Cortical changes in dental technicians exposed to vibrating tools

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To study the cortical reorganization after long time exposure to hand-held vibrating tools, we investigated 10 dental technicians with sensory neuropathy after long time exposure to vibrating tools and 10 controls for cortical changes using functional magnetic resonance imaging at 3 T. The activated volumes corresponding to individual fingers in the hand area of S1 were significantly larger in the neuropathy group than in controls. Activation in the primary motor cortex did not differ significantly from controls. These changes are likely the result of cortical reorganization following long-term non-physiological sensory input and they can partly explain the symptoms seen in vibration-induced neuropathy.

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Introduction

Long-term use of hand-held vibrating tools is a substantial occupational health risk [1] and may lead to a chronic hand-arm vibration syndrome (HAVS), a complex condition with three major components: vibration-induced white fingers, sensory symptoms and musculoskeletal symptoms. The symptoms in HAVS can only in part be explained by injury to the peripheral nerve and muscle structures [1]. The hand is represented in a large area in the primary somatosensory (S1) and motor cortex [2].

In the cortical somatotopy each finger corresponds to a distinct cortical area in S1. However, in the primary motor cortex representation areas of finger movements show a strong overlap between different fingers. Primate studies have shown that when the hand is exposed to synchronous stimulation, the cortical projection of the fingers melt together in S1 meaning that the normal finger somatotopy is changed to a more overlapping pattern [3]. This representational plasticity has been suggested to be of cortical origin as no equivalent reorganization has been noted in the ventro-posterior thalamus [3]. Training and learning of a tactile task, such as reading Braille, enhance task performance and result in enlargement of the corresponding cortical representation in S1 [4]. Interestingly, improvement of tactile performance in humans can also be achieved without training through passive stimulation [5]. Pleger *et al.* [6] used tactile coactivation, an unattended activation based learning protocol, to show a selective increase in representation size of the coactivated finger in the S1 and enhanced tactile perception on the coactivated finger.

Fusion of the digital representations in S1 has also been noted in pathological conditions such as in patients with hand dystonia, a condition involving loss of motor control of individual finger movements following long time repetitive synchronous movements of the digits [7]. Thus, an extensive simultaneous sensory or motor stimulation of the digits can produce a cortical reorganization of digital receptive fields. The aim of this study was to investigate if cortical reorganization occurs in humans exposed to long-term high frequency hand-held vibrating tools.

Methods

A screening questionnaire regarding experienced sensory and musculoskeletal problems in the upper extremity was performed by the Occupational Health Service at a dental technique laboratory [8]. Ten dental technicians reporting sensitivity problems participated in the study: seven women and three men, all right handed (median age 55 years, range 41–60 years, and median exposure time to vibrating tools 33.5 years, range 15–44 years). Ten healthy age matched controls, without history of exposure to vibrating tools, all but one right handed (median age 53 years, range 40–65 years) were also included. The dental technicians worked with hand-held high-frequency vibrating grinding equipment which exposes all fingers, both in the dominant and non-dominant hand, to synchronous vibration. The speed of the grinders varied between 15 000 and 40 000 revolution/min. The vibration level was moderate, in general < 1–$2\ m/s^2$ measured according to ISO 5349-1 and 2 (*www.iso.org*). The study design was approved by the local ethics committee and

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all participants gave a written informed consent. The experiments were conducted in accordance with the Helsinki declaration.

The sensory assessments were performed according to standardized procedure [9]. Semmes-Weinstein monofilament was used for assessment of thresholds for touch and classic two-point discrimination for tactile discrimination, both in index and little finger. Vibrometry (VibroSense-Meter, VibroSense Dynamics, Malmö, Sweden) was used for multifrequency analysis of vibration thresholds. Results are expressed in sensibility index where normal sensibility index is ≥ 0.8 [10]. All participants had at least 12 h rest from vibration exposure before examination.

