The Cortical Topography of Human Anorectal Musculature

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Background & Aims: The muscles of the anorectum are important in the volitional control of continence, yet virtually no information exists on their cortical representation in humans. Methods: Topographic cortical mapping of both cerebral hemispheres was performed in 9 healthy subjects by applying suprathreshold transcranial magnetic stimulation to individual points on a scalp grid centered over the vertex and then recording the electromyographic responses from the external anal sphincter, rectum, and tibialis anterior muscles. Results: Cortically evoked anal and rectal response latencies were similar (20.2 ± 1.7 and 19.8 ± 1.5 milliseconds, respectively) and were shorter than those from the anterior tibialis muscle (right, 29.7 ± 2.3 milliseconds; left, 29.9 ± 1.8 milliseconds; P < 0.0005). Cortical mapping showed that the anal responses were bilaterally represented on the superior motor cortex (Brodmann area 4) of both cerebral hemispheres; a similar topography was found for the rectal responses. By comparison, the tibialis responses showed predominantly contralateral medial motor cortex representation. Subtle but consistent differences in the degree of bilateral hemispheric representation were also apparent both between and within individuals for the anal responses and to a lesser extent for the rectal responses. Conclusions: The anorectal musculature has bilateral motor cortex representation with similar topography, but there is intersubject variation in the degree of symmetry.

The voluntary sphincter muscles of the anorectum are vital for the maintenance of fecal continence and are under strong descending control from the cerebral cortex. Animal data have shown that anal sphincter contractions can be elicited by direct electrical stimulation of the superomedial aspect of the motor cortex (adjacent to the falx cerebri), whereas data from human studies performed during neurosurgery could not specify which anorectal muscles responded to cortical stimulation, referring to the area as the perineum. It remains, unclear, therefore, whether the pelvic muscles that make up the anorectum are represented in the same areas of the cerebral cortex or if there indeed is representation on the motor cortex for rectal musculature.

Fecal incontinence is frequently encountered in instances in which there is peripheral nerve damage. However, there are instances in which fecal incontinence presents in a setting where central nervous system damage has occurred, such as in patients with stroke or frontal lobe damage. Nakayama et al. found fecal incontinence primarily in patients with larger strokes and when the cerebral cortex was involved. Central motor pathways may also be important in modulating sphincter muscle function (e.g., in patients who cannot relax the anal sphincter and pelvic floor properly, as in anismus). Constipation and fecal incontinence are also frequently found in patients with multiple sclerosis, and one study of anorectal function in subjects with multiple sclerosis has suggested there may be central motor mechanisms involved.

The recent development of transcranial magnetic stimulation, a noninvasive technique for assessing human cerebral motor function, now provides a reliable method for evaluating the corticofugal pathways innervating the striated musculature. Previous reports using this technique have described the conduction velocities and response characteristics of the anal sphincter and levator ani muscles after diffuse stimulation of the cortex but have not assessed their individual cortical representations in each hemisphere. We therefore studied the topographic representation of the anal sphincter within the motor cortex by applying focal magnetic stimuli to frontocentral areas over each hemisphere. Focal magnetic stimulation techniques can stimulate discrete areas of cerebral cortex to a mapping resolution of ~2 cm², with the central area being maximally stimulated. We also used an intrarectal electrode to take electromyographic (EMG) recordings from within the rectum. Because cortical mapping also allows a comparison of the magnitude of representation in each hemisphere, we were also able to conduct an assessment of the interhemispheric

Abbreviations used in this paper: EMG, electromyographic; MRI, magnetic resonance imaging; PET, positron emission tomography.

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symmetry between anal and rectal responses to cortical stimulation. Recordings of cortically evoked responses from the lower leg musculature, being contralaterally represented in the motor cortex, were used as a control for interhemispheric symmetry: the tibialis anterior muscle was thus used because it is represented on the medial surface of the cerebral cortex, distinct and inferior to the “perineal area” referred to by Woolsey et al.\(^5\)

**Materials and Methods**

**Subjects**

All subjects \((n = 9)\) were healthy adult volunteers recruited from personnel affiliated with the research units involved in the project. All claimed to have normal bowel function, and none reported a history of neurological or other illnesses. All had normal findings on examination of the perineum and anorectum before the study. This study was approved by the Salford Health Authority Ethics Committee, and all subjects gave informed written consent before participating in the study. The subjects were 8 men and 1 woman, and all were right-handed. Their mean \((\pm SD)\) age was 31.7 ± 7.9 years (range 22–45 years).

