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The Frequency Effect in the Somatosensory Cortex Response to Vibrotactile Stimulator in fMRI

Hyunsook Lee

Department of Computer and Electronic Physics, SangJi University

The fMRI response of the somatosensory cortex was investigated with vibrotactile stimulation. Three different frequencies of 8, 15, or 25 Hz were applied in order to mainly focus on the hemodynamic response of Meissner corpuscles sensitive to frequencies of 5~40 Hz. A closed-system, pneumatically-driven, rubber diaphragm was fabricated that overcame many of the limitations of existing vibrotactile devices and produced robust sensory cortex activation in an fMRI experiment. Increasing frequency vs. activation area was analyzed in terms of signal percent change and number of pixels. Our preliminary results indicated that the distribution of the signal percentage change widened and more activated pixels were obtained with higher frequencies.

Key Words: FMRI, Vibrotactile device, Signal percent change, Brain activity

INTRODUCTION

Functional magnetic resonance imaging (fMRI) has recently become as a technique for non-invasively mapping brain function based on the blood oxygenation level, volume, and flow changes.[1-3] The functional organization of the human primary (SI)[4-6] and secondary (SII) somatosensory cortex is also well known from previous imaging studies using fMRI.[7-8] There are several ways of stimulators as like pneumatically powered brushes,[9] cotton swabs and air puffs,[10] vibrating ceramic piezoelectric wafers[11] and benders.[12] Also many kinds of vibrotactors[13-15] were already developed to map the somatosensory cortex.

It has been known that vibratory stimuli on the skin are sensed by two types of receptors: Meissner corpuscles and Pacinian corpuscles, each of which is perceptive to different ranges of stimuli frequency.[7] Meissner corpuscles are most sensitive to frequencies of 5~40 Hz, while Pacinian corpuscles are most sensitive to frequencies of 60~300 Hz. A study examining the hemodynamic responses to vibratory stimuli in these regions showed different activation for each of frequency ranges. For this purpose a variety of stimulators has been used to map the somatosensory cortex. However, the relationship between somatosensory cortical response and increasing stimulation at frequencies below 40 Hz has not been well established yet. The present study therefore focused on the response of Meissner corpuscles, which were located just below the epidermis and had small receptive fields, and on the signal percentage change with increasing sensorimotor stimulation with the three different frequencies at the level of individual pixels. This was done based on histogram analysis.

The relationship between increasing stimulation at frequencies and supplementary motor cortex (SMA) controlling signal transfer as like initiation and preparation was also interested. The three hypotheses were investigated to better understand the relationship between somatosensory cortical response and increasing stimulation frequencies included the following: with increasing frequency of stimulation, 1) signal percentage change increases and the distribution of the signal percentage change broadens, 2) signal percentage change increases, but the distribution of the signal percentage is constant 3) signal percentage change is constant, but the

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Corresponding Auther : Hyunsook Lee, Department of Computer and Electronic Physics, Sangji University, Wonju 220-702, South Korea
Tel: 033-730-0416, Fax: 033-730-0410
E-mail: hslee@mail.sangji.ac.kr

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MATERIALS AND METHOD

fMRI Sensory Paradigms: Each fMRI data acquisition consisted of ten 3 sec vibration epochs alternating with 15 sec periods of no vibration. The acquisition began and ended with 15 sec without vibration. The acquisition began and ended with 15 sec without vibration. Total acquisition time was 3 min and 15 sec. Six acquisition runs, two at each of the three vibration frequencies, were performed. Vibrotactile stimulation was applied to the right middle finger, at a vibration rate of 8, 15, or 25 Hz. The tactor was taped so as to be just contacting the finger. The amplitude control knob was fixed for three different frequencies.

