Distinction of Individual Finger Responses in Somatosensory Cortex using ECoG High-Gamma Activation Mapping*

R. Prueckl, C. Kapeller, K. Kamada, F. Takeuchi, H. Ogawa, J. Scharinger, C. Guger

Abstract— **This study demonstrates the feasibility of high-gamma activity mapping for localization of somatosensory finger areas in the human brain. Identification of functional brain regions is important in surgical planning, such as for resections of epileptic foci or brain tumors. The mapping procedure is done using electrocorticography (ECoG), an invasive technique in which electrical brain signals are acquired from the cortical surface. Two epilepsy patients with implanted electrode grids participated in the study. Data were collected during a vibrotactile finger stimulation paradigm and showed significant cortical activation ($p < 0.001$) in the high-gamma range over the contralateral somatosensory cortex. The results are consistent with previous studies that used fMRI in test subjects without implanted electrodes. Therefore, the results suggest that localizing the cortical representations of the fingers in clinical practice using ECoG is feasible, even without the patient's active participation.**

I. Introduction

Neurons in our brains receive information from the bodily senses and through their complex network structure. They also send information to actuators like muscles to ensure functionality of our organisms. Revealing more functions of the brain, and the connectivity of its distinct regions, are preconditions for advancing basic research and improving treatment of neurological disorders. Electrical cortical activity has been measured both invasively and non-invasively since several decades **Error! Reference source not found.**. Invasive Electroencephalography (iEEG), or Electrocorticography (ECoG) is used in clinical practice and provides high temporal resolution combined with high spatial resolution. Therefore, it is a well-suited tool for studying electrophysiological features with high temporal variability by measuring the synchronous activity of more or less large neuronal populations [2]. High-gamma frequency band activity (HGA, 40Hz and above), resulting from changes elicited by cortical activity in specific regions of the brain, is of particular interest in this context [3]. An example for this effect is the power-increase over hand motor areas during movement execution. This activity is observable in a broad frequency range and is anatomically very specific depending on the movement of different body parts [4].

* Research supported by ENIAC Joint Undertaking Project DeNeCoR, (No. 324257) and by the European Union FP7 Integrated Project VERE (No. 257695)

R. Prueckl, C. Kapeller and C. Guger are with g.tec Guger Technologies OG, Schiedlberg, Austria. (Corresponding author: R. Prueckl. Phone: 0043 7251 22240; e-mail: prueckl@gtec.at).

K. Kamada, H. Ogawa, and F. Takeuchi are with the Department for Neurosurgery, Asahikawa Medical University, Asahikawa, Japan.

J. Scharinger is with the Department of Computational Perception, Johannes Kepler University, Linz, Austria.

Functional brain mapping is particularly important in surgical planning procedures for patients suffering from intractable epilepsy [5]. Since these patients are unresponsive to medication-based treatment, resective brain surgery to remove the source of the seizures could provide the only means to reduce epilepsy. Neurosurgeons must first distinguish healthy and important brain tissue from regions inducing malicious activity that have to be resected [6], [7]. The most widespread method, and the gold standard for functional brain mapping, is electrical cortical stimulation (ECS) [8], [9]. This method aims to elicit observable physiological responses by inducing electrical current directly in the patient's brain. The approach is effective, yet has substantial disadvantages such as patient discomfort and the risk of inducing seizures [10]. Hence, fMRI and other optical imaging technologies have been suggested [5]. Passive functional mapping using iEEG targeting HGA activation changes was also proposed to overcome some of these drawbacks [10].

The somatosensory cortex (SCX), which is the subject of this study, is located in and adjacent to the motor cortex on the postcentral gyrus (PoG) and has a generally somatotopic layout. Like in the motor cortex, the hand and finger representations in SCX occupy more cortical area in relation to other body parts [11], [12]. Previous studies utilizing fMRI showed that the individual fingers can be distinguished well when they are stimulated using electrical [13] or vibrotactile [14] pulses. Other modalities have also been used for this task. For a review, see [15].

