



Somatotopy of corticospinal tract fibres of the intercostal muscles: report of a case and review of literature

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Abstract

This study aimed at describing the first case of subcortical stimulation of the corticospinal tract leading to selective contraction of the intercostal muscles during surgery for removal of a tumour centred in the right central lobule/supplementary motor area. A 53-year-old male presented with partial motor seizures. Imaging demonstrated a low-grade glioma affecting the posterior aspect of the superior and middle frontal gyri and invading the precentral gyrus. Preoperative motor Transcranial Magnetic Stimulation and advanced diffusion tractography were performed to establish the relationship of the tumour with the motor cortex and corticospinal tract. Intraoperative motor mapping and monitoring were performed with monopolar stimulation (“train of 5” technique). At the posterior margin of resection, subcortical stimulation demonstrated a selective response from intercostal muscles, medial to responses from the lower limb and lateral to responses from the upper limb. PubMed literature search was performed to identify any case reporting similar findings. There were no cases previously reported in the literature. The location of the subcortical response for intercostal muscles confirms the somatotopy of the corticospinal tract. Intercostal muscles are controlled by selective fibres within the corticospinal tract. Damage to these fibres can lead to paralysis of voluntary respiratory muscles. Further studies are needed to define the cortico-subcortical network controlling voluntary respiratory muscles.

Keywords Corticospinal tract · Intercostal muscle · Motor cortex · Motor mapping · Subcortical stimulation

Introduction

Penfield and Boldrey (1937) was the first to obtain a comprehensive map of the motor and somatosensory areas in the human brain after direct cortical stimulation in

126 patients operated under local anaesthesia. Previous experimental work was performed on animals (Aminoff and Sears 1971), but Penfield and Boldrey (1937) had the advantage of operating on awake patients, being able to report on tactile sensation and elicit movements. This study led to the development of the *Homunculus*—a human-like figure, where each body part is proportional to the degree of cortical area dedicated to motor or somatosensory function (Fig. 1). In their original article Penfield and Boldrey (1937) wrote: “The voluntary muscles of the trunk and lower extremities respond only rarely”. From 26 points stimulated on the precentral cortex only one point was identified to activate trunk/ back muscles (Fig. 2). Later studies attempted to better identify the cortical representation of the trunk and the origin of the voluntary control of breathing in the cerebral cortex (Maskill et al. 1991; Gandevia and Rothwell 1987; Similowski et al. 1996) and direct stimulation of the primary motor cortex led to contraction of the diaphragm and the intercostal muscles (Maskill et al. 1991; Gandevia and

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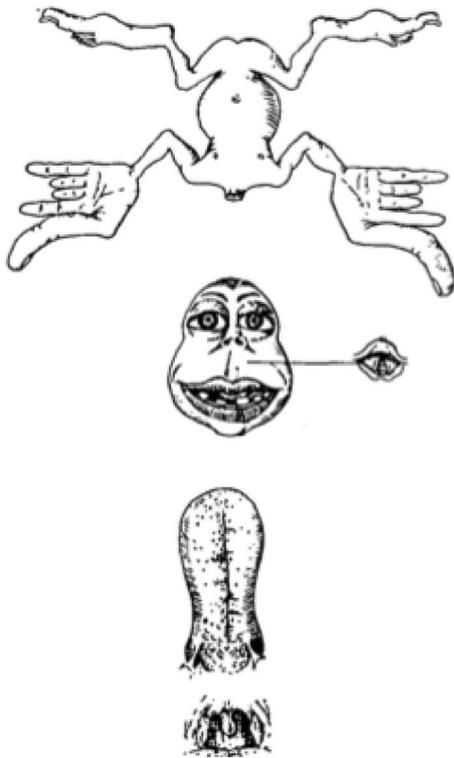


Fig. 1 Homunculus as represented by Penfield and Boldrey (1937)