Functional magnetic resonance imaging (fMRI) was used to investigate cortical activation during tactile stimulation and motor activation of the fingers. fMRI was performed using a whole body 3T scanner (Tim-TRIO, Siemens Medical Solutions, Erlangen, Germany) equipped with a 12-channel head matrix coil. Before fMRI a high-resolution three-dimensional anatomical scan was acquired with transversal slices oriented to form a plane through the anterior and posterior commissures. fMRI using tactile stimulation was then performed using a pneumatically driven and electronically controlled system to ensure precise and reproducible digit stimuli [11]. Membranes were attached with tape to the fingertips of the right hand's thumb, middle and little finger, delivering tactile stimulation during the functional acquisition (pulse frequency = 1 Hz, pulse width = 100 ms, 2.5 bars pressure) in a semi random block design. The order of finger stimuli was continuously changed between individuals, alternating with rest conditions of no stimuli. Motor stimulation was done by self-paced fist clenching at approximately 1 Hz. In both sessions the block length was 32 s, and the experiment started with a rest condition.

Blood oxygen level dependent imaging was performed using a gradient echo – echo planar pulse sequence with echo time/repetition time = 30/2660 ms, 128×128 matrix, 23 slices and $2 \times 2 \times 2\,mm^3$ voxel size (288 time points in the case of tactile stimulation and 96 time points in the case of motor activation) with the same orientation as the anatomical scan. The acquired volume was confined to the superior part of the brain, that is, from secondary somatosensory cortex and above, because of the limited slice coverage within the chosen repetition time and spatial resolution.

Evaluation of the fMRI data was performed using Brainvoyager QX 1.10 software (Brain Innovation B.V., The Netherlands). The functional data series were motion corrected, spatially smoothed using a 4 mm smoothing kernel width and subsequently normalized to the Talairach space [12] by co-registration to Talairach processed anatomical data. Furthermore, low frequency modulation was suppressed using a high pass filter with a cut-off frequency of three cycles per session. Activation maps were created using the general linear model and corrected for serial correlations using auto-regressive characterization of the first order, AR(1) [13]. As a default, statistical thresholds not corrected for multiple comparisons were used to more accurately compare activated volumes. All spatial coordinates were determined as centre-of-gravity of the clusters and presented as the Talairach coordinates [12].

Results

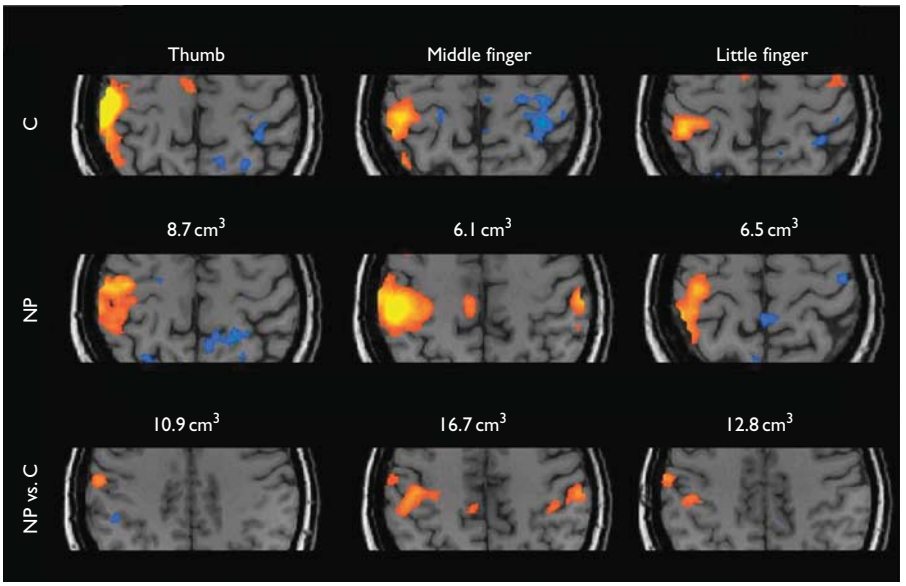
Results regarding motor and sensory symptoms from the screening questionnaire are given in Table 1. Perception of touch showed a predominance of slightly pathological values (SWM > 2.83) compared to controls. Tactile discrimination and vibrometry showed predominately normal values (Table 1). Tactile stimulation of the tip of the thumb, middle and little finger resulted in a three digit cortical activation in the S1 in 17 of 20 individuals. On group level the individuals with vibration-induced neuropathy showed more pronounced activation in S1 defined as increased activated volume compared with the control group at equal statistical threshold. This was mainly seen when stimulating the middle and little finger (Fig. 1, Table 2). This was also seen in individual fMRI data where the mean activated volume for middle finger stimulation was $4.8\,cm^3$ compared with $2.0\,cm^3$ for the