**Magnetic Stimulation of the Cerebral Cortex**

A commercially available magnetic stimulator was used in the experiments (Magstim 200; Magstim Co. Ltd., Whitland, Dyfed, Wales). When connected to a 70-mm figure-eight coil (model type 9790; Magstim Co.), this system allows the generation of maximal magnetic fields of 2.2 T that are focused at the cross point of the coil. The area of cortex stimulated by the figure-eight coil is \(\sim 2\) cm\(^2\), ideal for mapping purposes, and will preferentially activate interneurons of the motor cortex (transsynaptic stimulation). One of the natural advantages of magnetic stimulation is its ability to stimulate neural tissue deep to the scalp, skin, or bone with virtually no signal attenuation. Thus, lower energies are required to excite nerve fibers, which makes the technique almost painless. A single pulse of transcranial magnetic stimulation to the scalp, with the center of the coil at the cranial vertex, penetrates brain tissue to a depth of 4–5 mm,\(^\text{19}\) and even at high intensities there is little evidence that the stimuli penetrate beyond the gray matter of the cortex.

Because cortical excitation produced by magnetic stimulation is dependent on coil orientation relative to the scalp surface, the figure-eight coil was always placed with the anterior edge of the cross point positioned over the site of interest and with the handle pointing backward (for the midline grid points) or at an angle of 45° tangential to the scalp surface (for lateral grid points), as described by Mills et al.\(^\text{20}\)

**Anorectal and Anterior Tibial EMG Responses**

Anal sphincter EMG responses were recorded by using an anal plug electrode system with three Ag/AgCl EMG plate electrodes arranged radially 120° apart (EPS-30; Farrall Instruments, Inc., Grand Island, N.Y.) and positioned in the anal canal. Rectal EMG responses were recorded from a single pair of Ag/AgCl ring electrodes (inter electrode distance, 1.5 cm) mounted on a 5-mm-diameter catheter that was inserted into the rectum through the center of the anal plug (length, 5.5 cm) and positioned so that the rectal electrodes were 10 cm from the outside edge of the anal plug at the anal verge. The anal plug, constructed of hard plastic, was orientated in the anal canal to position the rectal catheter 4.5 cm above the inside edge of the anal plug against the anterior wall of the distal rectum close to the pelvic floor muscles. Anterior tibialis muscle responses were recorded by using a pair of Ag/AgCl surface EMG electrodes (no. 13L20; Dantec, Tonsbakken, Skovlunde, Denmark) placed over each muscle with an interelectrode distance of 1 cm. The EMG responses from all four sites were recorded with a multichannel EMG recording system (Counterpoint; Dantec) using filter settings of 20 Hz and 2 kHz, a sweep length of 100 milliseconds, and a full-scale deflection of 200–2000 µV. Electrode contact was monitored during the study at regular intervals by using real-time EMG responses to voluntary contractions of each muscle group.

**Topographic Mapping Procedure**

A 12 × 8-cm grid, with rows of points 2 cm apart anteroposteriorly and 1 cm apart mediolaterally, was superimposed onto a transparent plastic sheet and attached to a surgical hood that was securely fastened to each subject’s head. The grid was positioned to allow stimulation of sites up to 6 cm lateral and anterior to the vertex and up to 2 cm posterior to the vertex (Cz on the 10–20 international system\(^\text{21}\)) over both hemispheres. During the mapping procedure, subjects reclined on a comfortable examination couch, with their legs flat. After a digital examination to ensure that the rectum was empty, the EMG anal plug was inserted, and the rectal catheter was passed through the lumen of the anal plug and sited on the rectal wall 10 cm above the anal margin.

**Protocols**

Study 1: Topographic mapping of the cortical representation of the anorectum. All 9 subjects participated in this study. First, to determine the threshold intensity for cortical stimulation, a preliminary mapping study was performed. This was conducted by discharging the figure-eight coil with a stimulation intensity of 2.2 T (100% stimulator output) over the medial points of the scalp grid surrounding the vertex. By this means, the sites evoking maximal EMG responses were identified, and their positions were noted for each hemisphere.