In this study, we demonstrate the feasibility of functional mapping of the hand area of the SCX using HGA mapping.

II. Materials and Methods

Two female patients undergoing invasive monitoring (P1 and P2, aged 66 and 25) participated in this study. P1 had electrode grid coverage of the right somatosensory cortex and lower parts of the right hemisphere. P2 had bilateral coverage of the sensorimotor cortex and lower parts of both hemispheres (see Figure 1). The right somatomotor areas of the patients were covered by grids containing 60 electrodes with 1.5 mm exposure diameter and 5 mm inter-electrode distance. The left sensorimotor area of P2 was covered by a grid containing 20 electrodes with 3 mm exposure diameter and 10 mm inter-electrode distance. All electrodes were subdural platinum electrodes (Unique Medical Co. Ltd, Tokyo, Japan). Amplification ground and reference used a non-sensorimotor electrode grid in both patients.

The study was approved by the institutional review board of the Asahikawa Medical University, and written informed consent was obtained from the patients before the start of the study.

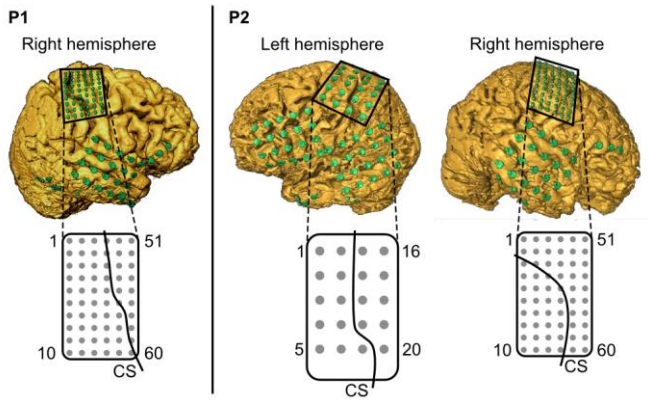

Figure 1. Anatomical MRI scans co-registered with post-implant CT scans for visualization of the implanted electrodes, along with the relevant electrode grids and their electrode numbers. CS is the approximation of the central sulcus.

The experimental setup is presented in Figure 2. Data were recorded using a g.HIamp (g.tec medical engineering GmbH, Graz, Austria) with a sampling rate of 1200Hz and open filters at the patients' bedsides. The amplifier was connected via USB to the recording computer. The recording software was MATLAB/Simulink (The MathWorks, Natick, MA, USA) and g.HIsys (g.tec medical engineering GmbH, Graz, Austria).

For the sensory experiments, the patients sat in their beds, with each fingertip of one hand connected to a vibrotactile stimulator driven by g.STIMbox (g.tec medical engineering GmbH, Graz, Austria) using adhesive tape.

During the experiment, the vibrotactile stimulators were turned on in random order for 1 s each, with a silent interval of 3 s. They applied a stimulation frequency of 80 Hz to the subject's skin. A trigger channel indicating stimulation state was recorded using the digital input of the amplifier that was connected to an output of the g.STIMbox, in parallel with the stimulus class information and the biosignal data.

The setup of the motor experiment, in which only P1 participated, was similar. However, P1 then wore a data glove (5DT, Irvine, CA, USA) that was connected to the recording PC and transferred the movement of the individual fingers with a sampling rate of 60 Hz. During this experiment, a computer monitor indicated which finger the patient had to continuously move until a stop instruction was given. Each trial lasted 3.5 s with a silent interval of 4.5 s. Class information was recorded in parallel to the biosignal data.

During offline analysis, all the data were filtered using a bandpass filter of 55 to 95 Hz. Channels containing transient or oscillatory artifacts were excluded after visual inspection. All remaining channels were re-referenced against the common average of the corresponding grid. Subsequently, the data was windowed according to the triggers, indicating vibrotactile stimulation or finger movement. The window lengths for this operation are given in Table 1. Then, the bandpower for the trials was estimated for each channel by taking non-overlapping windows of the data with a length of 200 ms each and calculating the variance.

