Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

A Compatible Electrocutaneous Display for functional Magnetic Resonance Imaging application

V. Hartwig, C. Cappelli, N. Vanello, E. Ricciardi, E. P. Scilingo, G. Giovannetti, M. F. Santarelli, V. Positano, P. Pietrini, L. Landini, A. Bicchi

Abstract— **In this paper we propose an MR (Magnetic Resonance) compatible electrocutaneous stimulator able to inject an electric current, variable in amplitude and frequency, into the fingertips in order to elicit tactile skin receptors (mechanoreceptors). The desired goal is to evoke specific tactile sensations selectively stimulating skin receptors by means of an electric current in place of mechanical stimuli. The field of application ranges from functional Magnetic Resonance Imaging (fMRI) tactile studies to augmented reality technology. The device here proposed is designed using safety criteria in order to comply with the threshold of voltage and current permitted by regulations. Moreover, MR safety and compatibility criteria were considered in order to perform experiments inside the MR scanner during an fMRI acquisition for functional brain activation analysis. Psychophysical laboratory tests are performed in order to define the different evoked tactile sensation. After verifying the device MR safety and compatibility on a phantom, a test on a human subject during fMRI acquisition is performed to visualize the brain areas activated by the simulated tactile sensation.**

I. INTRODUCTION

Microstimulation technique of tactile receptors by using electric current has been largely used to study the specific role of several types of mechanoreceptors and characterize their functional properties [1]. Passing small electric currents through microneurography electrodes placed directly on the nerve ending of the receptors, it is possible to evoke several localized sensations such as flutter or pressure.

Many authors have proposed several techniques to record this sensation in awake human: Trulsson et. al. [2] demonstrated that intraneuronal microstimulation of single afferents produces robust hemodynamic responses in somatosensory cortex that can be measured using functional Magnetic Resonance Imaging (fMRI) technique.

Another technique of electrical stimulation of skin receptors is known as *"electrocutaneous stimulation"*: with the term electrocutaneous (or electrotactile) is intended the evocation of a tactile sensation using an electric current flowing through the skin, via electrodes placed on the skin surface. A device that stimulates nerve afferents within the skin by electric current is known as "electrocutaneous display" and can be constituted by several surface electrodes. Several papers report the use of this technique in sensory substitution system for blind or deaf persons [3][4] and in training for prostheses use. Electrocutaneous stimulation has been also used in augmented reality and telepresence in order to provide the user with tactile information [5].

The mechanism of tactile stimulation was first described in literature approximately in 1960 and the first tactile display was proposed in 1970 [6]. It was based on the principle that an electric current pulse from surface electrodes generates an electric field inside the skin, which induces nerve activity.

Approximately 44% of mechanoreceptors lying into the human hand are found to be slowly adapting (SA) (i.e., they also respond with a sustained discharge to static tissue deformation), while the remaining are fast adapting (FA), only responding to the rate of skin indentation and its higher derivatives. Depending on the extension of their receptive fields, SA and FA tactile units can be subdivided into two categories: type I have restricted and sharply defined receptive fields and type II have larger fields and less precise contours. The correspondence between SAI and Merkel's complexes, FAI and Meissner corpuscles, SAII and Ruffini's endings, and FAII and Pacinian corpuscles is widely accepted [7]. Each class of mechanoreceptors responds to skin deformation and motion in a different way: if it could be possible to find the electric current which is able to elicit selectively each kind of afferent fibers analogously to mechanical stimulus, any sensation could be evocated by combining specific inputs.

Kajimoto et al. [8] have already shown that electrical selective stimulation is possible using anodic or cathodic current: they called the specific stimuli "tactile primary colours" in analogy to the visual system and its primary colours (red, green and blue).

Here we investigate the possibility of using electrotactile stimulation in order to evoke specific sensations related to specific types of mechanoreceptors varying the amplitude

Manuscript received April 24, 2006. This work was supported by E. U. project ImmerSence IST- 4-027141.