Vibrotactile Stimulus Unit: Six right-handed healthy volunteers (6 men, aged 30~45 years) were scanned at rest and while low (8 Hz), medium (15 Hz) and high (25 Hz) stimuli were given. A magnet compatible vibrotactile sensor[16] (Fig. 1a) was applied to the right middle finger. Fig. 1b shows the front panel of the vibrotactile unit. Both vibration frequency and intensity (proportional to duration of the air pulse) are controlled by RC timing circuits, provided by variable potentiometers connected to knobs on the front panel of the unit (Fig. 1c). The coarse and fine frequency knobs control the period of the cyclic on-off delivery of pressurized air to the tactor. The vibrotactor was activated under the computer control delivered from the parallel port of the computer through a cable to a standard D25 connector port on the rear panel of the vibrotactile control box (Fig. 1c). For the experiments reported here, the internal clock of a laptop computer and software written in-house in Visual Basic 6.0 (Microsoft) were used to generate the TTL timing pulses with 100 ms resolution for each channel.

Scanning protocol: An fMRI functional data were acquired with a whole-body 3T GE scanner with a dome shaped

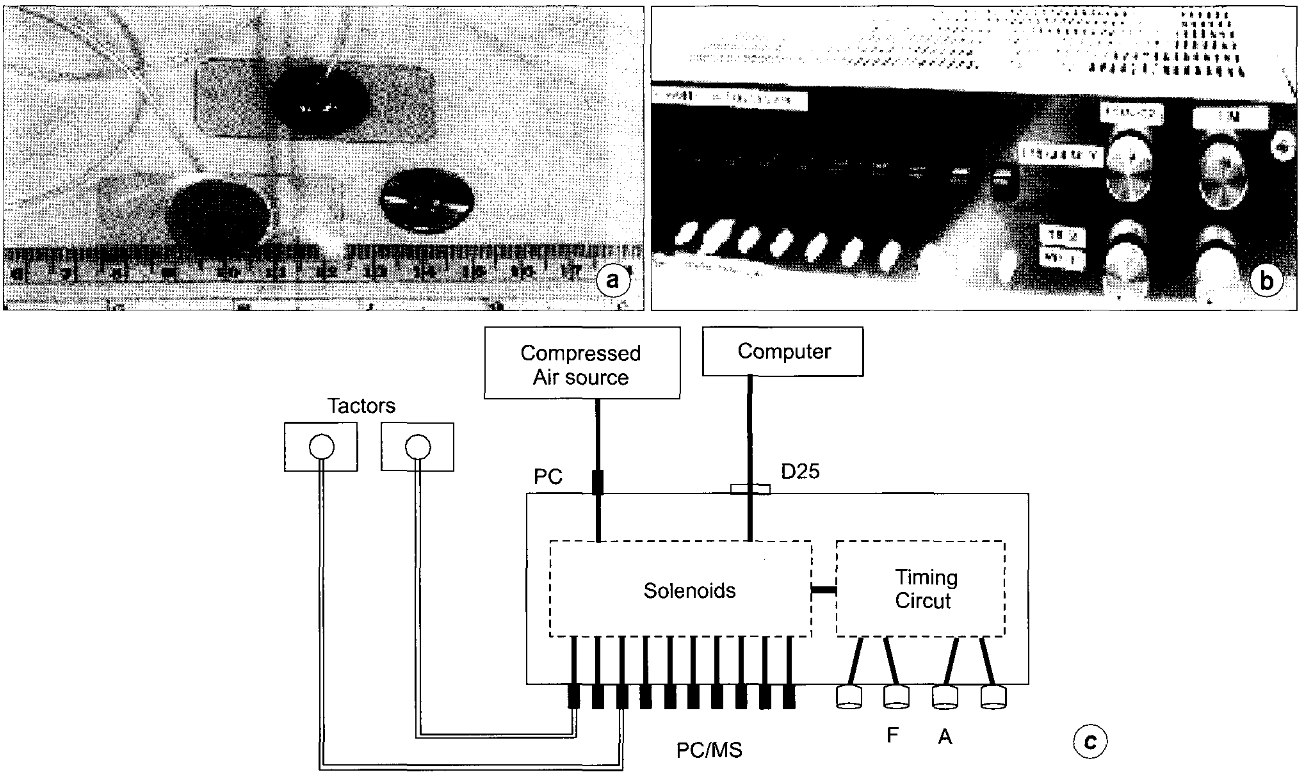