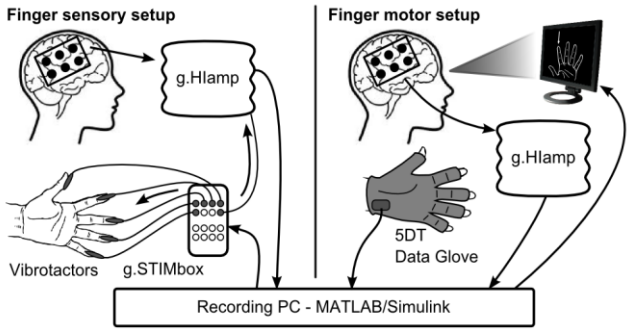

Figure 2. Experimental setup for the sensory (left) and motor (right) mapping experiments.

For data analysis, each finger was treated separately. For each trial, the variance values of the baseline and activity periods, according to Table 1, were collected separately in two groups. Activation periods were chosen such that the activation was maximized within the corresponding trigger line. The Pearson's correlation coefficient was calculated using the concatenated baseline and active periods together with a synthetic step function. The squared correlation values were normalized and plotted into schematic 2D electrode grids to visualize the activation. An electrode was considered statistically significant if the p value of the correlation was lower than 0.001, and the correlation value was higher than three times the standard deviation of the correlation coefficients of the output of a 1000-fold bootstrap procedure. Electrodes showing significant activation are plotted with a yellow edge in the result figures.

TABLE I. EXPERIMENTAL ATTRIBUTES

Sensory experiment				
Patient	***Number of trials***	***Window length***	***Baseline period***	***Active period***
1	150 left	3.2 s Pre: 1.2 s Post: 2.0 s	0.4 – 1 s	1.8 – 2.4 s
2	150 left 150 right		0.4 – 1 s	1.4 – 2.0 s
Motor experiment				
Patient	***Number of trials***	***Window length***	***Baseline period***	***Active period***
1	75 left	8.4 s Pre: 2.4 s Post: 6.0 s	0.6 – 2 s	4.4 – 5.8 s

III. RESULTS

A. Patient 1

The results of the sensory mapping of individual fingers of the left hand of P1 are depicted in Figure 3. This figure shows clear activation above the contralateral post-central sulcus that is spatially distributed depending on the finger, moving from an inferior rostral location (thumb) to a more superior caudal location (little finger). Also, the individual finger movements show clear activation, and are distributed with the same spatial pattern.

Figure 4 shows one example comparing bandpower of the baseline and activation periods of electrode channel 58 for the index finger (with clear activation) and the middle finger (without activation).

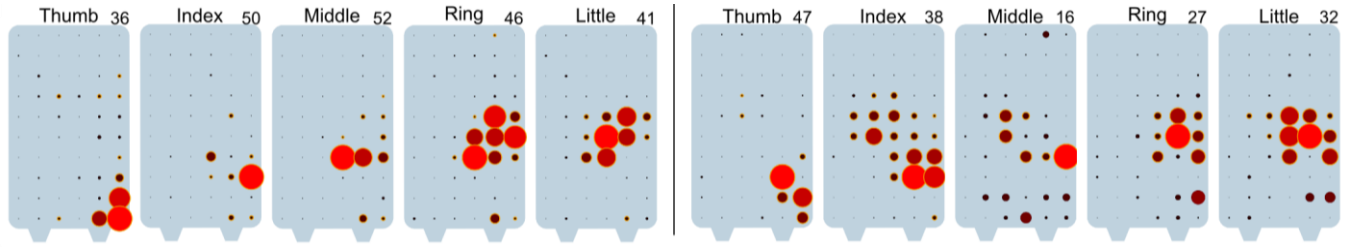

Figure 3. Left: Cortical activity during vibrotactile stimulation of the individual fingers of P1's left hand. Right: Cortical activity during individual finger movement of P1's left hand fingers. The maximum r² values of each result (*100) are indicated at the top right of each plot.