After identification of the sites that gave the largest responses, cortical stimulation of these sites was repeated, starting at a subthreshold intensity of 0.6 T (30% stimulator output) and increasing in 0.1 T steps until intensities were found that first evoked quantifiable anal, rectal, and tibial EMG responses in at least 3 of 6 consecutive trials. These values were defined as the stimulation threshold intensities.
After these thresholds had been determined, the stimulation coil was repositioned over each point on the scalp grid (the order of which was randomized between each subject), and the coil was discharged at 0.4 T (20% stimulator output) above the predetermined threshold intensity. By applying this constant, albeit relative, level of stimulation above that subject's threshold intensity, a uniform level of neural stimulation can be achieved and assessable EMG responses recorded. The use of 120% of the threshold intensity for mapping is recommended by the guidelines proposed for magnetic stimulation technique, because at this level the maps generated are considered to give a relatively reliable estimate of the representative size of the motor cortex area devoted to a muscle group.

Three stimuli, at least 15 seconds apart, were delivered at each point, and the EMG responses from each muscle group were recorded.

Study 2: Reproducibility of the cortical topography. To provide an assessment of reproducibility, 3 subjects who participated in study 1 underwent a second identical mapping study at least 14 days after the first.

Study 3: Coregistration of topographic scalp data with surface-rendered magnetic resonance brain images. In 3 subjects, the cortical structures underlying the grid points from which EMG responses were obtained were identified by performing magnetic resonance imaging (MRI) of the head with a 1.0 T field strength Magnetom Impact Scanner (Siemens, Erlangen, Germany). The topographic data obtained for each of the 3 subjects were then coregistered with their surface-rendered MRI brain image by using magnetic source digitalization (Polhemus 3-space Isotrak system; K aiser Aerospace Inc., Colchester, VT) of each of the scalp grid coordinates. Those interested in these techniques are referred to an excellent review of their application to study of the brain-gut axis by Aziz and Thompson.

Data Analysis
For each grid point, the mean value of the three EMG responses evoked for each muscle group was calculated. In using the averaged data, any potential trial-to-trial variation in the shape of the response tracing can thus be reduced.

Definition of Terms
Latency. Latency was the interval from the onset of the stimulus to the onset of the individual muscle EMG response, expressed in milliseconds. To provide a single figure for analysis in each subject, the shortest five latencies for each muscle group were identified, and the mean value was calculated.

Amplitude. Amplitude was the peak-to-peak voltage of the EMG responses, expressed in microvolts. Only responses of $\geq 5 \mu V$ were used. A mean amplitude value for each subject was calculated by using the five largest responses.

Magnitude of representation. The magnitude of representation was the number of sites on the scalp grid over each hemisphere (including midline sites) from which an EMG response was obtained.

Interhemispheric asymmetry. The intraindividual hemispheric magnitudes of representation were calculated as a percentage of each hemisphere's responses (number of grid sites) to the total number of responses from both hemispheres and were considered asymmetric if the larger hemisphere representation was $\geq 60\%$.

Construction of Topographic Scalp Maps
Scalp maps representing the area of response for each muscle group were generated in each subject by assigning to each scalp grid point an EMG response amplitude. These data were then imported into the UNIRAS interactive program UNIMAP (AVS/UNIRAS Systems, Waltham, MA) and were interpolated onto regular two-dimensional grids.

Statistical Tests
The Wilcoxon rank sum test was used to compare data for significance, and the Spearman rank correlation was used to assess correlation of the paired data. Amplitudes from each muscle group in each patient were converted into a ratio of response and visually compared after cortical maps of the amplitude response had been generated. The statistical package Instat (GraphPad Software, San Diego, CA) was used as appropriate. Data are expressed as means $\pm SD$, unless stated otherwise, and a $P$ value of $< 0.05$ was taken to indicate statistical significance.

Results
In all subjects, cortical stimulation (mean threshold intensity, 2.0 $\pm 0.1$ T) evoked assessable biphasic or triphasic EMG tracings in each muscle group. Examples of the averaged responses are presented in Figure 1.

Response Characteristics
Latencies. There were no consistent latency differences between anal sphincter and rectal responses. The mean anal latency was 20.2 $\pm 1.7$ (SD) milliseconds, and the mean rectal latency was 19.8 $\pm 1.5$ milliseconds, significantly shorter than the mean right tibial latency of 29.7 $\pm 2.3$ milliseconds and the mean left tibial latency 29.9 $\pm 1.8$ milliseconds ($P < 0.0005$). As expected, there was a strong latency correlation between the right and left tibial responses (Spearman correlation $r = 0.91$; $P < 0.0001$). There was also a strong correlation between the anal and rectal latency responses (Spearman correlation $r = 0.71$; $P < 0.005$).