Fig. 1. (a) Rubber diaphragm tactors, air delivery tubes, and a U.S. penny. Units of the ruler scale at the bottom are centimeters and inches. (b) Front panel of the vibrotactile unit showing knobs controlling frequency and magnitude. There are 10 solenoid valves that can be used for different fingers. (c) Schematic diagram of the vibrotactile unit and tactors. PC-pneumatic connectors, MS-manual switches, D25-25-pin connector, F-coarse and fine frequency knobs, A - coarse and fine amplitude knobs.

quadrature coil. Twenty contiguous coronal 4-mm slices covering the supplementary motor area (SMA), the primary motor cortex and the somatosensory cortex were acquired using a 1-shot spiral sequence (TR=1000 ms, TE=18 ms, FA=60°, matrix size=64×64, FOV=200 mm, 195 time points per run). Anatomic images were obtained using both a high-resolution MR angiogram (TR=17 ms, TE=4.9 ms, FA=50°, matrix size=256×128, FOV=200 mm, 4 mm thickness) and a T1-weighted 3D-spoiled GRASS sequence (TR=23 ms, TE=7 ms, FA=25°, matrix size=256×192, 1.3 mm thickness, 124 slices, FOV=240 mm). Foam padding was used to minimize head motion. Subjects gave informed consent to participate, as approved by the Institutional Review Board for human studies.