B. *Patient 2*

Figure 5 depicts the results of the sensory mapping of individual fingers of P2's left hand. The maps show clear activation on the contralateral grid, depending on the finger that was stimulated. In comparison to P1, a similar spatial distribution can be observed. The ipsilateral standard grid also shows some activation that is invariant to the individual fingers. Figure 6 presents the activations during the stimulation of the right hand. Higher activation on the contralateral standard electrode grid can clearly be observed, whereas the ipsilateral grid shows lower activation with no clear pattern. The observation of the finger-dependent spatial pattern is less clear in this case.

IV. Discussion

P1 shows very distinct activation over PoG and parts of the CS resulting from vibrotactile stimulation, according to the hand area of the homunculus, which is arranged from anterior and inferior for the thumb to more posterior and superior for the little finger in the SCX [11]. The principal part of the activation is located above and to the left of the CS, which is in concordance to the SCX being located inside and posterior to the CS [11]. This also applies to P2's results. However, P2 shows a broader and less specific activation. Some outliers located on the frontal side of the CS might result from sporadic finger and hand movement of P2 during the experiment. The broad activation is not significantly different when using different and higher frequency bands for analysis like 105-145 Hz. Another hypothesis is that the (non-adjustable) stimulation for P2 was eliciting overlapping activation, as presented in [16]. In general, a more detailed consideration of stimulus parameters would be desirable to optimize the response activation [14].

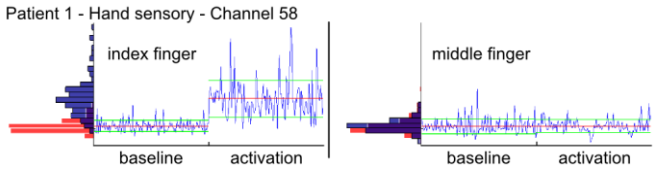

Figure 4. Comparison of the baseline and activation periods of electrode channel 58 of P1 during vibrotactile stimulation of the index (left) and middle (right) fingers. At the right side of each plot, the bandpower raw values are depicted. The red line is the mean and the green lines are the standard deviations, respectively. At the left sides, the histograms show the baseline distribution in red and the activation distribution in blue.

The results are consistent with fMRI studies that measured the Euclidean distances between the thumb and other fingers [17], [18]. They found distances between the thumb and little finger of about 15 and 18 mm for areas 1 and 3b of the SCX, respectively. This is consistent with our results, since that normalized r² activation > 0.75 is located within a diagonal of 22 mm, considering the grid inter-electrode distance of 0.5 cm. The fMRI study also states that there is a distance of only 2 mm between the ring and the little finger, which is reproduced here and explains the small difference in activation between those two fingers. The highest distance of neighbor fingers of about 8-10 mm between the thumb and the index finger is also well represented.

There is a difference in latency for the vibrotactile stimulus maximum activation between the two subjects. It is known that a number of reasons can cause variances in latencies, such as body height, arm length, or age [19].

Finger movements in P1 show a very similar distribution of activation but with lower correlation values compared to the activation during vibrotactile stimulation on average. The topographic area of the hand and fingers of motor cortex is not covered by the grid, so the sensory activation that can be seen on the maps is assumed to be caused by skin and ankle sensory input during movement. Another fMRI study has shown similar activation superior to somatosensory activation during hand motor tasks in somatosensory cortex [13].

Activation on the ipsilateral side of the stimulated fingers was observed by a group studying inter-hemispheric

