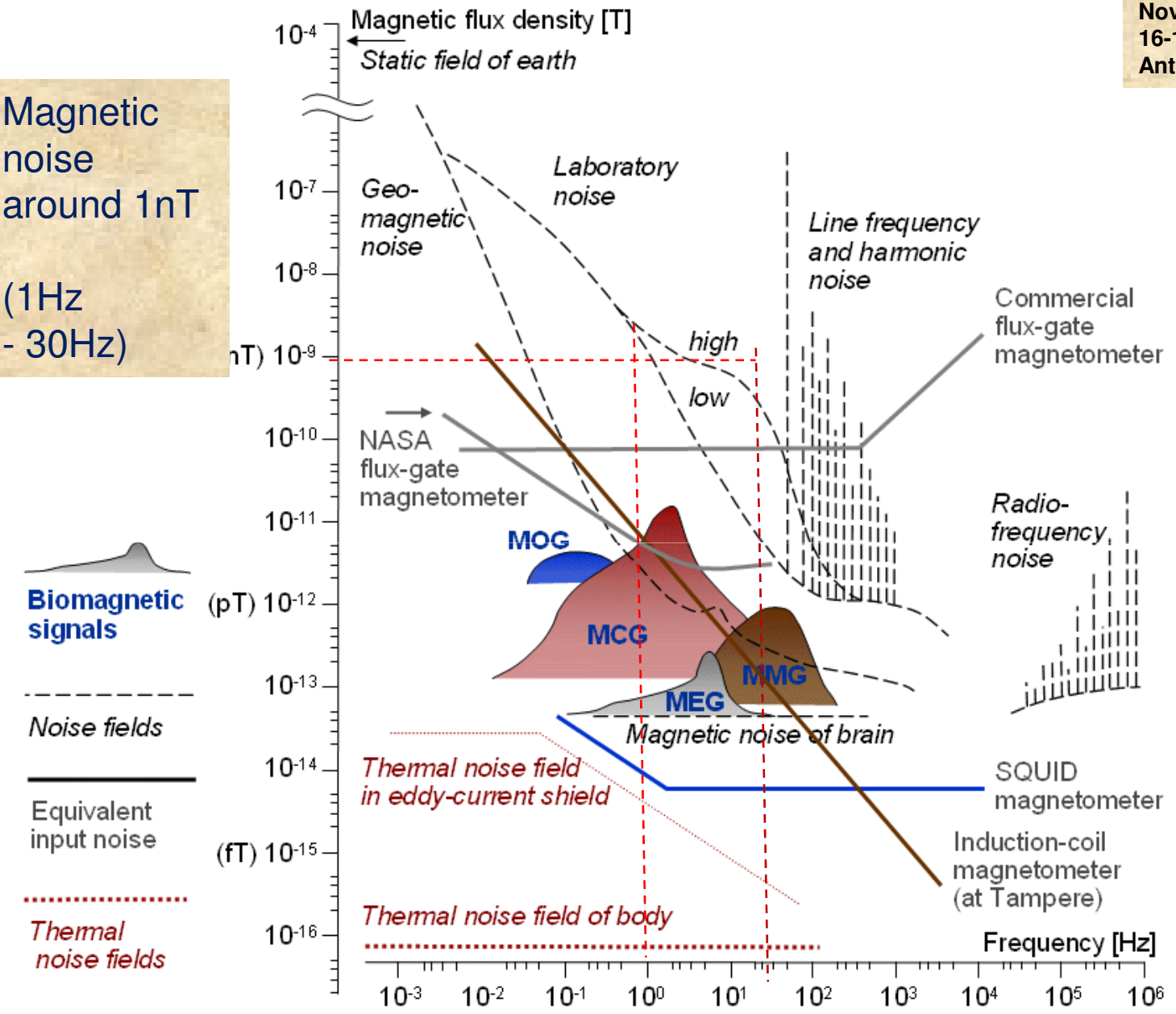
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Magnetic Field and Magnetic Sensors



Magnetic noise around 1nT

(1Hz
- 30Hz)

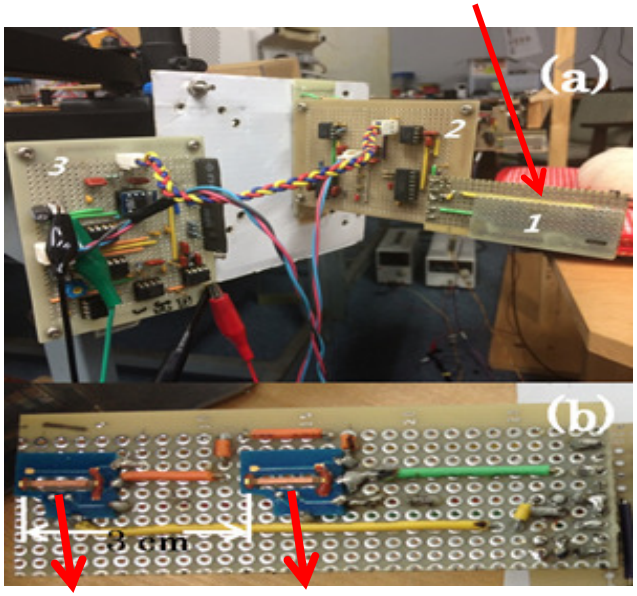


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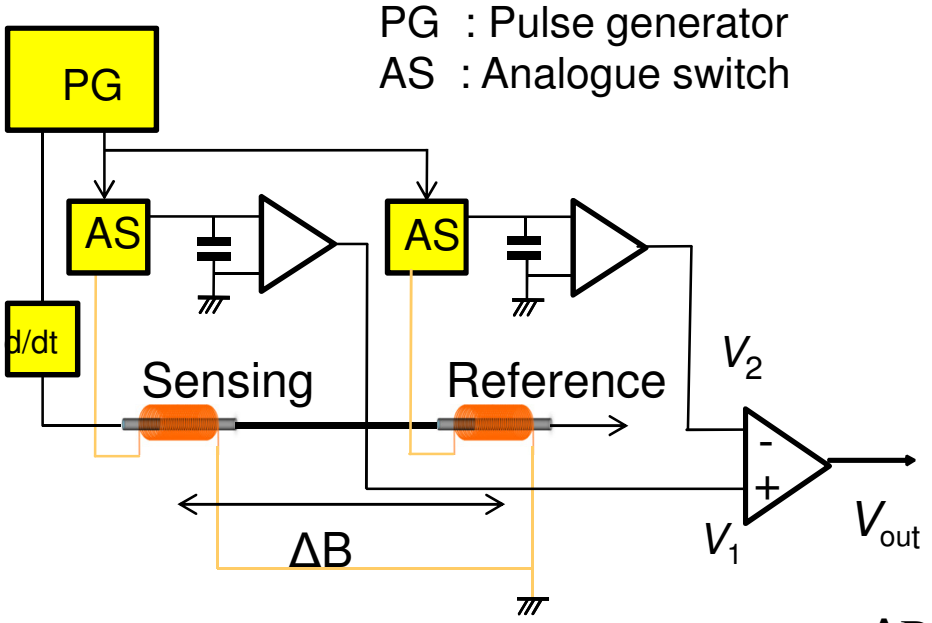
Prototype Biomagnetic Field Measurement System