Data Analysis: The image processing and statistical

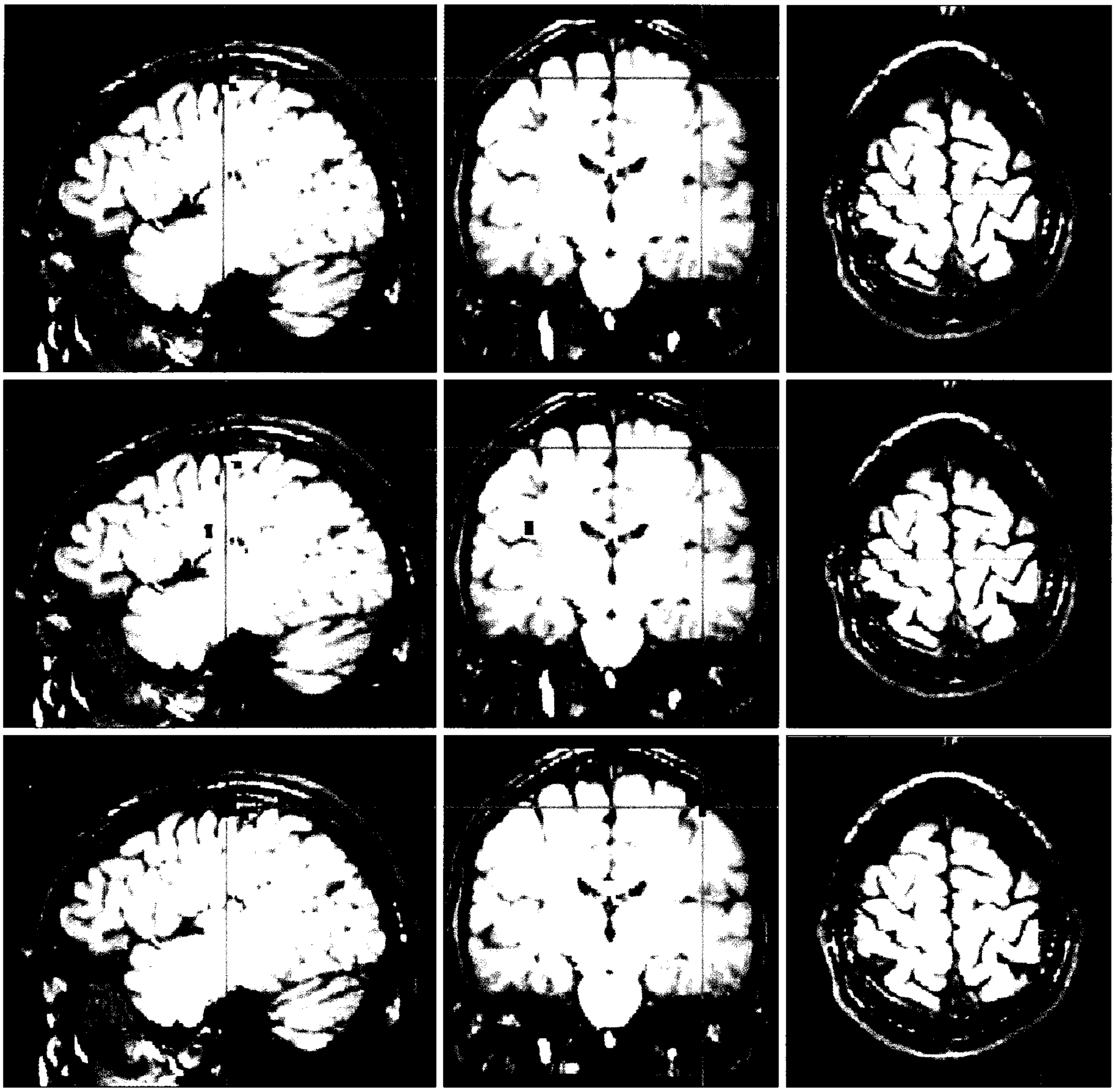

Fig. 2. Three T activation maps obtained with the device. Sagittal (left column), coronal (middle column), and axial (right column) images of left-hemisphere S1 activity (43, 17, 55; highlighted by green crosshairs) produced by right middle finger vibrotactile stimulation at 8 Hz (top row), 15 Hz (middle row), and 25 Hz (bottom row). The highlighted region in the coronal view just superior and medial to the crosshairs was shown by MRA images to coincide with a large draining vein. An individual voxel p of 10^{-5} and a cluster size threshold of 160 μL (4 voxels) yielded alpha <0.001. Significant activation of the S1 cortex in the contralateral left hemisphere is shown in all cases.

analysis were performed with the use of AFNI software.17) The reconstructed fMRI data were realigned using a 3D rigid-body registration method in order to minimize residual motion between images in the time series. After the linear trends of each time series were removed and then three fMRI runs for each task were then concatenated. A cross correlation analysis using the gamma variate function was applied to the concatenated time course data of each level of frequency and phase shifting was allowed to select the best reference waveform and then to localize activation in the somatosensory cortex.

ROIs (Regions of Interest) were drawn in three slices showing sensorimotor cortex (S1) based on the activation map, and pixels were selected in the ROIs. The same ROIs were used for three different (low, medium, and high) frequency activation maps. The whole time series of each pixel in the ROIs were averaged to obtain a hemodynamic response (HDR) curve. Maximum and minimum signal intensities were obtained from the curve and used to calculate the signal percentage change of the same pixels for different frequencies. Pixels showing signal intensity change caused by noise were not counted. The histograms were presented a number of activated pixels versus bins based on the signal percentage change and five bins were conveniently displayed.