Valentina Hartwig, Claudia Cappelli, Nicola Vanello, Enzo Pasquale Scilingo, and A. Bicchi are with Interdepartmental Research Center "E. Piaggio", University of Pisa, Italy (e-mail: corresponding author valeh@ifc.cnr.it; claudia.cappelli@katamail.com; nicvanel@ifc.cnr.it; e.scilingo@ing.unipi.it; bicchi@ing.unipi.it)

G. Giovannetti, V. Positano, M. F. Santarelli and L. Landini are with the MRI Laboratory, CNR Institute of Clinical Physiology, Pisa, Italy (e-mail: giovannetti@ifc.cnr.it; positano@ifc.cnr.it; santarel@ifc.cnr.it; llandini@ifc.cnr.it)

E. Ricciardi and P. Pietrini are with Laboratory of Clinical Biochemistry and Molecular Biology, University of Pisa, Italy (e-mail: emiliano.ricciardi@bioclinica.unipi.it; pietro.pietrini@bm.med.unipi.it)

1-4244-0033-3/06/$20.00 ©2006 IEEE.

and the frequency of the stimulating electric signal, but maintaining the same waveform. We hypothesize that, according to a different specificity of the mechanoreceptors at different mechanical stimulus, [9] there might exist receptor specificity for different amplitude and frequency of electrical stimulus. In this case it could be possible to stimulate specifically several type of mechanoreceptors maintaining the same waveform and varying only its amplitude or frequency, with the possibility of creating different sensation for fMRI tactile studies and augmented reality application. In several virtual reality applications, the electrostimulation could be a viable solution in substituting for tactile displays, increasing the augmented reality performance.

In order to verify the evocation of a tactile sensation by means of the electrical signal, we use the fMRI technique [10].

II. METHODS

A. Safety Criteria

As the microstimulation is performed by an electric device, *safety criteria* for electric safety, in terms of high voltage and pulsed current, were considered and studied [11]. Moreover, the design of the electric microstimulator was developed in accordance to results from MR safety and compatibility studies. The observance of these criteria is a crucial aspect in view of performing specific experiments inside the MR scanner during a fMRI acquisition of brain functional activation.

Before introducing any device into the MR suite, MR safety and compatibility of the device and its operation in the magnetic field should be carefully verified according to systematic rules and procedures [12]. Hence, in order to design a new device which allows tactile stimuli inside the MRI scanner environment during fMRI studies, definitions and classifications regarding MR safety and compatibility and the interaction between MRI primary components and mechatronic devices have been considered. The FDA (Food and Drug Administration) document on medical device interactions with Magnetic Resonance Imaging systems [13] reports the most descriptive definitions and classifications regarding MR safety and compatibility that should be used for experimental protocols of compatibility evaluation.

B. Design of the Stimulation Device

The stimulator device is supplied by low power batteries and is able to generate high voltage pulses; it is equipped with two independent channels for stimulation of both hands. By means of a couple of potentiometers for each channel, it is possible to set the output voltage amplitude and frequency values, in order to vary the kind of the stimulus and obtain different sensations due to specific classes of stimulated mechanoreceptors.

The output voltage ranges from 0 to 450 V, while frequency varies between 90 and 110 Hz; however because of the very high skin impedance the electric current flowing is 1-2 mA. The output waveform is a pulsed decreasing exponential wave. This permits to reduce the Joule effect produced by the electric current flow through the skin. According to the electric safety criteria the stimulator device is floating and supplied by batteries.

According to the MR safety and compatibility criteria, the part which should be placed within the scanner room does not present metallic materials. For this reason, the stimulator pad is created choosing MR-compatible and non-toxic materials, Plexiglass and Aluminum, because it has to be placed on the subject hand inside the scanner room. Two 1mm x 1mm Aluminum square electrodes, at distance of 5 mm, are fixed on the pad.

Coaxial cables are used to connect the two stimulator electrodes inside the MR scanner room with the device inside the console room in order to minimize RF interferences.

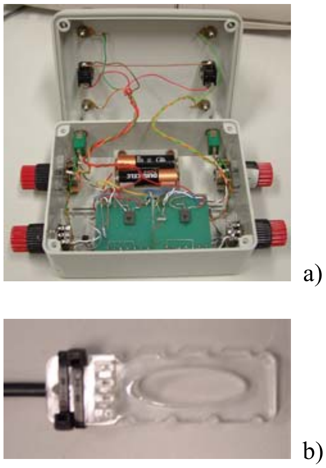

Fig. 1. Photo of a) designed electrical stimulator internal, b) stimulator pad with two aluminum electrodes.