(First order gradiometer)

MI sensor head

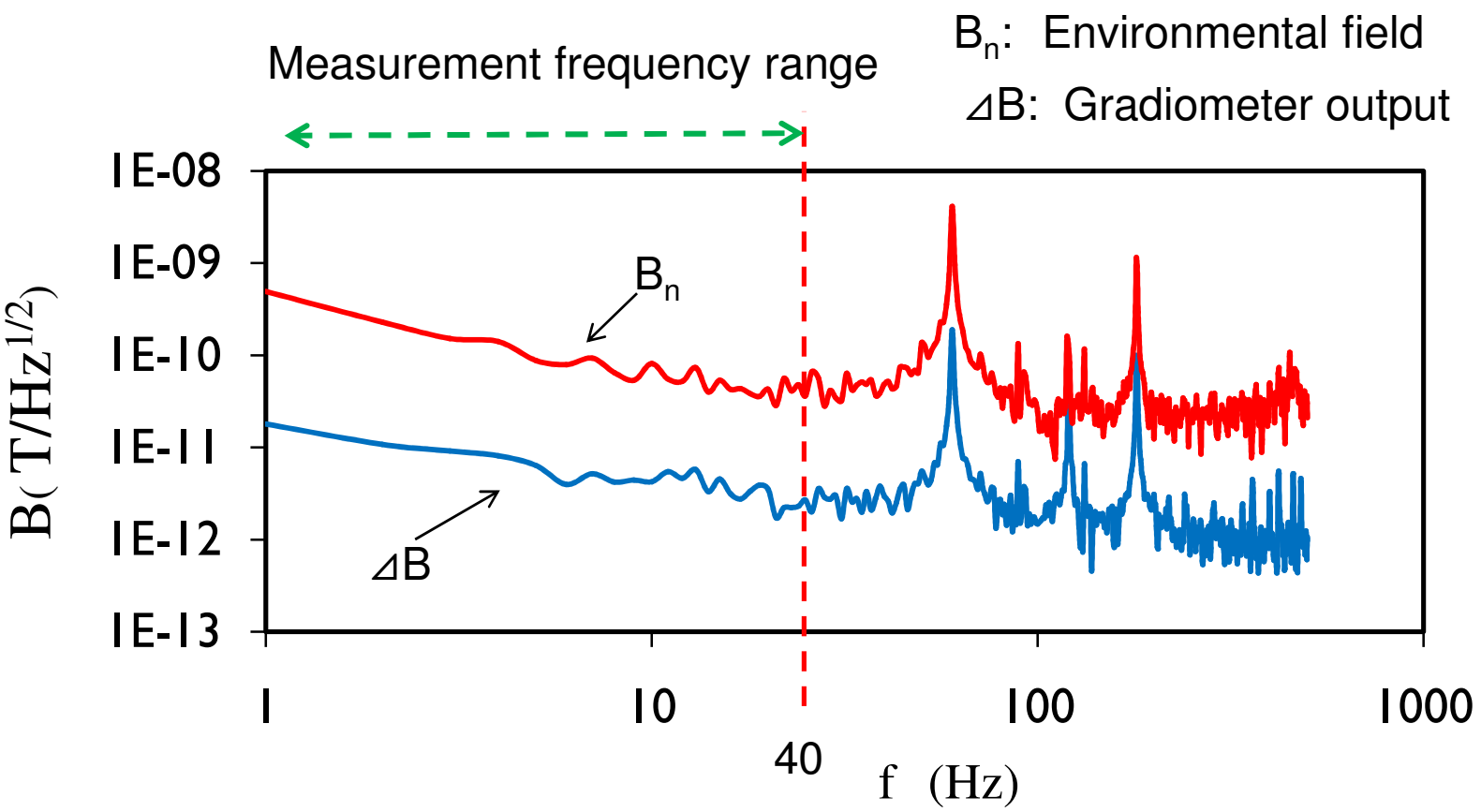


Sensing | Reference



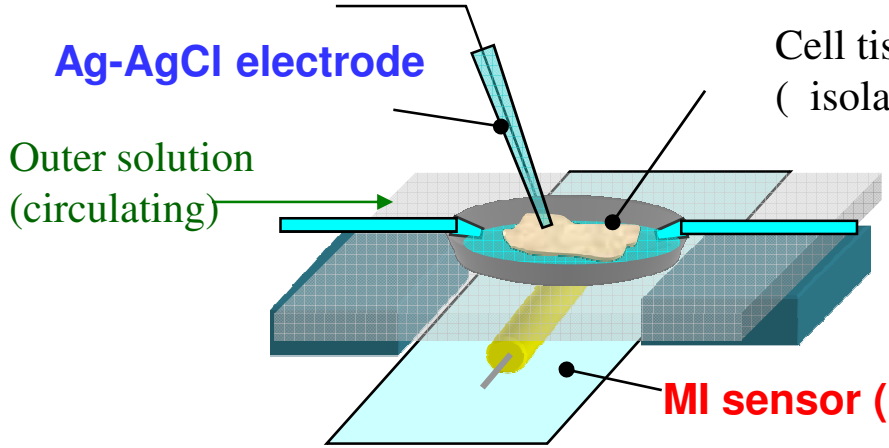
This sensor element was supplied by Aichi Steel Corp..

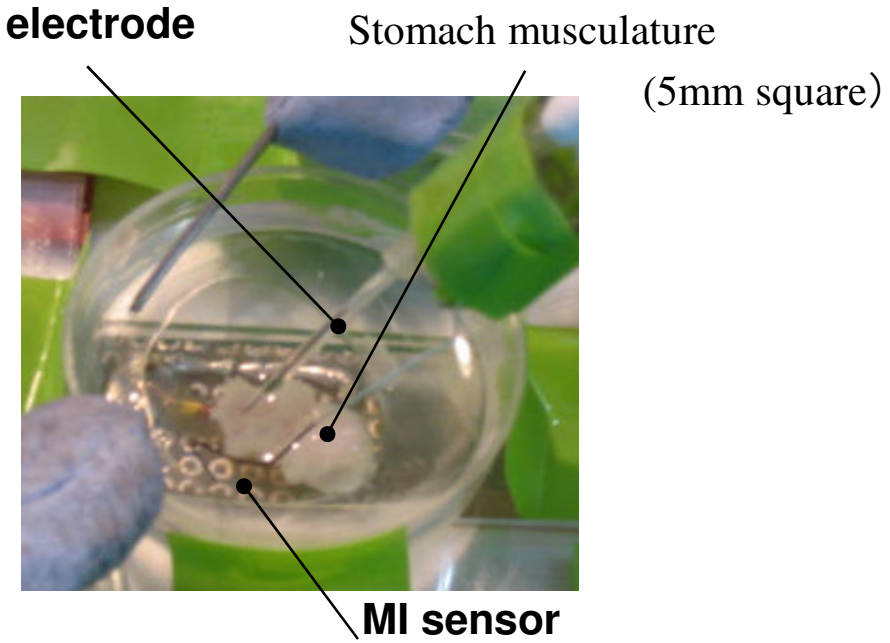
Environmental Magnetic Field in Our Lab



Influence of environmental magnetic field noise as small as 10 pT in the measurement frequency range.