Table 1 Clinical screening results

	Musculo-skeletal problems		Sensory problems		SWM digit II/V		2PD digit II/V		Vibrometry digit II/V	
	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
NP1	3	3	3	3	**3.61/3.22**	**3.22/3.22**	4/5	3/4	0.87/0.80	0.87/0.92
NP2	2	2	3	3	**3.22/3.22**	**3.22/3.22**	4/**6**	3/4	1.01/0.96	0.99/0.89
NP3	3	3	3	3	**3.22/3.22**	**3.22/**2.83	2/4	3/4	1.07/0.94	1.18/1.01
NP4	3	3	3	4	**3.22/3.22**	**3.22/3.22**	3/4	3/3	1.06/1.09	1.04/1.07
NP5	3	3	4	4	**3.22/**2.83	**3.22/**2.83	3/4	5/4	1.01/0.97	0.96/0.93
NP6	4	3	4	4	**3.22/3.22**	**3.22/3.22**	5/**6**	5/**8**	0.91/1.12	1.13/1.00
NP7	2	2	3	3	**3.22/3.22**	**3.22/3.22**	3/3	3/3	1.00/**0.68**	**0.60/0.32**
NP8	1	1	4	3	**3.22/3.22**	**3.22/3.22**	2/2	2/3	1.10/0.98	1.01/0.95
NP9	3	1	4	2	**3.22/3.22**	**3.22/3.22**	3/4	3/3	**0.67/0.67**	**0.73**/0.85
NP10	3	3	4	2	**3.22/**2.83	**3.22/**2.83	3/2	2/3	0.91/0.86	1.01/0.85

Musculoskeletal and sensory problems following exposure to vibrating tools are classified as: 1 = none, 2 = minor, 3 = moderate, 4 = substantial. Pathological values for SWM (filament number > 2.83), 2PD (> 5 mm) and vibrometry (sensibility index < 0.8) are presented in bold.

Fig. 1



Group activation during tactile stimulation of the thumb, middle and little finger in neuropathy individuals (NP) and healthy controls (C). NP individuals activated larger cortical regions in all fingers seen as an increase of the cluster size and further visualized by the NP versus C contrast (bottom row) with clusters representing statistically increased neural activation ($P < 0.0005$) in NP individuals compared with controls. The left side of the brain on the images corresponds to the left hemisphere.

controls and the mean activated volume for little finger stimulation was 2.6 cm^3 compared with 1.5 cm^3 for controls (Table 2). These differences were still present if potential outliers were excluded, that is, the individual showing the largest and smallest activation extent in each of the two groups (NP6, NP7, C3 and C9). Exclusion of these outliers resulted in a mean activated volume of 4.4 cm^3 compared with 0.9 cm^3 (controls) for middle finger stimulation and 2.8 cm^3 compared with 0.6 cm^3 (controls) for little finger stimulation. Although the mean individual activated volume of the thumb did not significantly differ, a significant ($P < 0.0005$) activation increase was seen for the thumb as well as for the middle and little finger when comparing the two groups (i.e. vibration-induced neuropathy individuals versus controls, with and without potential outliers) in the analysis (Fig. 1; bottom row). A significant increase in activation in the S1 was also seen bilaterally for tactile stimulation of the middle finger in the group of individuals with vibration-induced neuropathy. The mean centre-of-gravity coordinates for the activation of S1 for the different fingers were comparable between individuals with vibration-induced neuropathy and controls.