RESULTS AND DISCUSSION

The vibrotactile device with pneumatically-driven, rubber diaphragm tactors has produced a perceptible tactile sensation, with an amplitude of 4 mm and frequency range of 1~100 Hz that can be easily controlled. It was shown that the vibrotactile equipment reported here can be used to localize the sensorimotor (S1).16) But SMA area functioning signal transfer were not activated, unlike expected. It can be explained that our applied frequencies are not high enough to activate SMA area. Our device is similar to the pneumatic system reported by Golaszewski, Zschiegner et al,15) although they did not report amplitude capabilities and characterized the tactor only as a latex tube. And their studies were done at the frequency of 50 Hz in the upper range of the Meissner corpuscle scale and in the low range of the Pacinian corpuscle scale. Therefore, our results are useful for understanding the relation of increasing stimulation frequencies below 40 Hz to somatosensory cortical response. Fig. 2 shows activation maps in which the vibrotactile device was used to deliver stimuli with vibration frequencies of 8 (top row), 15 (middle row), and 25 Hz (bottom row) to the distal pad of the right middle finger. Significant activation (43, 17, 55; highlighted by green crosshairs) of the contralateral S1 cortex in sagittal (left column), coronal (middle column), and axial (right column) images of left-hemisphere was produced. The highlighted region in the coronal view just superior and medial to the crosshairs was shown by MRA images to coincide with a large draining vein. An individual voxel p of 10 ^{5} and a cluster size threshold of 160 μL (4 voxels) yielded alpha <0.001. Fig. 3 illustrates the averaged histogram of 6 subjects showing individual pixels' signal percentage change at different frequency levels. As patterns show, for medium and high frequencies, the pixels distributed at higher signal change are dominant, reflecting signal percentage change increases with increasing frequency. Therefore, our preliminary results indicated that the distribution of the signal percentage change widened and more activated pixels were obtained with higher frequencies. The results from our post-hoc study indicates that 1) our vibrotactile equipment using rubber tactors and air pressure could produce the sensory stimulation within low frequency levels (below than 25 Hz), 2) further study would be to localize S1 activation generated by very low frequency levels and thus providing spatial focus, 3) there is a limitation on the increase of the frequencies because there is danger of a diaphragm rupture.

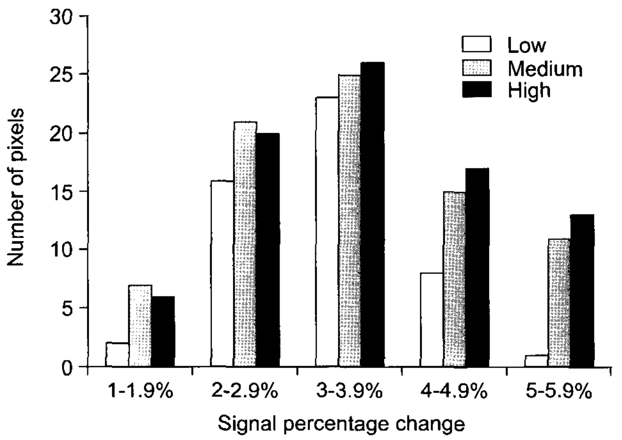

Fig. 3. Histograms showing signal percentage distributions of the pixels in sensorimotor cortex at different frequencies.

Finally, it is important to explore the BOLD signal change of the individual pixels with increasing motor or sensory stimulation using motor parameters including force, frequency, and duration. This is because we can design an fMRI experiment with the minimum required stimuli to get localized activation in the ROIs.

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기능적 자기공명영상에서 진동자의 자극 주파수가 감각피질의 반응에 미치는 영향

상지대학교 컴퓨터전자물리학과

이 현 숙

기능적 자기공명영상을 이용하여 진동자의 자극에 따른 감각 피질의 반응에 대하여 연구하였다. 주로 40 Hz 이하의 주파수에 반응하는 촉각소체의 혈류반응을 조사하기 위하여 8, 15, 그리고 25 Hz의 주파수를 사용하였다. 사용되고 있는 진동자의 한계를 극복한 공기의 압력을 이용하여 진동할 수 있는 진동자를 특수 제작하였다. 예측한 바와 같이 감각 피질의 촉각소체 부위가 주파수에 따라 반응하는 모습을 볼 수 있었다. 주파수 대 반응 면적을 각 pixel의 개수와 signal percent change로 분석하여 주파수가 증가할수록 signal percent change의 분포는 넓어지고 더 많은 pixel들이 반응한다는 것을 알 수 있었다.

중심단어: 기능적 자기공명영상, 진동자, Signal percent change, 뇌활성도