Measurement of Biomagnetic Field from Living Tissue

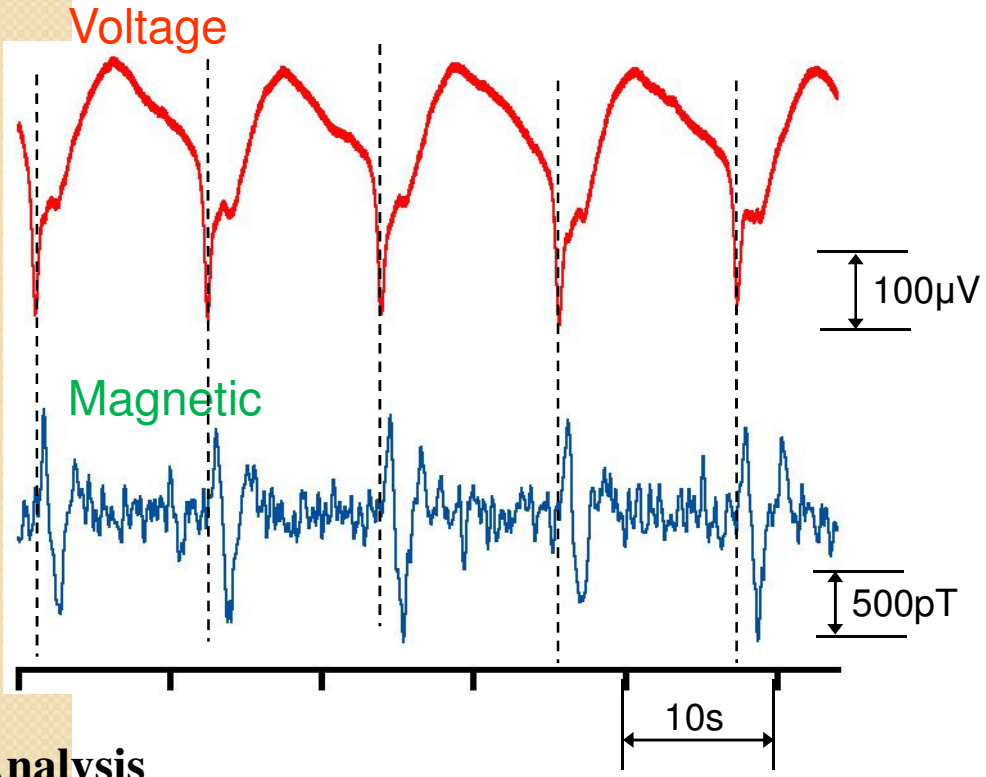


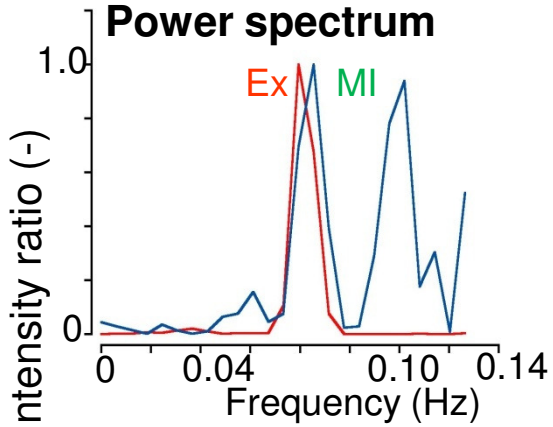


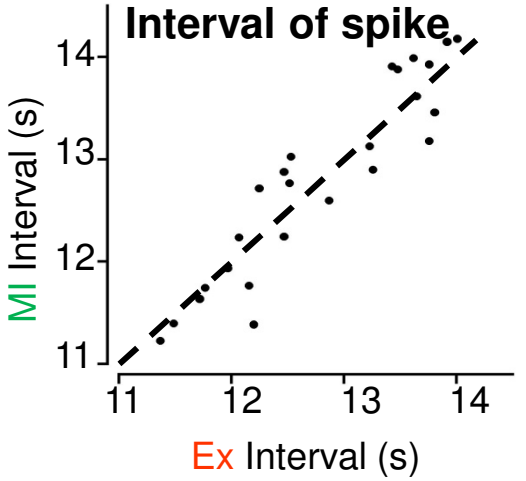
Measurement results ; Biomagnteic field from living tissue sample

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It is known that regular electrical wave is observed in stomach musculature (after isolated)







Analysis

Fundamental frequency corresponds with each other.
The time interval of the spike has correlation y=x (R=0.93).

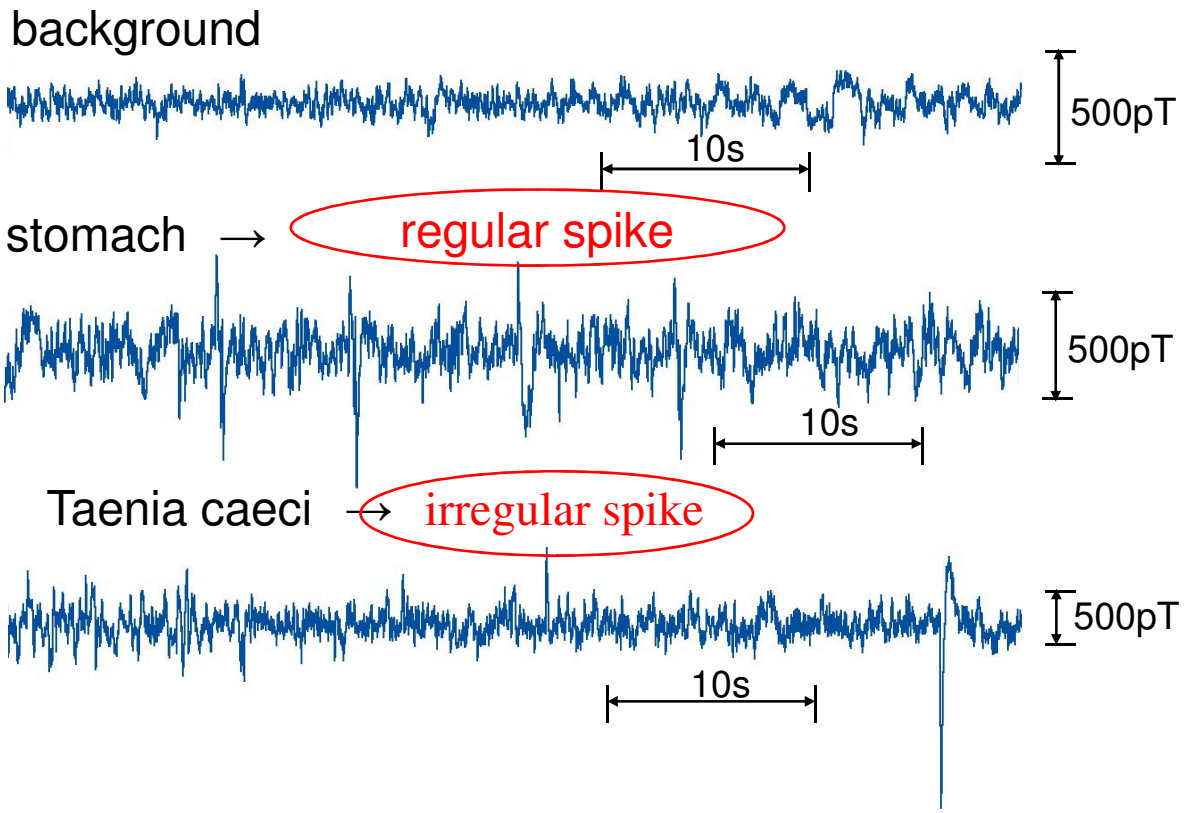
by Shinsuke Nakayama
Graduate school of medicine

