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Activation of the supplementary motor area (SMA) during voluntary pelvic floor muscle contractions—An fMRI study

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To identify cortical and subcortical regions involved in voluntary pelvic floor muscle control, functional magnetic resonance imaging (fMRI) was performed at 1.5 T in thirty healthy subjects (15 women, 15 men). The participants performed rhythmical (1 Hz) pelvic floor muscle contractions, which imitated the repetitive interruption of voiding. Since previous reports concerning the representation of pelvic floor muscles in the cortex of the medial wall are inconsistent, a conservative statistical threshold (FWE-corrected $P<0.05$) was used to detect the most robust foci of activation, and cytoarchitectonic probability maps were used to correlate the results with structural anatomical information. We found a strong and consistent recruitment of the supplementary motor area (SMA), with foci of peak activity located in the posterior portion of the SMA, suggesting that this region is specifically involved in voluntary pelvic floor muscle control. Further significant activations were identified bilaterally in the frontal opercula, the right insular cortex and the right supramarginal gyrus. They may reflect the attentive processing and evaluation of visceral sensations. Weaker signals were detected in the primary motor cortex (M1) and the dorsal pontine tegmentum. There was no significant correlation between bladder volumes and brain activation induced by pelvic floor muscle contractions. We found no significant gender-related differences.

Keywords: Human brain; Functional magnetic resonance imaging (fMRI); Micturition control; Pelvic floor; SMA

Introduction

The control of micturition and continence by the central nervous system involves a cascade of control centers, i.e. spinal reflex pathways, areas of the brainstem and diencephalon, and cortical regions (Jänig, 1996). Intact neural control of pelvic floor muscles is crucial for the maintenance of fecal and urinary continence (Fowler, 1999). The external urethral sphincter muscle, innervated by the pudendal nerve, is part of the pelvic floor. During urine storage, it contracts tonically, while the detrusor muscle of the bladder is relaxed. During micturition, the sphincter and other pelvic floor muscles relax, and the bladder empties by detrusor contraction. Neural structures responsible for the switch from urine storage to micturition are located in the pontine micturition center (PMC), which sends projections to the sacral spinal cord that innervates neurons of the main bladder (pelvic) and urethral (pudendal) nerves (Blok, 2002; Griffiths, 2002). Higher brain centers such as the prefrontal and cingulate cortex, as well as the insula, are involved in the cognition of bladder sensation and the voluntary initiation or postponement of micturition (Kavia et al., 2005).

The motor cortex is important for the voluntary control of pelvic floor muscles (Blok, 2002). Voiding can be intentionally interrupted by contractions of the external urethral sphincter and ancillary pelvic floor muscles (Madersbacher, 2004). Three neuroimaging studies, which investigated brain activity during voluntary contractions of pelvic floor muscles in healthy subjects, came to divergent conclusions (Blok et al., 1997a; Seseke et al., 2006; Zhang et al., 2005). Using positron emission tomography (PET), Blok et al. (1997a) found activity in the superolateral and superomedial precentral gyrus, i.e. the primary motor cortex (M1), during repetitive pelvic floor straining in healthy women. Zhang et al. (2005), who studied pelvic floor muscle contractions during empty- and full-bladder conditions in men, did not find M1 activity, and hypothesized that these muscles are "not significantly represented in M1 and much less predominant than abdominal muscles in terms of motor cortical representation" (their page 178). Instead, Zhang et al. (2005) report strong activity of the supplementary motor area (SMA) and other regions (parietal cortex, limbic system, cerebellum, putamen) especially in the full-bladder condition. A very recent fMRI study of 11 healthy women (Seseke et al., 2006) found that relaxation and contraction of pelvic floor muscles induced activation patterns which included both M1/S1 and SMA, as well as the frontal cortex, cerebellum and basal ganglia.

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Another fMRI study of 17 healthy subjects examined voluntary contractions of the external anal sphincter (Kern et al., 2004). The authors report multifocal fMRI activity in the sensorimotor, anterior cingulate, prefrontal, parietal and occipital regions. Interestingly, the insular cortex was more often recruited in women than in men. Unfortunately however, due to methodological reasons, the study of Kern et al. (2004) lacks a group analysis with stereotaxic coordinates of the common activation sites, which makes a comparison with the aforementioned studies problematic.

Patients with stress urinary incontinence were repeatedly examined in a recent fMRI study (Di Gangi Herms et al., 2006). Comparing the activation patterns before and after pelvic floor muscle training, these authors describe neuroplastic changes. After a 12-week training period, there was more focused activation of the M1/S1 during sphincter contractions, and reductions in brain activation were also found in the insula, anterior cingulate cortex and frontal operculum after training.