Amplitudes. The individual amplitudes of the responses for each muscle studied are shown in Table 1. Amplitude responses were more variable between subjects, the anal and rectal responses being smaller than the leg responses.

Scalp Topography
Figure 2 illustrates the scalp topography of the anal and rectal responses in 3 subjects. In general,
responses from both muscle groups were localized either adjacent to or anterior to the vertex and showed similar, but not identical, topographic representation, with little evidence for discrete somatotopic organization on the motor cortex. Although both the anal and rectal responses could be evoked by stimulation of either hemisphere, indicating a bilateral representation, subtle differences in the magnitude of representation from the two hemispheres were observed. Compared with the anterior tibialis responses, there is only 1 subject who lateralized anal representation to the left hemisphere (subject 2, Tables 2 and 3), with a hemisphere asymmetry of 60%. Two additional subjects (subjects 6 and 8, Tables 2 and 3) had clearly asymmetric anal sphincter representation, with 67% and 61% of the responses from the right hemisphere; anal representation appears more symmetric in the other 6 subjects. By comparison, only 1 subject lateralized the rectal response representation to the left hemisphere (subject 3 in Tables 2 and 3), with a hemisphere asymmetry of 61%. The rectally recorded responses in the other 8 subjects had more equal representation in both hemispheres.

Responses from the tibialis anterior muscles were also located in medial sites adjacent to the vertex, and they overlapped with the anorectal representations. Not surprisingly, the right and left leg muscles showed clear contralateral hemisphere lateralization, although some ipsilateral hemisphere responses were observed (probably related to stimulus spread; Tables 2 and 3). The left hemisphere/right leg representation was usually larger than the right hemisphere/left leg representation, reflecting the right-handed bias in this study group.

Reproducibility

Comparisons of the topographic maps between the two studies indicated that the magnitude of representation was similar in each of the 3 subjects investigated. In addition, the interhemispheric differences in representation showed a reasonable degree of consistency for both the anal sphincter and the rectal responses, being always in the same direction (Tables 2 and 3).

Table 1. Individual Cortically Evoked Response Amplitude Characteristics

<table>
<thead>
<tr>
<th>Subject</th>
<th>Study</th>
<th>Anal mean (μV)</th>
<th>Rectal mean (μV)</th>
<th>Right leg (μV)</th>
<th>Left leg (μV)</th>
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<td>16.1</td>
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Coregistration Data

An example of the coregistered data in one subject is shown in Figure 3. For all 3 subjects who had MRI scans, the colocalization of the cortical maps with the MRI scans showed the maximal response for both the anus and rectum to overlay the precentral gyrus of the motor cortex (Brodmann area 4) just anterior to the central sulcus, corresponding to the area previously described by Woolsey et al.3 for perineal motor localization in animals.

Discussion

These data show, for the first time, that the human anal sphincter has discrete motor representation within both hemispheres of the cerebral cortex, possibly implying a bilaterally integrated pattern of recruitment at the cortical level during the volitional control of anal continence. In addition, our observation that the representation for the anal sphincter is located at the most medial aspect of the superior motor cortex, adjacent to the interhemispheric fissure, is consistent with data from both animal2,3 and human studies4,5,25 that used direct cortical stimulation methods and have shown that this muscle is represented on the mesial motor strip (Brodmann area 4). Indeed, tracer studies in rats26 have shown strong projections from the motor cortex to the sacrocaudal spinal cord, which innervates the pelvic muscles, whereas functional positron emission tomography (PET) imaging during the task of pelvic floor straining in women has also shown activation of the superomedial precentral gyrus. This PET study raised the intriguing possibility that a difference might exist between men and women, although the similarity of findings in our study (consisting of mostly male subjects) and those in

Table 2. Topographic Mapping Data for Each Subject Showing the Magnitudes of Representation

<table>
<thead>
<tr>
<th>Subject</th>
<th>Study no.</th>
<th>Magnitude of representation (no. of grid points)</th>
<th>Right hemisphere</th>
<th>Left hemisphere</th>
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<td>13</td>
<td>12</td>
<td>7</td>
</tr>
</tbody>
</table>

NOTE. See Definition of Terms for explanation of cortical lateralization.