C. Device Set Up

Before testing the device during a fMRI acquisition, we performed several psychophysical experiments in laboratory. A group of subjects, stimulated by an electric current which was varied in amplitude and frequency, was asked to report the perceived tactile sensation. Specifically, starting from the lowest amplitude and highest frequency, the electric current was firstly increased in intensity up to subjects felt some sensation. In the 95% of the cases the sensation was defined like a slipping, vibration sensation.

Afterwards, we decreased the frequency of the electric current down to subjects were able to feel a different sensation. In the 90% of the cases this second sensation was defined like a pin-prick sensation.

According to [7], *Meissner* corpuscles (RA1 afferents) are very sensitive to dynamic skin deformation and they transmit a robust neural image of skin motion. For this reason, we can hypothesize that the specific value of amplitude and frequency used in the first case, in which subjects perceived slipping sensation, could elicit RA1 receptors.

Instead, *Merkel* corpuscles (SA1 afferents) are more sensitive to points, edges and curvature, which is a consequence of their selective sensitivity to strain energy density. They are responsible for shape, orientation and texture perception. Therefore, we can conjecture that, the specific value of amplitude and frequency of the electric current achieved in the case where subjects felt pin-prick sensation, could be responsible for eliciting SA1 receptors.

D. MR Safety and Compatibility Test

The designed device was examined in a MR environment (Signa Horizon 1.5T, GE Medical Systems) during image acquisition in order to test its MR safety and compatibility. We placed the device inside the console room and the stimulator electrode inside the scanner room on the patient bed in the right position for the stimulation task on a patient (the cable that connects the stimulator electrode to the device passed through the wire guides of the MR shield).

During the test we scanned a spherical phantom of $CuSO_4$ solution, using a GE-EPI (gradient echo, eco planar imaging) with the following parameters: TE/TR 40/3000 msec, bandwidth 62.5 kHz, FOV 24 cm, resolution 64x64 pixels, Flip angle 90°, Slice thickness 5 mm, number of slices 25, 25 volumes acquired: this is a common use sequence for fMRI studies. After the images acquisition the Signal to Noise Ratio (SNR) was calculated [14]. As a second parameter we estimated the standard deviation of the image intensity time course (*SD*) in each image sequence.

We looked for differences between image sets acquired with no device (reference images) and the image sets acquired with the electrode placed on the patient bed in several conditions: no electric current and electric current with different amplitude and frequency for different sensation stimulations. In order to evaluate the device compatibility with the MR environment it is not sufficient to compare the two sets of images because several artifacts are not visible, so we used statistical t and z tests to detect parameter differences [15]. The analysis of these images and the application of the statistical tests to the images, confirms the compatibility in MR–environment and the absence of unexpected and dangerous effects.

E. fMRI Acquisition on a Subject

After the evaluation of MR safety and compatibility of the device, we performed a pilot fMRI study on one subject.

The subject was a female 27 years old: she has been lain down on the sliding bed and the operator placed the birdcage head coil around her head. The stimulator electrode was placed on the subject left index finger and fixed in order to avoid relative movements.

First of all we acquired the anatomic image of the subject brain and subsequently we performed a functional study using a classical fMRI sequence (GE-EPI: TE/TR 40/3000 msec, bandwidth 62.5 kHz, FOV 24 cm, resolution 64x64 pixels, Flip angle 90°, Slice thickness 5 mm, number of slices 25, 25 volumes acquired).

In order to explore brain activity during electric stimulation by using fMRI we used a block design approach with a stimulation of 10 seconds, an interstimulus interval of 20 seconds, an initial and a final baseline condition of 25 seconds each (total number of stimulation interval=8). The choice of this experiment block designed was guided by safety criteria (for example the Joule effect presence) and analysis criteria (the stimulus intervals have to be short to avoid saturation effects on the receptors).