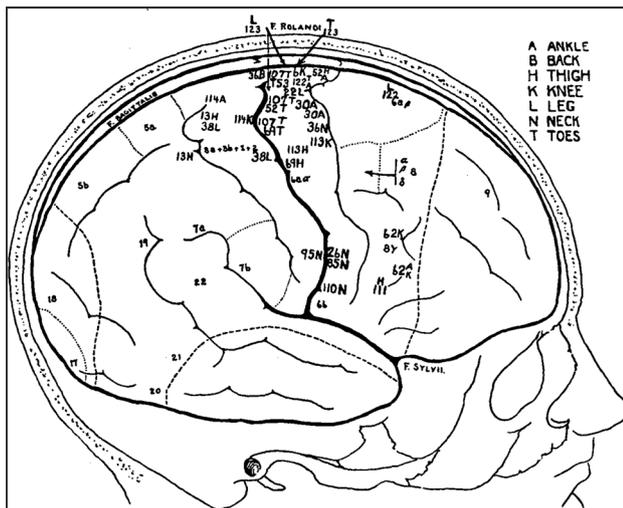


Fig. 2 Recordings of trunk and lower extremity activations (Penfield and Boldrey 1937)

Rothwell 1987; Similowski et al. 1996). Davenport et al. 1993 reported activation of the intercostal muscles through electrical stimulation of the cerebral cortex at the vertex in cats. In humans, Maskill et al. (1991) and Gandevia and Plassman (1988) showed that an area localized in the middle cortex 1 cm posterior to the vertex caused contraction

of intercostal muscles and diaphragm when stimulated by transcranial magnetic stimulation.

Despite previous demonstration of a cortical area related to the control of trunk muscles, no previous report has described activation of the intercostal muscles by stimulation of subcortical fibres of the cortico-spinal tract. We report the case of a patient where subcortical motor stimulation during removal of a brain tumour elicited selective contraction of the intercostal muscles. The intraoperative findings are presented, along with a literature review on this topic.

Description of the case report

A 53-year-old right-handed, professional chef, male patient presented to his local hospital with three seizure-like episodes occurring in the space of 1 h. The seizures manifested with jerking of the left upper and lower limbs, with associated facial and eyelid twitching, followed by left-sided weakness and slurred speech. An MRI head with and without contrast demonstrated a lesion which appeared hyper intense on T2 and FLAIR sequences, involving the right supplementary motor area and extending into the central lobe, with invasion of both the precentral and postcentral gyri. There was no enhancement after gadolinium administration (Fig. 3). In addition, perfusion and spectroscopy MRI did not show any evidence of a high-grade lesion. Overall, the imaging was suggestive of a low-grade glioma. Pre-operative functional neuroimaging was acquired with fMRI and Transcranial Magnetic Stimulation (TMS), which both showed an overlap between eloquent motor areas and tumour, particularly at the medial edge, corresponding to the foot region (Figs. 4, 5). Preoperative tractography demonstrated the proximity and likely infiltration of the cortico-spinal tract by the tumour (Figs. 4, 5).

The case was discussed within our neuro-oncology multidisciplinary team (MDT) and the consensus decision was to offer surgery for maximal debulking of the lesion with intraoperative motor mapping and monitoring. The patient agreed to surgery and an informed consent was obtained.

At surgery, the pre-central gyrus and the posterior portion of the superior frontal gyrus (corresponding to the SMA) were exposed and found to be expanded by tumour invasion (Fig. 6). The central sulcus was identified and verified with somatosensory evoked potential (SSEP) “phase reversal” technique (4 contacts strip electrode, Inomed®), thus confirming the anatomo-functional location of the pre and post-central gyri. Monopolar mapping was performed with monopolar “train of 5 technique” (Szelényi et al. 2010; Bello et al. 2014), eliciting positive sites corresponding to hand and foot region (at a motor threshold of 10 and 12 mA, respectively) (Figs. 6, 7). After a thorough mapping of the

Fig. 3 Pre-operative T2, T1 MRI showing low-grade glioma involving posterior SFG, MFG and invading precentral gyrus (black arrow)