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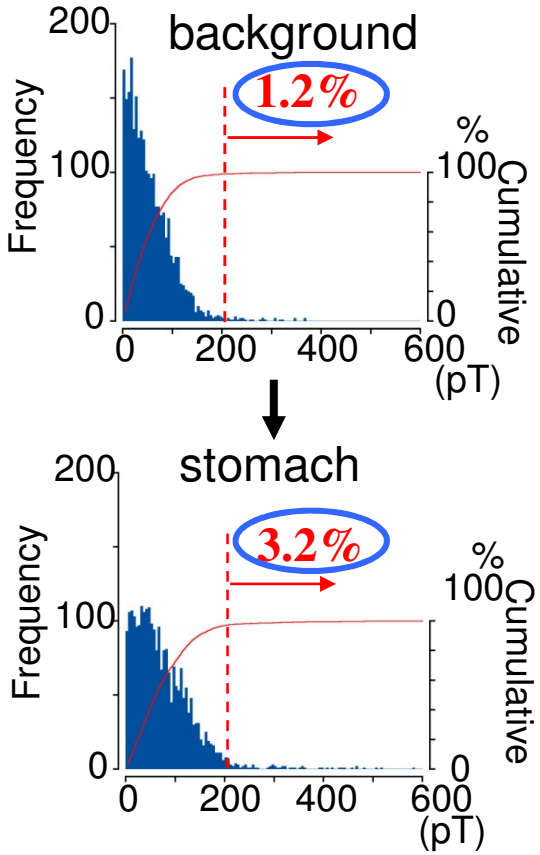
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We have been detect active magnetic field several kinds of smooth muscle preparations

Magnetic field ; cell tissue isolated from guinea pig



Histogram ;



by Shinsuke Nakayama
Graduate school of medicine

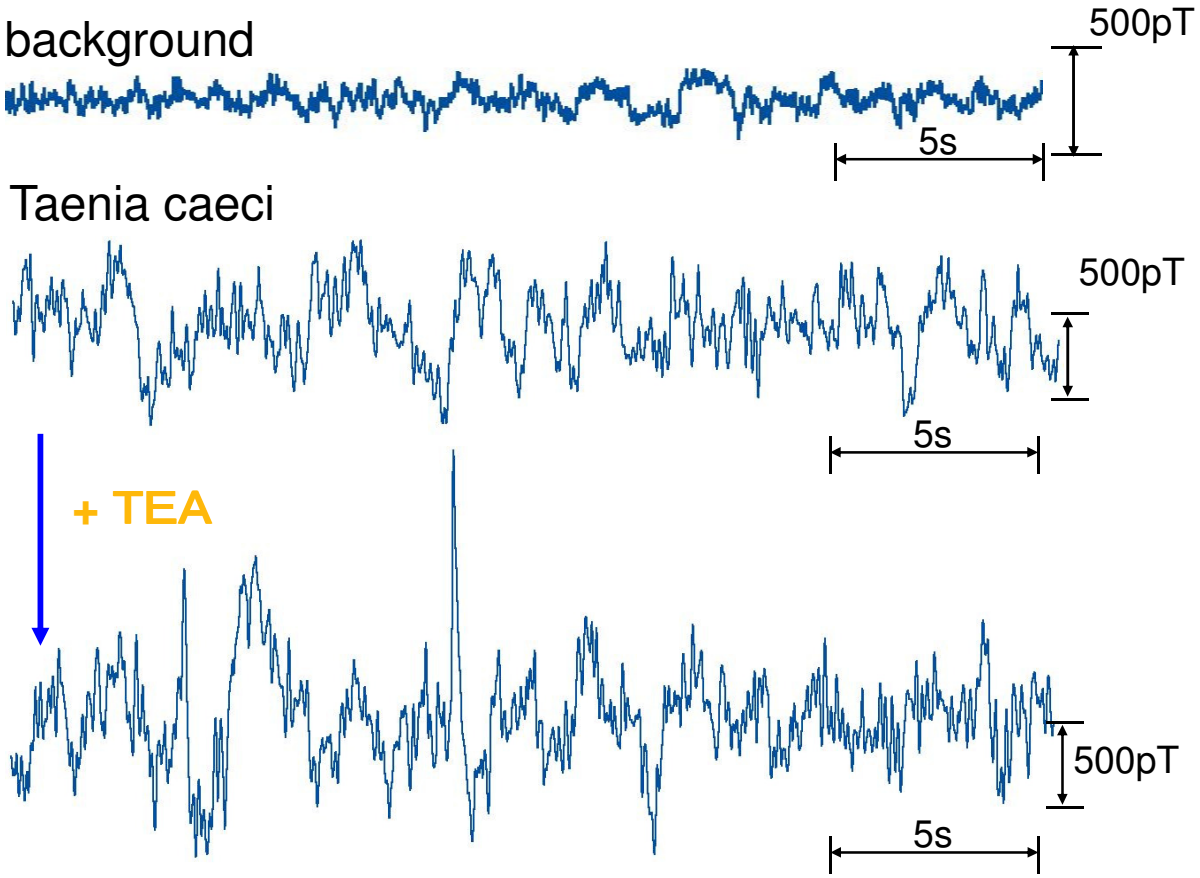
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Effect of T E A (Tetra ethyl ammonium) application