The activation pattern in the primary motorcortex during finger motor task was in general weaker and more scattered in individuals with vibration-induced neuropathy compared to controls. Motor responses did not differ significantly on group level. No correlation was found between the clinical status and the individual fMRI findings.

Discussion

Clinical sensory patterns in individuals with vibration-induced neuropathy were similar in our study compared to those seen in other neuropathies, with preserved tactile discrimination and pathologic perception of touch [14].

An earlier small study, using fMRI at 1.5 T on patients with HAVS showed increased activation in the superior parts of S1 [15]. Our fMRI findings showed changes in S1 in neuropathy individuals as compared to healthy controls. Although the mean centre of gravity for the activation of the different fingers in the S1 were similar in individuals with neuropathy and controls the activated volume following stimulation of different fingers in neuropathy patients was significantly larger than in controls indicating a possible overlap between the fingers. In this study an uncorrected statistical threshold was used as a default when evaluating the activation maps to prevent cluster size bias originating from activation based thresholds [16].

For humans, normal stimulation on several fingers generated by every day use of the hand is consistently non-simultaneous. Earlier studies have shown that synchronous stimulation of multiple digits when actively

Table 2 Cortical activation in neuropathy individuals (NP) and controls

	Thumb		Middle finger		Little finger	
Participants	x, y, z	mm^3	x, y, z	mm^3	x, y, z	mm^3
NP1	−55, −11, 34	997	−49, −4, 37	1089	−55, −10, 34	968
	−38, −9, 52	919	−32, −13, 55	1433	−37, −8, 53	2172
NP2	−46, −15, 48	22	−48, −22, 42	773	−46, −24, 42	471
	−52, −15, 30	672	−38, −34, 52	104	−53, −15, 31	197
NP3	−49, −33, 46	1132	−38, −34, 51	9614	−50, −31, 41	221
	−32, −26, 60	316			−38, −38, 56	20
NP4	−46, −30, 41	2993	−40, −34, 46	7120	−40, −40, 50	2670
	−35, −39, 56	55			−52, −29, 37	2207
NP5	−53, −15, 36	573	−52, −16, 32	599	−54, −15, 31	307
			−35, −15, 56	137	−34, −19, 53	358
NP6	−48, −28, 43	5280	−37, −36, 48	12760	−42, −33, 46	4300
NP7	−47, −28, 53	7	−50, −21, 43	4		
NP8	−51, −16, 43	748	−46, −25, 45	7993	−55, −17, 35	762
					−43, −29, 52	211
NP9	−49, −17, 41	4999	−49, −21, 43	2807	−47, −23, 41	6541
NP10	−51, −25, 40	4422	−49, −24, 41	3404	−47, −28, 44	4950
	−36, −19, 52	655				
Mean	−46, −22, 45	2379	−43, −23, 46	4784	−46, −24, 43	2636
SD	7.2, 8.8, 8.5	2068	6.8, 9.7, 6.9	4322	7.0, 9.8, 8.4	2400
NP_{Group}	−46, −23, 44	10936	−44, −26, 44	16660	−46, −26, 43	12827
C1	−45, −13, 46	3719	−48, −24, 51	118	−47, −27, 53	21
			−48, −13, 38	191		
C2	−46, −24, 48	2115	−45, −31, 49	1698	−49, −8, 39	567
			−38, −20, 55	1083	−39, −34, 53	238
C3	−47, −22, 44	4403	−42, −28, 46	11928	−32, −17, 55	3095
					−45, −33, 44	6818
C4	−48, −27, 39	3574	−51, −17, 39	359	−50, −20, 39	1284
			−43, −39, 48	397	−40, −35, 50	342
C5	−48, −13, 43	547	−50, −21, 46	1073	−48, −8, 39	275
			−38, −19, 54	190		
C6	−49, −17, 45	1502	−38, −23, 57	673	−53, −20, 41	38
C7	−44, −33, 47	4536	−55, −29, 54	816	−55, −29, 41	1069
	−37, −16, 55	1062	−39, −26, 54	596	−38, −35, 50	858
C8	−50, −25, 46	1172			−56, −26, 39	20
C9	−54, −24, 46	19				
C10	−34, −21, 57	852	−47, −33, 49	24	−48, −12, 46	35
	−49, −20, 41	1574				
Mean	−46, −21, 46	2508	−45, −25, 48	1915	−46, −23, 45	1487
SD	5.5, 5.9, 5.2	1787	5.6, 7.1, 6.0	3622	7.1, 10.0, 6.2	3052
C_{Group}	−46, −22, 46	8744	−42, −26, 51	6148	−45, −27, 46	6469