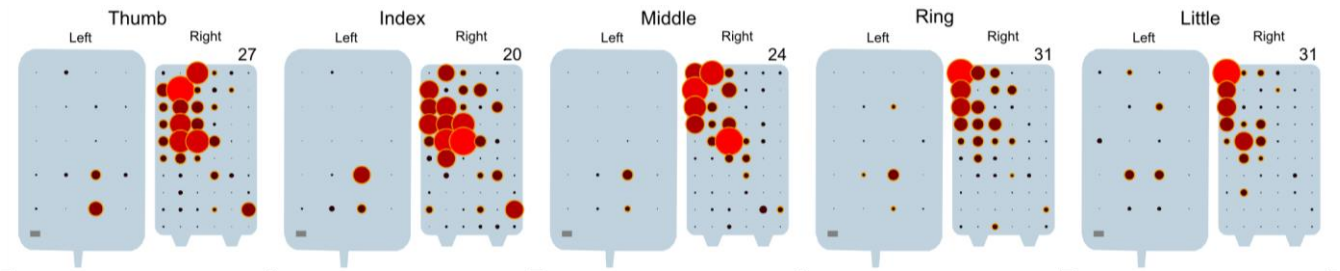

Figure 5. Cortical activity during vibrotactile stimulation of the individual fingers of P2's left hand. The maximum r² values of each result (*100) are indicated at the top right of each plot.

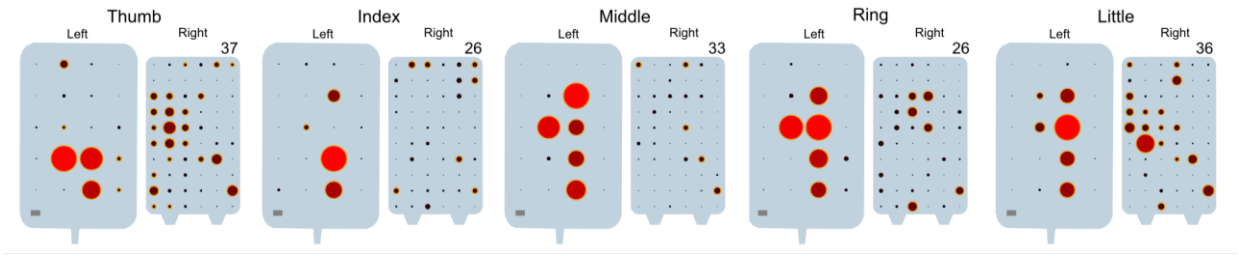

Figure 6. Cortical activity during vibrotactile stimulation of the individual fingers of P2's right hand. The maximum r^2 values of each result (*100) are indicated at the top right of each plot.

connectivity of the SCX during pressure stimulation [20]. This effect can be observed in P2. Interestingly, ipsilateral activation is only observed during left-hand stimulation. A hypothesis is that this is caused by the fact that the right hemisphere is the patient's dominant one, which was validated via the WADA test. It is important to note that the higher spatial resolution of the grid covering the right SCX leads to a much better ability to discover the spatial dependence of activation depending on the finger that is stimulated in contrast to the standard ECoG grid placed on the left hemisphere.

The distances between cortical finger representations, and the fact that fMRI studies currently map the SCX with spatial resolutions below 1x1x1 mm [20], encourage minimizing the size of the electrodes used in future ECoG studies. As fMRI provides rather high time-constants, only this new approach could increase both the temporal and spatial resolution of study data. Increasing the spatial resolution for ECS is problematic, as increased charge densities found in smaller electrodes might be harmful for the brain tissue stimulated. ECoG does not suffer from this problem.

For clinical practice, the somatomotor capability of all the fingers (not only the most important ones) should ideally be preserved. Nevertheless, after seizure focus identification the finger somatosensory identification procedure described here is adequate, as fMRI investigations will not be possible anymore for the patient with implanted electrode grids. Due to the easy setup and short investigation time, this procedure can be used also intraoperatively and immediately before a resective surgery, since operating rooms typically do not have fMRI scanners. The described study also involves less patient compliance and is therefore easier than fMRI investigations, since tactile stimulation might be difficult in the scanner due to electromagnetic compatibility or movement artifacts induced by the stimulation. We are not aware of ECS studies aiming for identification of the finger representations. This could occur because the spatial resolution of ECS is too low.

An interesting application of the mapping procedure outside the clinical environment would be to find important electrode positions for brain-computer interface control. The identification of finger regions, for example, is very important to control fingers of a robotic hand or avatar in real-time. The motor mapping performed within this study would be perfectly suited as a starting point for such an approach.