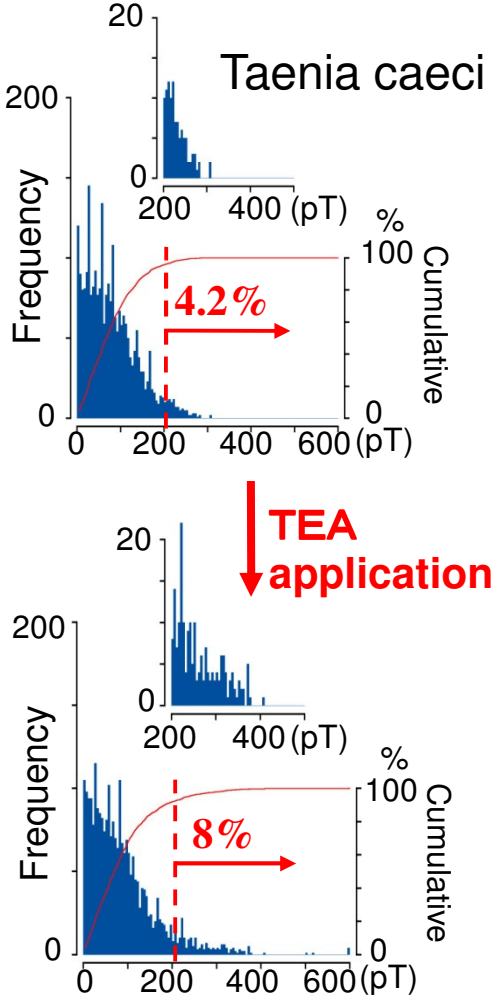
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T E A ; K^+ channel blocker , enhance self electrical activity

Magnetic measurement



histogram ;

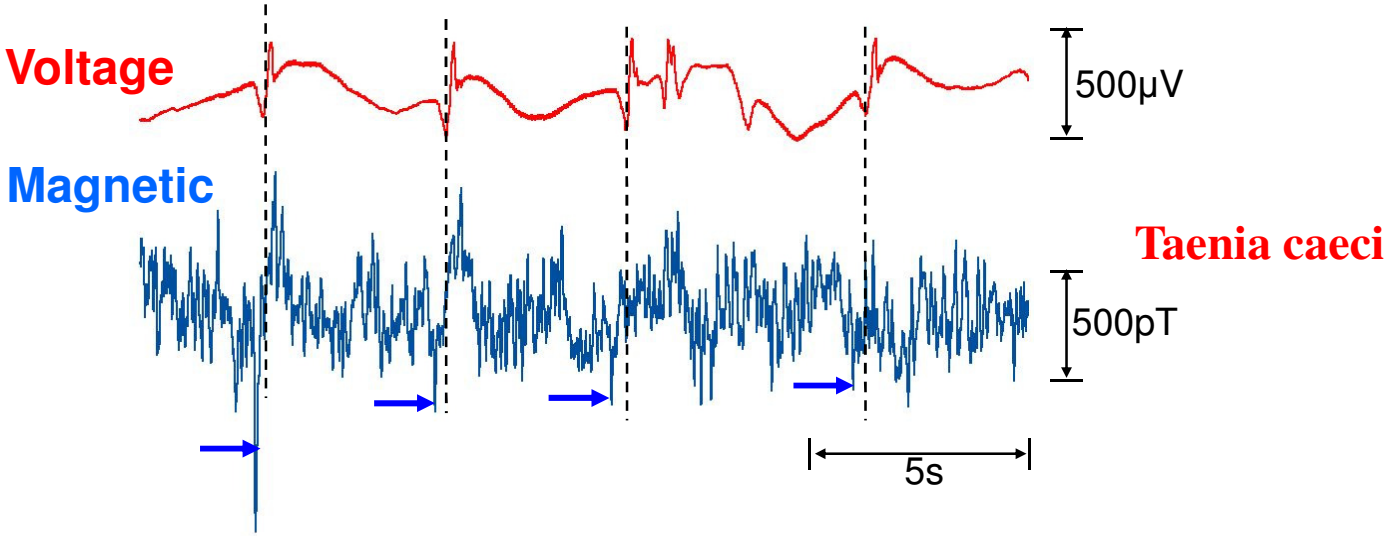


+ TEA →**sharp pulse appears frequently**

by Shinsuke Nakayama
Graduate school of medicine

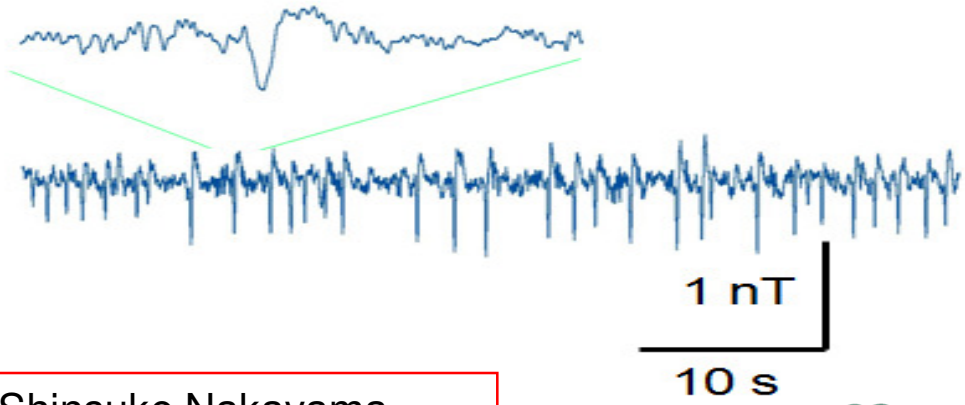
Biomagnteic measurement from different kinds of living tissue

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Taenia caeci

Simultaneously measurement electrical and magnetic activity after Tetraethylammonium (TEA) application.



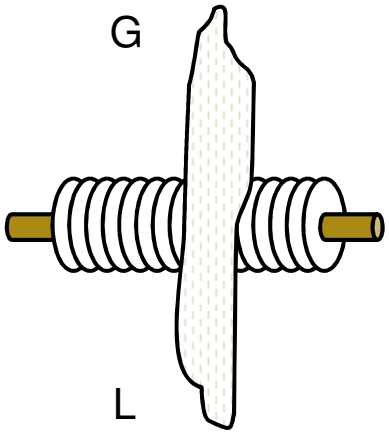
Mouse heart

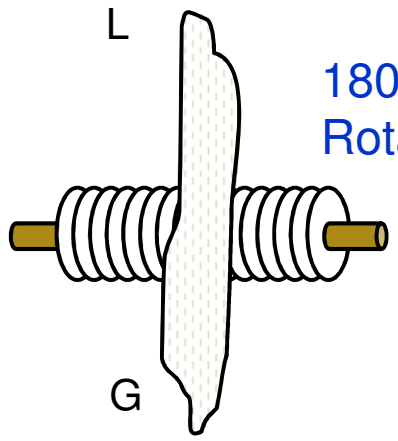
by Shinsuke Nakayama
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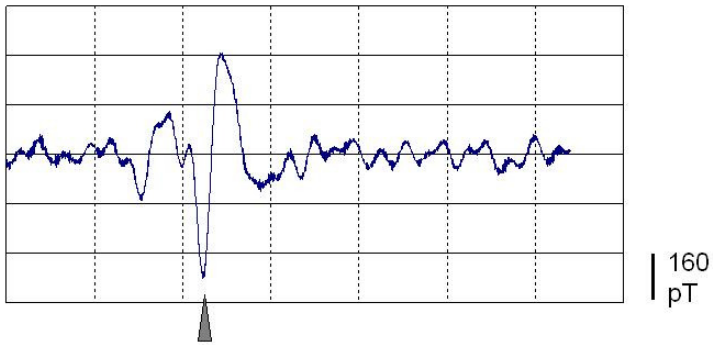
Vector magnetic field depending on current Propagation direction