The fMRI acquisition involved the following runs:
Run 1: stimulation with specific value of amplitude and frequency of electrical signal in order to obtain a relative slipping sensation between the electrode and the subject finger.
Run 2: subject finger stimulation moving, by an operator in the scanner room, a piece of velvet in order to obtain a functional activation of a real tactile sensation.
Run 3: stimulation with specific value of amplitude and frequency of electrical signal in order to obtain a pin prick sensation on the subject finger.

Before the acquisition, a calibration of the device was made asking to the subject what kind of sensation she perceived.

III. EXPERIMENTAL RESULTS

For every one of the three stimulation runs performed, a robust hemodynamic response was observed. Fig. 2 shows the results for run 1, which are typical of all data acquired.

In correspondence of the primary sensorimotor cortex (SI) area [10], the statistical analysis (performed using AFNI [16]) shows a neuronal activation; this confirm the hypothesis that the electric current caused a tactile sensation.

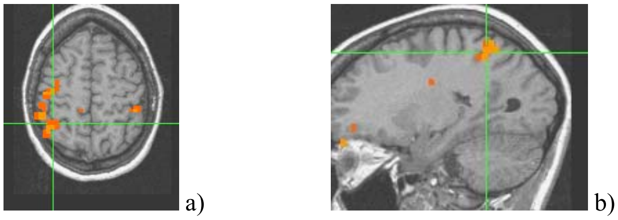

Fig. 2. Cortical activation during run 1 (slipping sensation). a) axial view, b) sagittal view.

The graph in Fig. 3 shows the correlation between the stimulation block and the intensity level for an image pixel that corresponds to the hemodynamic response: it is possible to note the good correlation between the stimulus intervals (red line, high intervals) and the activation.

Low frequency fluctuations are usually observed in fMRI time series. These may be related to long range physiological changes or slow movements of the subjects' head. For acquisition lengths of some minutes these changes can be modelled with a linear ramp. The raw data in Fig. 3 show an offset linear with time. Neural activity related to signal changes are small with respect to the baseline level and may be hidden by noise. In this task even electrodes displacement due to subject finger movement may occur. For this reasons it is difficult to judge signal behaviour related to each single event, and the correlation between the entire time series and the stimulus paradigm must be evaluated.

These results demonstrate unequivocally that the electric stimulation really produces a robust hemodynamic response in the SI cortex, where touch resides, and it can be measured using fMRI.

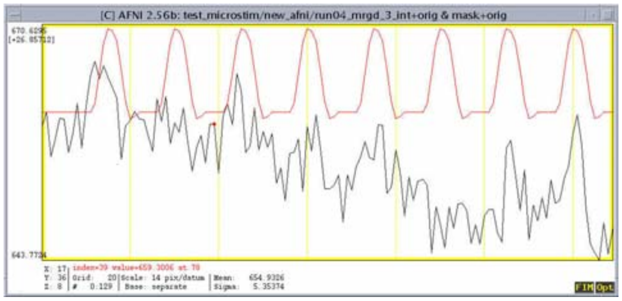

Fig. 3. Activated area pixel intensity (bottom black line) and electrical stimulus (up red line) time evolution.

IV. DISCUSSION AND CONCLUSIONS

The goal of this work was to investigate on the possibility of stimulating selectively different mechanoreceptors to evoke specific tactile sensations by means of injection of electric current through the finger skin. Possible fields of application are fMRI tactile studies or augmented reality technology. In this preliminary work we described the first prototype of an electric stimulator, verifying the MR safety and compatibility, and performed a preliminary experiment with a subject under fMRI exam.

In the device design the electric and magnetic safety criteria was followed in order to avoid every dangerous effect due to the use of electric current in the human body.

The MR safety and compatibility of the prototype has been demonstrated using a statistical test to the localization of eventual artefacts in the MR images. Finally, the prototype was tested on a subject during a fMRI examination in order to analyze the functional brain activation due to the tactile sensation caused by the electric current through the electrode. The AFNI analysis showed the effective activation of the primary and secondary sensorimotor areas in which the touch resides, and a good correlation between the stimulation block paradigm and the brain specific areas activity. These preliminary results demonstrate that electrocutaneous stimulation performed by means of our device produces robust and focal hemodynamic responses in somatosensory cortex that can be measured by fMRI technique.