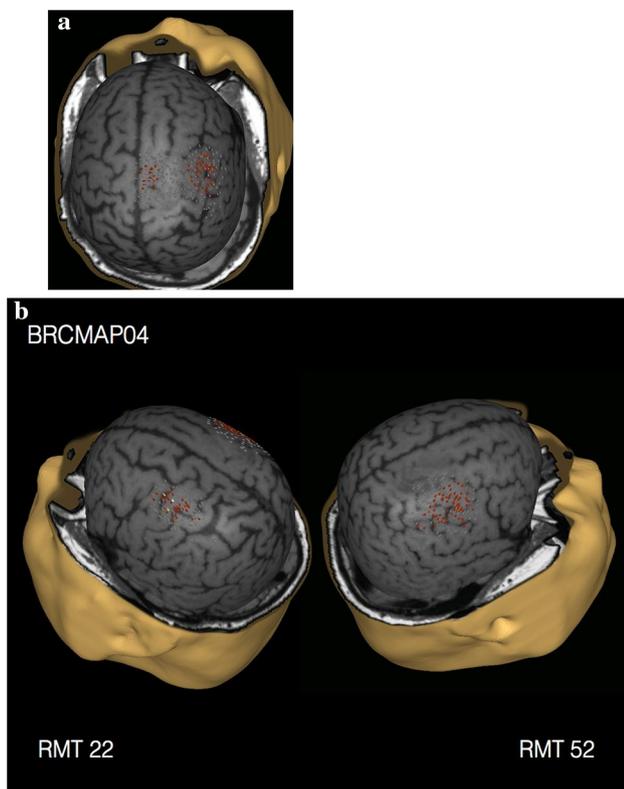
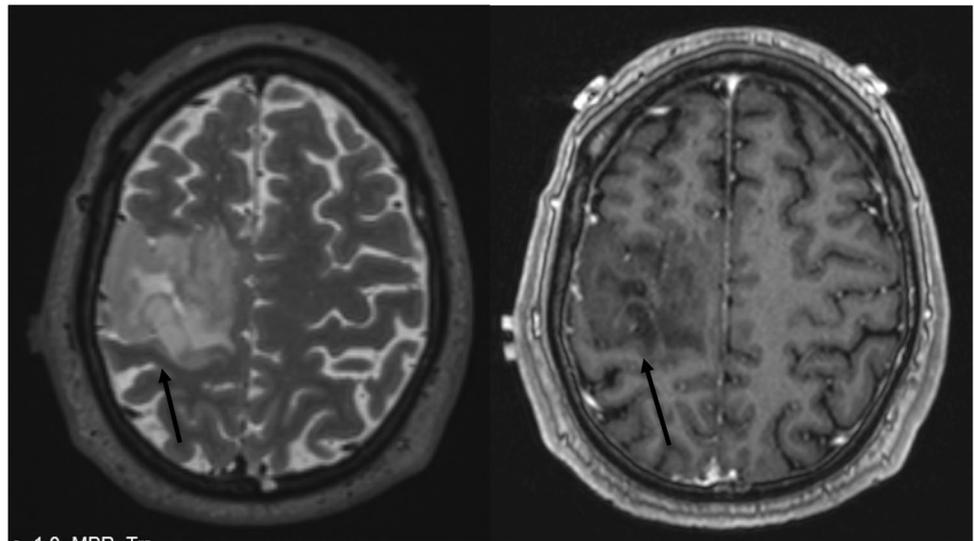


Fig. 4 Pre-operative TMS showing hand and foot area (red dots = positive site of stimulation). *RMT* resting motor threshold

motor cortex was completed, a 4 contact strip electrode was positioned over the motor cortex and motor evoked potentials (MEPs) were recorded continuously.