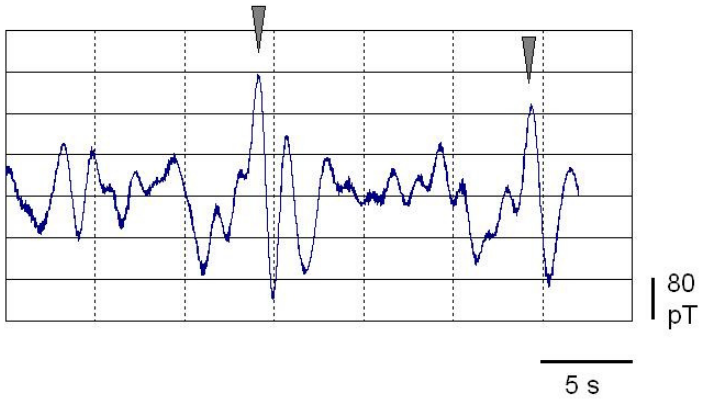
Stomach



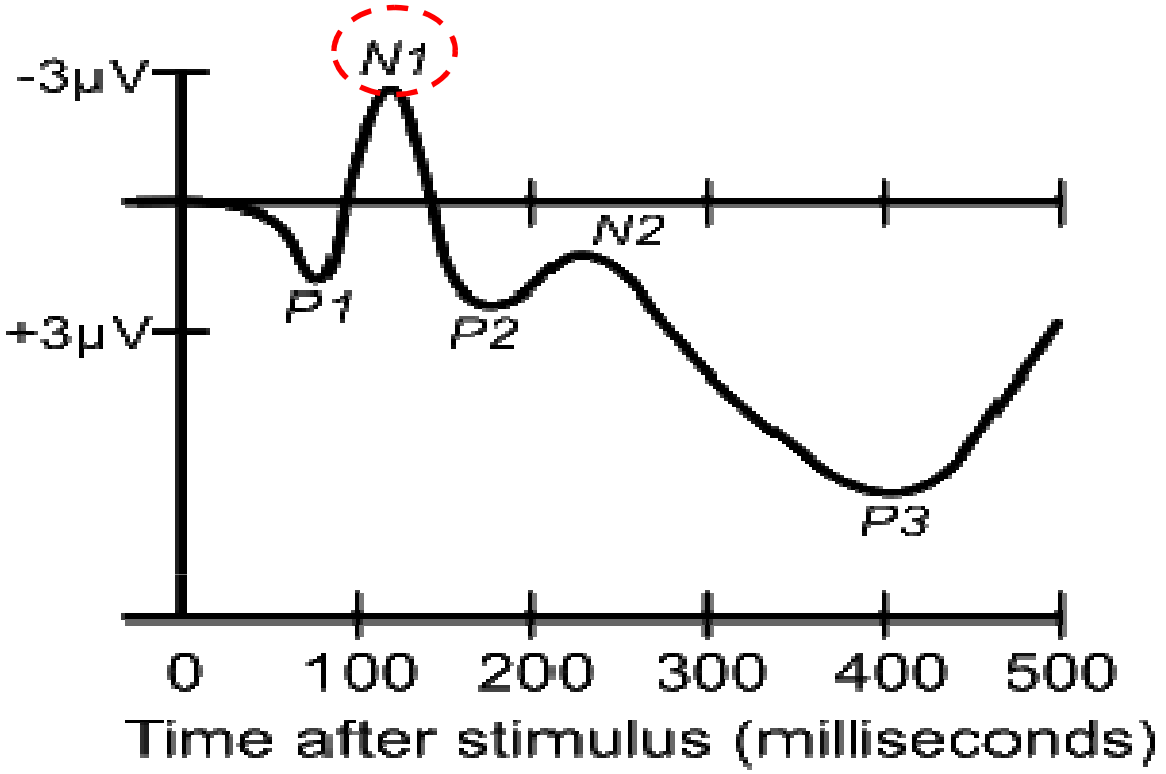


180º
Rotated





Event-Related Potential

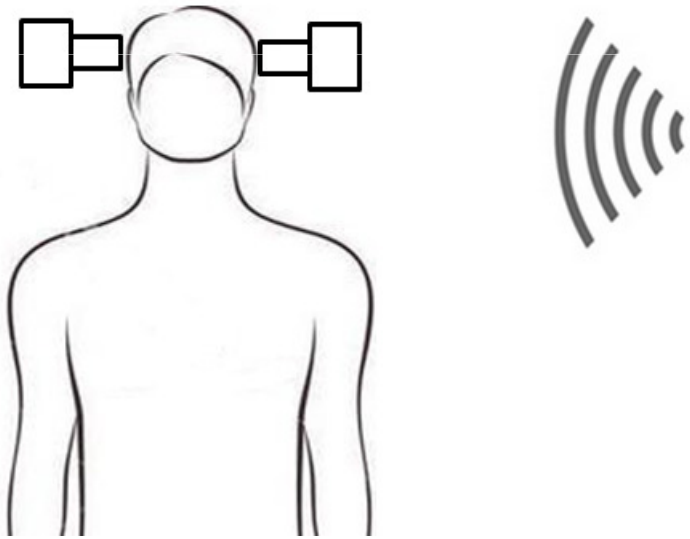


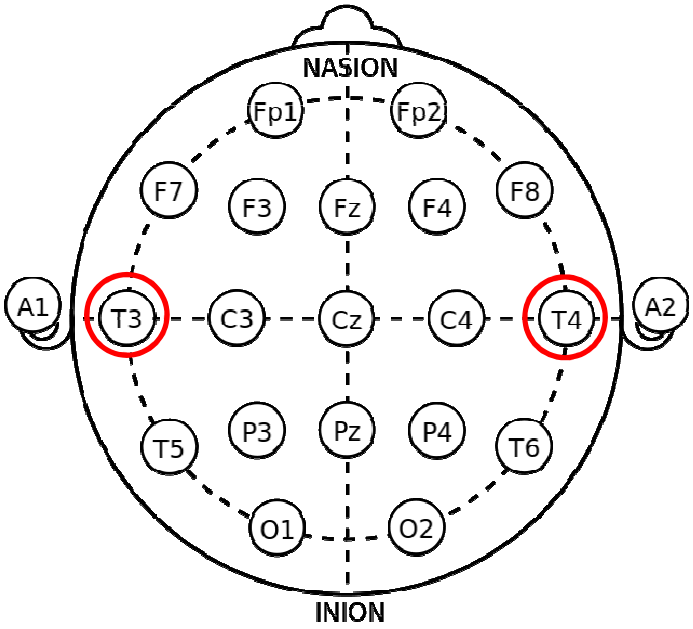
An **event-related potential** (ERP) is the measured brain response that is the direct result of a specific sensory, cognitive, or motor event. More formally, it is any stereotyped electrophysiological response to a stimulus.