aSubject lateralized anal responses to the left hemisphere.
bSubject lateralized rectal responses to the left hemisphere.
cSubject lateralized anal responses to the right hemisphere.

table 3. Hemisphere Symmetry as a Percentage for Each Subject

<table>
<thead>
<tr>
<th>Subject</th>
<th>Study no.</th>
<th>Anal</th>
<th>Rectal</th>
<th>Right leg</th>
<th>Left leg</th>
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<th>Rectal</th>
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NOTE. See Definition of Terms for explanation of hemispheric percentage score for each muscle.
Thus it appears that the primary motor control of anorectal function does reside in the mesial region of the motor strip. Our data also provide the first description of the cortical topography of responses from within the human rectum, indicating that it appears to have a separate, but overlapping, medial motor cortex representation compared with the anal sphincter. The question that arises, however, is which striated muscle structure within the pelvis generated these responses. The most plausible explanation for these responses is that they arose from the pelvic floor muscles via conduction of the EMG signal through the rectal wall, because motor cortex stimulation predominantly activates pyramidal motor pathways to striated muscle (including the levator ani muscles), and the only striated muscle in immediate proximity to the intraluminal electrode within the rectum is that of the pelvic floor. It could be argued, however, that these responses might simply represent an EMG artifact induced by catheter movement generated in the rectum, a consequence of anal sphincter contraction. This seems unlikely for the following two reasons. First, we identified scalp sites where rectal responses could be evoked in the absence of an anal sphincter response (Figure 1D), a finding difficult to reconcile if the rectal responses were dependent on anal sphincter activation. Second, we observed that although the scalp topography of the anal

Figure 2. (A-C) Topographic scalp maps of the cortical representation of the anal and rectal responses for 3 subjects. All plots are oriented as viewed from above, with the vertex of each plot marked with an X. Scale indicates the percentage of the amplitude of the maximum response evoked from either hemisphere for each muscle group in each subject. Subject in A has bilateral anal and rectal representation, whereas subjects in B and C show clear lateralization of both the anal and rectal responses to the left and right hemispheres, respectively.

Figure 3. Individual data from 1 subject shown as a series of right lateral oblique surface-rendered brain MRI images onto which scalp map data have been colocalized. Arrow indicates central sulcus. The areas of cortex under the colocalized representation of the anal, rectal, right leg, and left leg responses are shown. The responses from all four muscle groups localize to the superomedial motor cortex (Brodmann area 4), but they have different morphologies and extents of representation. In particular, in this individual, the anal and rectal responses have bilateral representation, whereas the leg responses show clear lateralization to the contralateral hemisphere.
and rectal representations overlapped, they were neither at identical sites nor directly similar in contour shape, which is inconsistent with the hypothesis that anal sphincter contraction generated both responses. It should also be emphasized that the anal plug used for recording sphincter EMG was constructed of hard plastic with the rectal catheter inserted through the plug lumen, thus isolating the rectal catheter from any artifact associated with anal sphincter contractions. A further, but improbable, explanation for the rectal responses is that they could have originated from the smooth muscle of the rectum. This is unlikely, because the elicitation of myoelectric activity within the smooth muscle fibers of visera by single pulse magnetoencephalometric stimulation of motor cortex has not been shown previously, and the pattern of EMG response that was found was more typical of striated muscle.

We observed that within individuals there were subtle but consistent differences in the motor representation of anal and rectal responses between hemispheres. From our data, it appears that the anal sphincter may have greater representation in the right hemisphere of right-handed subjects, whereas the rectal responses tend to be more bilaterally represented. It could be suggested, however, that these interhemispheric differences are simply a reflection of differences in the ability of the magnetic stimulus to access motor fields within the smooth muscle fibers of visceral by single pulse magnetoencephalometric stimulation of motor cortex has not been shown previously, and the pattern of EMG response that was found was more typical of striated muscle.

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In conclusion, we have found that anal musculature is bilaterally represented in the superomedial motor cortex but appears to display subtle interhemispheric differences. Further studies are now needed to assess the relevance of these findings in patients after central nervous system injury to help develop a better understanding of the pathophysiology of fecal incontinence and constipation after cerebral damage.

References
3. Woolsey CN, Settlage PH, Meyer DH, Sencer W, Pinto Hamuy T, Travis AM. Patterns of localisation in precentral and “supplementary” motor areas and their relationship to the concept of a