During tumour resection, positive subcortical responses were obtained at the postero-lateral margin of resection following stimulation at 5 mA, inducing selective activation

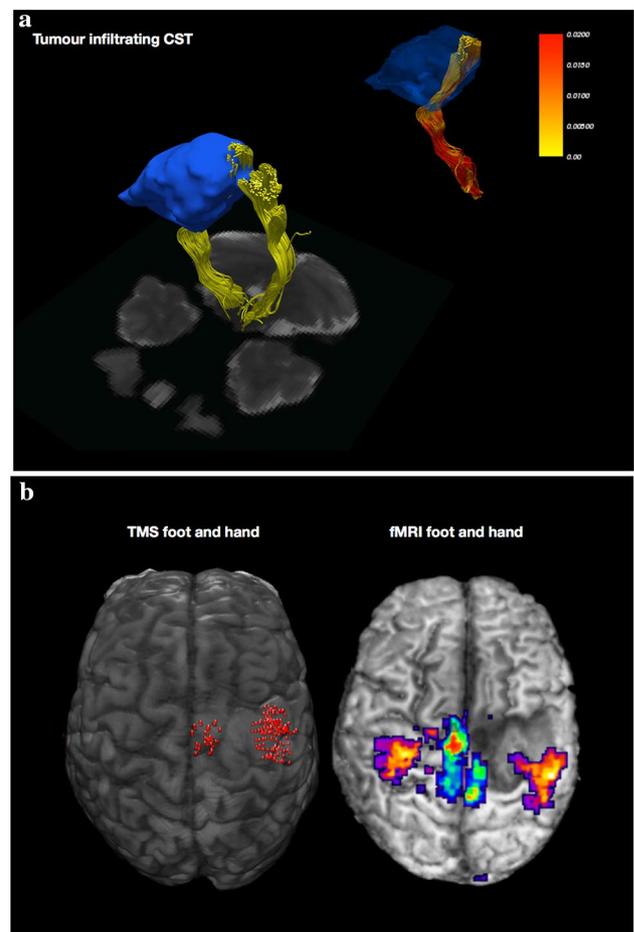


Fig. 5 **a** MRI showing the right central lobule/SMA tumour and its infiltration of the corticospinal tracts corresponding to hand and foot; the subcortical stimulation in the area between them resulted in stimulation of intercostal muscles subcortical and cortical corticospinal tract infiltrating the tumour. **b** TMS and fMRI images for foot and hand on the index patient

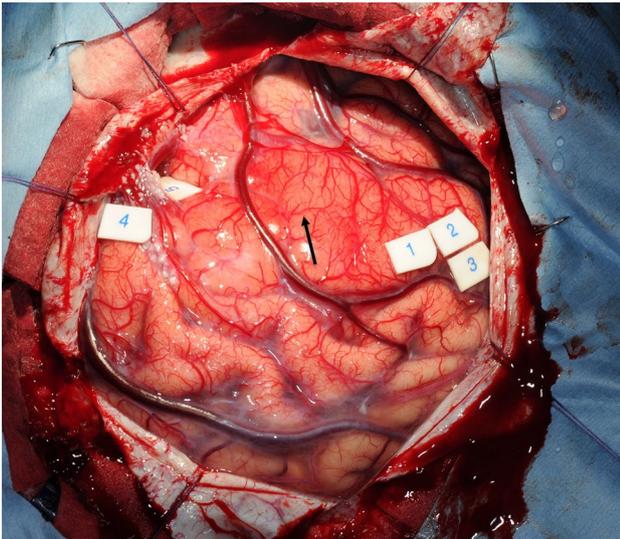


Fig. 6 Intra-operative direct cortical stimulation. Tags 1–3: hand and forearm responses obtained at 10 mA. Tags 4, 5: positive foot and leg responses obtained at 12 mA. Black arrow: expanded pre-central gyrus

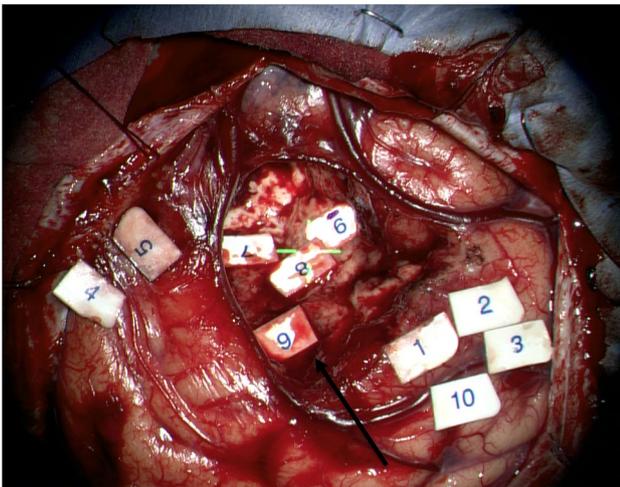


Fig. 7 Cavity at the end of tumour resection. Tags 1–3, 10: hand and forearm responses obtained at 10 mA. Tags 4, 5: positive foot and leg responses obtained at 12 mA. Subcortical mapping—tags 7, 8: foot and leg response; tag 6: torso (black arrow); tag 9: hand and forearm (subcortical responses obtained at 5 mA)