In summary, the previous neuroimaging studies of voluntary pelvic floor muscle control in normal subjects are not entirely consistent. While some authors reported activation of the primary sensorimotor cortex (Blok et al., 1997a; Seseke et al., 2006), others found activation of the SMA, but not of M1/S1 (Zhang et al., 2005). There are indications that cortical activity can be influenced by bladder volume (Zhang et al., 2005), previous training (Di Gangi Herms et al., 2006), and possibly also gender (Kern et al., 2004). Only one fMRI study so far could demonstrate activation in the midbrain and pons during pelvic floor muscle contractions (Seseke et al., 2006). We reevaluated these published data, taking into account methodological differences (e.g. different activation conditions), and used probabilistic cytoarchitectonic maps (Eickhoff et al., 2005) to correlate the functional imaging data with structural information.

Furthermore, a larger sample of normal subjects, namely thirty untrained volunteers (15 men, 15 women) were studied with fMRI to delineate brain activity during repetitive pelvic floor muscle contractions. A random-effects group analysis and a conservative statistical threshold were applied to detect the most robust foci of activity. Possible correlations between brain activity and bladder volume were investigated, and the data of men and women were compared. The results show a strong and consistent involvement of the SMA during voluntary repetitive contractions of pelvic floor muscles in normal subjects.

Materials and methods

Subjects

Thirty adults (15 women, 15 men), with no history of neurological or psychiatric disease and without urinary symptoms, participated in the study which was approved by the local ethic committee. The age of the participants was 26.6±2.8 years (mean ±SD), ranging from 18 to 33 years. All subjects gave their written informed consent. Half of the subjects work in the Department of Urology at the University of Kiel, and most of the others are medical students who are familiar with the function and anatomy of the pelvic floor. Nevertheless, the experimental procedures were explained in detail to each subject and repetitive pelvic floor muscle contractions were briefly practiced before the fMRI examination to ensure that every participant was able to do the task correctly. The bladder volumes differed between subjects, since the time interval between the last micturition and the first fMRI scan varied between 5 min and ~3 h. Immediately after scanning, the bladder was emptied and urine volume of each participant was measured.

MR imaging and paradigm

A 1.5 T Philips Gyroscan tomograph (Philips, Hamburg, Germany) with a phased-array head coil was used. The subjects wore headphones for noise protection and lay comfortably in a supine position inside the magnet bore. Their eyes were closed and covered with sleeping masks. Head motion was restricted by foam pads and the investigators observed the subjects via video camera. High-resolution T1-weighted anatomical MR images of the entire head were obtained for each subject (3D fast field echo, echo time 4.3 ms, flip angle 8°, repetition time 9.1 ms, 1×1×1 mm voxels). Functional imaging was performed using a T2∗-sensitive echoplanar imaging technique (EPI, echo time 50 ms, flip angle 90°, field of view 220 mm, pixel size 2.3×2.3 mm). Each EPI volume was acquired within 4.4 s (TR) and comprised of 36 axial slices (3 mm slice thickness, 0.3 mm interslice gaps), which covered the brain from the vertex to the cerebellum. Two fMRI sessions with 55 image volumes (duration 258 s) were acquired in each subject. Four volumes preceding each session were discarded to reach signal equilibrium.

The participants performed voluntary rhythmical contractions of pelvic floor muscles at 1 Hz, similar as in the study of Zhang et al. (2005). They were instructed to contract the same muscles which they would activate to interrupt voiding, i.e. the external urethral sphincter and auxiliary pelvic floor muscles. The subjects were explicitly asked to lie still in the scanner, to avoid Valsalva maneuvers and to breath normally. The short contractions were paced by the sounds of a metronome (1 Hz) and were to be performed with moderate effort (about 25% of maximum force), and not with maximum effort to avoid fatigue. During each fMRI session, five periods (23.5 s each) of voluntary contractions alternated with periods of rest (23.5 s). Start and stop signals as well as the metronome sounds, which were audible during both the contraction and the resting periods, were given via headphones.

Electromyography

Electromyograms (EMG) were obtained from eight subjects during a practice session (consisting of 5 blocks of 23 contractions at 1 Hz, separated by periods of rest), which was performed in a room next to the MR tomograph before scanning. Two further subjects who were examined with EMG at a later date. Bipolar surface EMG electrodes (Ag/AgCl, electrode distance 3 cm) were attached to the skin above the rectus and obliquus abdominis muscles and on the perineal skin; a reference electrode was attached to the ankle. EMG signals were sampled at 600 Hz and processed by a Noraxon 2008 differential voltage amplifier (Noraxon, Vienna, Austria), bandwidth 10 to 1000 Hz. The EMG signals of the pelvic floor muscle contractions were inspected and their pace was evaluated.

Image processing and analysis

Data preprocessing and analyses were performed using SPM2 (available at http://www.fil.ion.ucl.ac.uk/spm) and Matlab on a Sun Sparc Ultra 10 workstation. The time series of fMRI image volumes were realigned using a least-squares approach and six-