REFERENCES

[1] E. Niedermeyer (1993). "Historical Aspects". *Electroencephalography: Basic Principles, Clinical Applications, and Related Fields*. E. Niedermeyer and F. L. d. Silva. Baltimore, Lippincott Williams & Wilkins**:** 1-14.

[2] G.Schalk and E.C. Leuthardt. "Brain-computer interfaces using electrocorticographic signals." *Biomedical Engineering, IEEE Reviews in* 4 (2011): 140-154.

[3] J.-P. Lachaux et al. "High-frequency neural activity and human cognition: past, present and possible future of intracranial EEG research." *Progress in neurobiology* 98.3 (2012): 279-301.

[4] K.J. Miller et al. "Decoupling the cortical power spectrum reveals real-time representation of individual finger movements in humans." *The Journal of neuroscience* 29.10 (2009): 3132-3137.

[5] S. Tharin and A. Golby. "Functional brain mapping and its applications to neurosurgery." *Neurosurgery* 60.4 (2007): 185-202.

[6] C. Kapeller et al. "CortiQ-based Real-Time Functional Mapping for Epilepsy Surgery." *Journal of clinical neurophysiology*: official publication of the American Electroencephalographic Society (2015).

[7] H. Ogawa et al. "Rapid and Minimum Invasive Functional Brain Mapping by Real-Time Visualization of High Gamma Activity During Awake Craniotomy." *World neurosurgery* 82.5 (2014): 912-e1.

[8] K. Hara, S. Uematsu, R. Lesser, B. Gordon, J. Hart, E. Vining, Representation of primary motor cortex in humans: studied with chronic subdural grid, *Epilepsia* 32(suppl) (1991) 23–24.

[9] G.A. Ojemann, Cortical organization of language, *J Neurosci* 11 (8) (1991) 2281–2287.

[10] P. Brunner et al. "A practical procedure for real-time functional mapping of eloquent cortex using electrocorticographic signals in humans." *Epilepsy & Behavior* 15.3 (2009): 278-286.

[11] D.G. Amaral (2000). The Functional Organization of Perception and Movement. *Principles of Neural Science*. E. R. Kandel, J. H. Schwartz and T. M. Jessell, McGraw-Hill: 337-348.

[12] E.P. Gardner and E.R. Kandel (2000). Touch. *Principles of Neural Science*. E. R. Kandel, J. H. Schwartz and T. M. Jessell, McGraw-Hill: 337-348.

[13] J.A. Maldjian et al. "The sensory somatotopic map of the human hand demonstrated at 4 Tesla." *Neuroimage* 10.1 (1999): 55-62.

[14] S.T. Francis et al. "fMRI of the responses to vibratory stimulation of digit tips." *Neuroimage* 11.3 (2000): 188-202.

[15] P. Hluštík et al. "Somatotopy in human primary motor and somatosensory hand representations revisited." *Cerebral Cortex* 11.4 (2001): 312-321.

[16] T. Krause et al. "Representational overlap of adjacent fingers in multiple areas of human primary somatosensory cortex depends on electrical stimulus intensity: an fMRI study." *Brain research* 899.1 (2001): 36-46.

[17] D. Van Westen et al. "Fingersomatotopy in area 3b: an fMRI-study." *BMC neuroscience* 5.1 (2004): 28.

[18] A.J. Nelson and R. Chen. "Digit somatotopy within cortical areas of the postcentral gyrus in humans." *Cerebral Cortex* 18.10 (2008): 2341-2351.

[19] M. Stöhr „Somatosensible Reizantworten von Nerven, Rückenmark und Gehirn (SEP)". *Evozierte Potenziale*. M. Stöhr, J. Dichgans, U. W. Buettner and C. W. Hess. Heidelberg, Springer Medizin Verlag: (2005) 21-252.

[20] Y. G. Chung et al. „Intra- and inter-hemispheric effective connectivity in the human somatosensory cortex during pressure stimulation." *BMC Neuroscience* 15:43 (2014).