Future developments will concern a more accurate discrimination of the specific sensations reproduced using the electric current and major efforts will be focused in finding a reliable relationship between mechanical and electric stimuli eliciting mechanoreceptors. It would be interesting to stimulate different locations in order to study how different the elicited patterns are.

REFERENCES

[1] A. B. Vallbo, K. A. Olsson, K. G. Westberg, F. J. Clark, “Microstimulation of single tactile afferents from the human hand”, *Brain*, vol. 107, pp. 727-749, 1984.

[2] M. Trulsson, S. T. Francis, E. F. Kelly, G. Westling, R. Bowtell, F. McGlone, “Cortical responses to single mechanoreceptive afferent microstimulation revealed with fMRI”, NeuroImage, pp. 1-10, 2001.

[3] M. Bak, J. P. Girvin, F. T. Hambrecht, C. V. Kufta, G. E. Loeb, E. M. Schmidt, “Visual sensations produced by intracortical microstimulation of the human occipital cortex”, *Med. Biol. Eng. Comput.*, vol. 28, pp. 257-259, 1991.

[4] L. S. Eisenberg, A. A. Maltan, F. Portillo, J. P. Mobley, W. F. House, “Electrical stimulation of the auditory brainstem in deafened adults“, *J. Rehab. Res. Develop.*, vol. 24, pp. 9-22, 1987.

[5] T. Nojima, D. Sekiguchi, M. Inami, S. Tachin, “The smarttool: a system for augmented reality of haptics”, *Proc. IEEE VR’2002*, pp. 67–72, 2002.

[6] R. M. Strong, D. E. Troxel, “An electrotactile display”, IEEE *Trans. Man-Mach. Sys.*, vol. MMS-11, pp. 72-79, 1970.

[7] K. O. Johnson, “The roles and functions of cutaneous mechanoreceptors”, *Current Opinion in Neurobiology*, vol. 11, pp-455-461, 2001.

[8] H. Kajimoto, N. Kawakami, T. Maeda, S. Tachi, “Electrocutaneous display with receptor selective stimulations”, Electronics and Communications in Japan, Part 2, vol. 85, pp. 120-128, 2002.

[9] K. A: Kaczmarek, J. G. Webster, P. Bach-y-Rita, W. J. Tompkins, “ Electrotactile and vibrotactile displays for substitution systems”, *IEEE Ttrans. on Biomed. Eng.,* vol. 38, pp. 1-16, 1991.

[10] T. A. Hammeke, F. Z. Yetkin, “Functional magnetic resonance imaging of somatosensory stimulation”, *Neurosurgery*, vol. 35, pp. 677-681, 1994.

[11] S. Brummer, M. Turner, “Electrochemical considerations for safe electrical stimulation of nervous system with platinum electrodes”, *IEEE Ttransactions on Biomedical Engineering*, vol. 10, pp. 60-62, 1977.

[12] F. G. Shellock, “Pocket Guide to MR Procedures and Metallic Objects: Update 1998”. Lippincott-Raven pub., Philadelphia; 1998.

[13] U. S. Department of Health and Human Services, Food and Drug Administration, Center for Devices and Radiologicial Health (Eds.), Magnetic ResonanceWorking Group Draft released for comment on: February 7, 1997, A Primer on Medical Device Interactions with Magnetic Resonance Imaging Systems, Available from: http://www.fda. gov/cdrh/ode/primerf6.html

[14] J. Sijbers, A. J. Den Dekker, J. Van Audekerke, M. Verhoye, D. Van Dyck, “Estimation of he noise in magnitude MR images”, *Magnetic Resonance Imaging*, vol. 16(1), pp. 87-90, 1998.

[15] R. Gassert, N. Vanello, D. Chapuis, V. Hartwig, E. P. Scilingo, A. Bicchi, L. Landini, E. Burdet, and H. Bleuler, “Active Mechatronic Interface for Haptic Perception Studies with Functional Magnetic Resonance Imaging: Compatibility and Design Criteria”. *Proc. of IEEE ICRA 2006*, pp. 3832-3837, 2006.

[16] R. W. Cox, “AFNI: software for analysis and visualization of functional magnetic resonance neuroimages”, *Comput. Biomed. Res.*, vol. 29, pp. 162-173, 1996.