We challenged to measure event-related magnetic field

N100 (N1) Experiment : Method

Audio stimuli : f = 1000 Hz
Duration 200 ms
Interval 800ms-1400ms
(random)

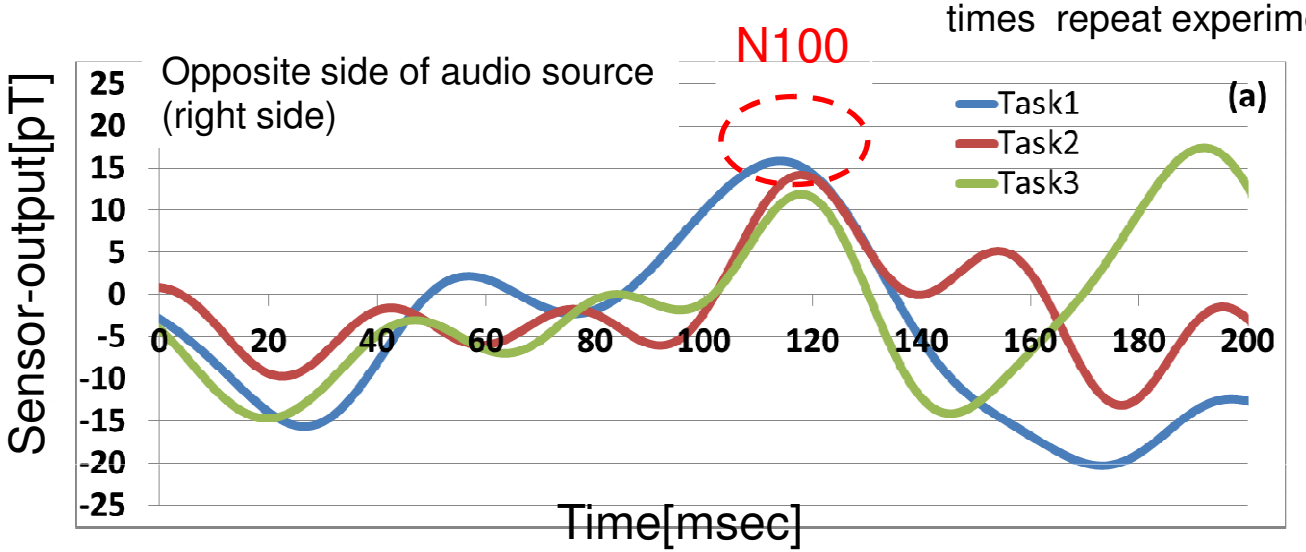




N100 Experiment : Result

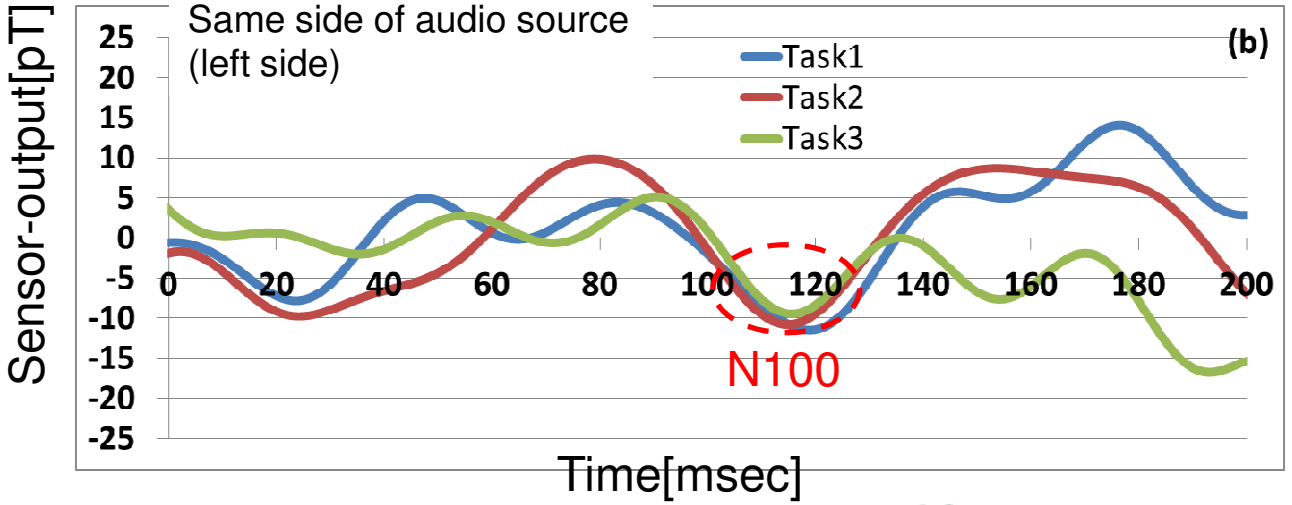
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100 times averaged data (Three times repeat experiment)