of the left hemi-thorax (Fig. 7). In particular, contraction of the left intercostal muscles was observed. The subcortical area appeared to be located 15 mm deep to the cortex. The stimulation was reproduced to verify the exact location and video imaging was taken (See Supplementary Video Material). Interestingly, while obvious contraction of the left hemi-thorax was observed, no other muscle groups were activated and no MEPs from other muscle groups were

recorded. Electrodes for MEPs recording were not placed in the intercostal muscles.

In the postoperative period, the patient demonstrated partial motor seizures again involving the left side of the body including the left hemithorax and dense hemiparesis. The seizures resolved by increasing the levetiracetam dose from 500 to 750 mg BD and adding clobazam for 10 days. The patient made a full recovery and was discharged home. The postoperative MRI demonstrated a subtotal tumour removal. Histology confirmed the diagnosis of anaplastic oligodendroglioma grade III ATRX preserved, IDH1 negative, 1p/19q co deletion and methylated MGMT. Patient underwent further adjuvant radiotherapy as suggested by the neuro-oncology multidisciplinary team (MDT).

Literature review

Following our observation, we decided to review the literature for documentation of activation of the intercostal muscles through direct electrical subcortical stimulation. The literature search was performed in PubMed using the *MeSH Terms* (((subcortical stimulation) AND intercostal muscle) AND corticospinal tract) AND brain mapping) OR (((subcortical stimulation) AND intercostal muscle) AND corticospinal tract). The expanded search showed no results.

Discussion

Several attempts have been made to identify the region of the motor cortex for the control of trunk muscles involved in respiratory function, including the diaphragm and the intercostal muscles. Foerster, in his 1936 lecture on Huggings Jackson's doctrine (Foerster 1936), showed that the activation of the diaphragm/chest was possible through direct stimulation of the cortex, while inactivation could be possible by excising the cortical area of representation. Penfield and Boldrey (1937) defined the homunculus by means of bipolar stimulation of the motor cortex, recording the motor responses observed in awake patients during surgery. The homunculus included the representation of the trunk, defined as an area including the muscles of the neck, back and thorax down to the pelvis (Penfield and Boldrey 1937). However, reviewing the data presented in the original article, out of 126 patients just a single point in a single patient caused activation of the back muscle, and this point was considered representative of the trunk area (Penfield and Boldrey 1937). It, therefore, appears that Penfield did not identify any cortical point causing activation of the intercostal muscles specifically. Aminoff and Sears (1971) studied the spinal integration of cortical, segmental and breathing inputs to thoracic motor neurons

in 22 anaesthetized, paralyzed cats. They were able to stimulate with a monopolar electrode an area of the primary motor cortex that produced the contraction of the abdominal and thoracic musculature (Aminoff and Sears 1971). Further research into the mechanisms of the central control of breathing was performed by Planche (1972) and Bassal and Bianchi (1981) who, upon stimulation of the motor cortex, were able to demonstrate the activation of the phrenic nerve and of the diaphragm, respectively. Non-invasive percutaneous transcranial electrical stimulation of the motor cortex was performed in human subjects by Gandevia and Plassman (1988). He was able to show in three healthy subjects that stimulation applied near the vertex during inspiration could reproduce a contraction of the diaphragm muscle. Maskill et al. (1991) applied transcranial magnetic stimulation to the motor cortex and produced similar results, showing that activation of the respiratory muscles including diaphragm and intercostal muscles occurred when applying a stimulus 1 cm behind the vertex along the midsagittal line. Both these studies, despite their relevance in describing the activation of the diaphragm and intercostal muscles in humans, were performed without the help of image-guidance, and, therefore, are lacking in anatomical precision.