Presented coordinates (x, y, z) represent the centres-of-gravity of the activation cluster and are standardized according to Talairach and Tournoux. Cluster sizes are presented in mm^3. In cases of multiple clusters, the two largest are presented.

performing a task such as the Braille reading [4] or playing a string instrument [17] results in a breakdown of the normally sharply segregated representations of adjacent digits in S1 to multiple-digit receptive fields covering two or three adjacent digits.

Similar results have also been seen following passive synchronous stimulation using a coactivation protocol [6]. Synchronous and asynchronous multi-finger coactivation for 3 h resulted in reorganization of the representations of the stimulated fingers in S1 [18,19]. Representations of synchronously coactivated fingers move closer together, accompanied by more mislocalization of sensory stimulation on co-activated fingers. Asynchronously applied coactivation resulted in a segregation of cortical finger representation and a decrease in mislocalization between the stimulated fingers [18,19].

When comparing the results of our study with studies investigating use dependent cortical changes and coactivation similarities exist such as cortical enlargement of the stimulated fingers. Although not studied specifically here, mislocalization of finger stimuli, as seen in the Braille readers and following synchronous multifinger coactivation, is a very common clinical finding in patients with vibration induced neuropathy and HAVS [1]. On the other hand both use dependent reorganization following Braille reading and the multifinger coactivation resulted in improved tactile discrimination thresholds [4,18], which was not noted in vibration-induced neuropathy. However, there are some features that separate vibration-induced neuropathy patients from individuals with use dependent changes and multidigit coactivation. First, in the times scale, the effects of repeated multidigit coactivation on longer time scale have not been thoroughly investigated. The exposure time to the Braille reading is some hours a day for several years whereas the individuals described in this study have been exposed to vibrations several hours a day for a median of 33.5 years. Second, long time exposure to vibrations has been shown

to result in pathological changes in peripheral nerves [1] likely resulting in a changed afferent signal pattern to the brain and thus a cortical reorganization. The cortical changes seen in our patients likely represent the summation of changes because of long time exposure to synchronous cutaneous stimulation and a changed afferent signal pattern because of peripheral nerve injury.

During the last decade it has been shown that peripheral nerve injury and neuropathy result in changes in the central nervous system [20]. This opens interesting perspectives for treating sensory disturbances in vibration-induced neuropathy using selective forearm deafferentation, a method which has shown promising results in median and ulnar nerve injuries [21]. Selective forearm deafferentation has been tested with promising results in a single case of vibration induced neuropathy [22] but larger randomized studies are needed to confirm the effects and to optimize the treatment.

Understanding the central and peripheral ramifications of peripheral neuropathy because of long time exposure to hand-held high frequency vibrations may facilitate the development of new therapeutic strategies and intervention programs.

Conclusion

Long time exposure to hand-held high frequency vibrating tools results in increased activated volumes of individual fingers in S1. Furthermore, the results presented provide evidence of central reorganization of cortical somatotopy that is not functional, but because of prolonged exposure to synchronous vibrations. The results may have important therapeutic implications.

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