Noise level
≒1pT

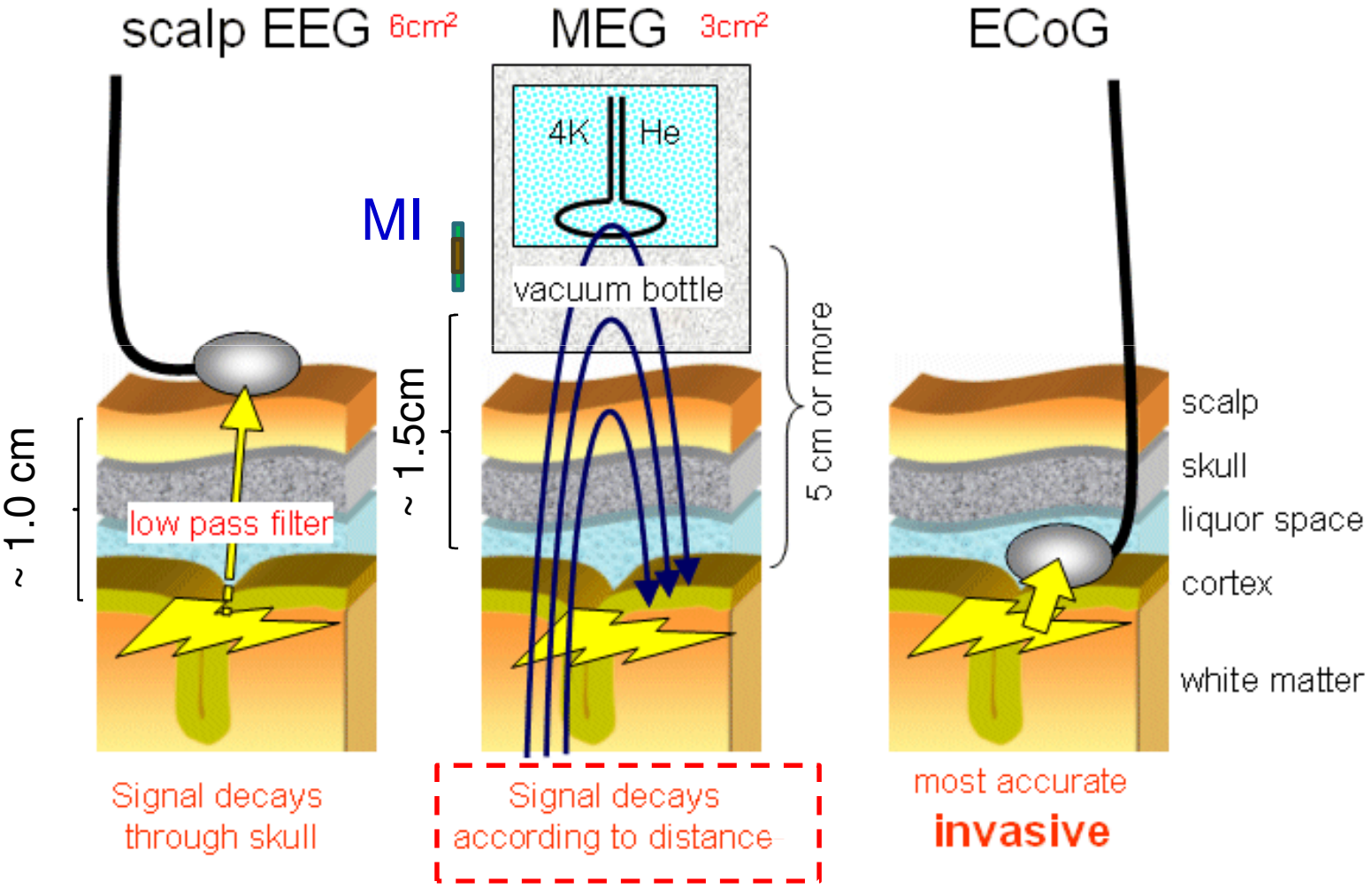
Because of 100 times averaging.



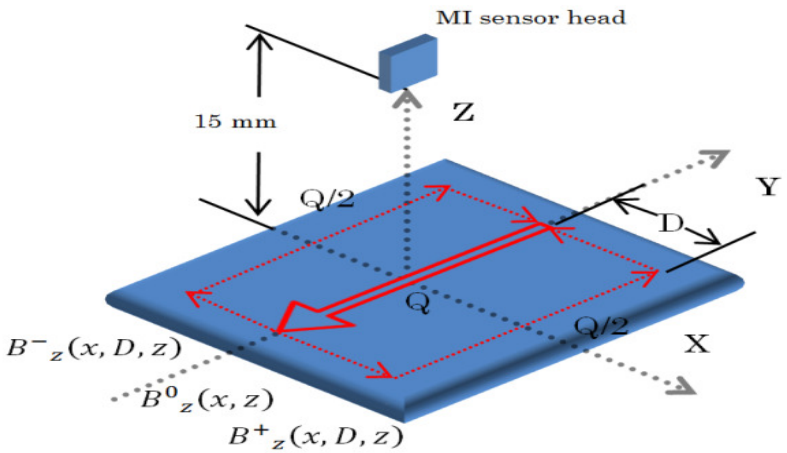
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Discussions

Magnetoencephalography : MEG



Dipole Current Model with Return Current



In this formula, μ0 is the vacuum permeability. Using this model on SQUIDs, where the z is about 60 mm, assuming the Q is 50 nAm for N100 on temporal region[10][11], D is 20 mm and the maximum value of magnetic field of N100 is estimated as 0.090 pT when x is 10.8 mm(experimental value is about 0.08pT[12]). And on MI sensor, z is about 15 mm. The maximum value of magnetic field of N100 is estimated as 10.858 pT. It is approximately 120 times bigger than the estimated value of SQUIDs.

[10] Bernd. Lütkenhöner, Jan-Stefan. Klein, "Auditory evoked field at threshold," Hearing research 228 (2007) 188-200

[11] Timm. Rosburg, "Effects of tone repetition on auditory evoked neuromagnetic fields," Clinical Neurophysiology 115(2004) 898-905.

[12] Godey. B, Schwartz. D, de. Graaf. JB, Chauvel. P, Liégeois-Chauvel. C, "Neuromagnetic source localization of auditory evoked fields and intracerebral evoked potentials a comoarison of data in the same patients" Clin Neurophysiol. 2001 Oct;112(10):1850-9.

$$B_z = \frac{\mu_0}{4\pi}\frac{\mathbf{Q}\times(\mathbf{r}-\mathbf{r_Q})\cdot\mathbf{e_z}}{|\mathbf{r}-\mathbf{r_Q}|^3}. \qquad (1)$$

$$B_z(x,D,z) = B^0{}_z(x,z) + B^+{}_z(x,D,z) + B^-{}_z(x,D,z), \qquad (2)$$

$$B^0{}_z(x,z) = \frac{\mu_0 Q}{4\pi}\frac{x}{\sqrt{(x^2+z^2)^3}}, \qquad (3)$$

$$B^+{}_z(x,D,z) = \frac{\mu_0}{4\pi}\frac{Q}{2}\frac{D-x}{\sqrt{((D-x)^2+z^2)^3}}, \qquad (4)$$

$$B^-{}_z(x,D,z) = \frac{\mu_0}{4\pi}\frac{Q}{2}\frac{-D-x}{\sqrt{((D+x)^2+z^2)^3}}, \qquad (5)$$

Q = 50nA·m

~100 fT for Z = 60 mm (SQUID)

~10 pT for Z = 15mm (MI)

Parameter : D = 20mm

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Summary

We carried out biomagnetic field measurement from living cell tissue using developed precise gradiometer. We have detected magnetic field synchronized with electric potentials at the surface of stomach tissue isolated from guinea pig. Vector magnetic field depending on current propagation direction can be measured. In addition, magnetic field from mouse heart with rhythmical activity can be detected using developed gradiometer system.

We have also tried to measure biomagnetic field from brain of the human. The signal strength of N100 evoked magnetic field measured by MI sensor is compared with the strength measured by SQUID.

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Thank you for your attentions !

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