In terms of activation of the respiratory muscles through subcortical stimulation of fibres of the cortico-spinal tract, our detailed literature review did not yield any results.

Thus given that direct activation of the respiratory muscles with cortical and subcortical stimulation remains elusive, any contribution that could better describe the anatomo-functional arrangement of the central control of breathing is welcome. In the present case report, we describe for the first time the direct activation of intercostal muscles after subcortical stimulation of fibres belonging to the cortico-spinal tract. Some elements are worthy of further consideration.

First, we were not able to describe a cortical region involved in the control of the trunk muscles. This could be due to several factors. The cortical representation of the trunk could be very small, as suggested by Penfield, and a significant overlap with other cortical areas, more extensively represented, could be present (Catani 2017). In addition, we do not routinely position muscle electrodes for continuous MEPs monitoring in the intercostal muscles (Berger et al. 1989; Meyer et al. 2001; Neuloh and Schramm 2002; Sala et al. 2002; Simon et al. 2009; Simon 2011). Without EMG recording, it is possible that we missed subclinical activation of the intercostal muscles, when cortical stimulation was applied at the motor threshold. Alternatively, the motor threshold of the intercostal muscles could be higher compared to the threshold for the hand and foot region, which are normally established for the purpose of clinical mapping.

Second, the location of our subcortical response is consistent with the somatotopy of the previously described homunculus. In our case, the fibres eliciting direct activation of the intercostal muscles appear to be located medially to the cortical area of the lower limb and laterally to the cortical area of the upper limb. The somatotopy is present also at the subcortical level, where the fibres of the trunk are located in between fibres coming from the lower limb (medially) and fibres coming from the upper limb (laterally). Following the fibres of the intercostal muscles along the cortico-spinal tract was difficult, as they merged at the deep margin of resection with the fibres coming from the foot and hand.

Finally, the motor mapping described in this case report was performed according to the “train of 5” technique previously described in the literature (Szelényi et al. 2010; Bello et al. 2014). Stimulation at both cortical and subcortical level was applied with a monopolar probe, with anodal polarity at cortical level and cathodal polarity at subcortical level. Compared to a bipolar probe, a monopolar probe provides a homogeneously radiant spreading electric field, which potentially leads to a larger (i.e. less focal) area of stimulation. However, it is unlikely that the effect observed on the intercostal muscles during subcortical stimulation was due to current spread, since no other muscle activity was recorded from either the upper or lower limb (as would be expected in case of spreading of the current through the fibres of the cortico-spinal tract). In addition, the subcortical stimulation was performed with cathodal polarity at a low threshold (5 mA). Previous studies suggested a linear distance between site of stimulation and cortico-spinal tract of approximately 1 mm for each mA of current intensity, when cathodal subcortical stimulation is applied (Seidel et al. 2013). This means that in our case the distance between cortico-spinal fibres and site of stimulation was extremely low, only about 5 mm.

The findings in this case report have a clinical relevance. Damage to motor fibres controlling the intercostal muscles could lead to paralysis of accessory respiratory muscles as demonstrated in studies of patients with spinal cord injury involving motor injury to respiratory muscles (Zimmer et al. 2007; de Terson et al. 2011). This in turn could increase the risk of postoperative respiratory complications, including pneumonia and/or respiratory failure, with an increase risk of morbidity and even mortality (Silver and Moulton 1969; Zimmer et al. 2007; de Terson et al. 2011). In view of the current finding, further clinical experience and research is required to evaluate the role of routine monitoring of the intercostal muscles during surgery for lesions in eloquent motor areas.

Conclusion

In this case report, surgery with neuro monitoring and brain mapping for removal of a tumour involving the right frontal and central lobe led to the activation of intercostal muscles through direct subcortical stimulation of the corticospinal tract. The somatotopy of the fibres controlling the intercostal muscles is consistent with the previously described arrangement of the motor homunculus.

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Compliance with ethical standards

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