SHORT REPORT

The contribution of lesion location to upper limb deficit after stroke

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ABSTRACT

Background Motor deficit after stroke is related to regional anatomical damage.

Objective To examine the influence of lesion location on upper limb motor deficit in chronic patients with stroke.

Methods Lesion likelihood maps were created from T1-weighted structural MRI in 33 chronic patients with stroke with either purely subcortical lesions (SC, n=19) or lesions extending to any of the cortical motor areas (CM, n=14). We estimated lesion likelihood maps over the whole brain and applied multivoxel pattern analysis to seek the contribution weight of lesion likelihood to upper limb motor deficit. Among 5 brain regions of interest, the brain region with the greatest contribution to motor deficit was determined for each subgroup.

Results The corticospinal tract was most likely to be damaged in both subgroups. However, while damage in the corticospinal tract was the best indicator of motor deficit in the SC patients, motor deficit in the CM patients was best explained by damage in brain areas activated during handgrip.

Conclusions Quantification of structural damage can add to models explaining motor outcome after stroke, but assessment of corticospinal tract damage alone is unlikely to be sufficient when considering patients with stroke with a wide range of lesion topography.

INTRODUCTION

Poor upper limb motor function is a major contributor to reduced quality of life after stroke.1 Understanding the causes of motor deficit will help to identify therapeutic approaches for all.2 A major contributor to upper limb motor deficit is the initial severity of stroke, but a number of other factors appear to be important, not least of which is the infarct location.3 The optimal way of assessing this quantitatively has not been determined and so anatomical damage is not routinely used to predict recovery potential after stroke. Although quantification of corticospinal tract damage is currently popular for explaining variability in motor outcome,4 it has largely been applied in patients with subcortical infarcts. We assessed the contribution of damage to other motor-related brain regions by creating individual lesion likelihood maps in an automated way and using multivoxel pattern analysis to determine the relation between damage within a number of a priori brain regions of interest (ROIs) and upper limb motor deficit. We then specifically asked whether quantification of damage in the corticospinal tract (or rather in a more widespread motor network) was enough to account for the variability in upper limb motor deficit in patients with either subcortical or combined cortical/subcortical damage.

METHODS

Thirty-three patients with stroke with first ever stroke at least 6 months previously (age 57.15 ±9.69 years, 12 females) were included in the study (table 1). We have previously characterised corticospinal tract damage in these patients.5 Patients were a priori divided into two subgroups: those with infarcts involving only subcortical areas (SC patients) and those with combined cortical/subcortical infarcts involving cortical motor areas (CM patients). CM areas were defined as primary motor cortex, premotor cortex and supplementary motor area, according to both approved anatomical and connectivity-based suggestions for parcellation.6–8 Twenty-three age-matched healthy participants (50.70±13.39 years) who reported no history of neurological illness, psychiatric history, vascular disease or hypertension, were employed to derive maps of normal brain structure, which acted as our ROIs. Full written consent was obtained from all participants in accordance with the Declaration of Helsinki. The study was approved by the Joint Ethics Committee of the Institute of Neurology, UCL and National Hospital for Neurology and Neurosurgery, UCL Hospitals National Health Service Foundation Trust, London, UK.

We defined five prespecified ‘normal’ ROIs from healthy participants or the template brain (see online supplementary methods for details):1 cortical sensorimotor areas (SM),1 brain areas activated during simple hand grip in healthy participants (activated sensorimotor (aSM)),4 all grey matter (GM) and5 all white matter (WM). The ROIs defined from healthy participants or the template brain, were used to assess the likelihood of damage to different brain structure thought to be important for motor function.

All patients underwent the following: (1) a structural T1-weighted high-resolution MRI from which an individual voxel-wise lesion likelihood map was generated using the ALI toolbox (see online supplementary methods).9 We were then able to quantify the likelihood of damage within each of the ROIs defined above in each patient. (2) Measurement of upper limb motor deficit using the Action Research Arm Test, Nine-Hole Peg Test, Motricity Index and grip strength. A single representative score was calculated using principal component analysis in order to minimise floor and ceiling effects of individual tests. These data were used to determine the
likelihood that damage in each voxel contributed to upper limb motor deficit, using Bayesian inference for regression termed a ‘relevance vector machine’ (http://www.mlnl.cs.ucl.ac.uk/pronto/). Leave-one-subject-out cross-validation was performed and the contribution weight of each ROI to upper limb motor deficit was calculated for each patient subgroup, where a more negative value indicates that a lesion in that voxel is more likely to be associated with greater upper limb motor deficit.

Last, we calculated the contribution weight of each ROI to upper limb motor deficit as the average of voxel-wise values over the ROI in the weight map (for each patient subgroup). The lesion load was compared between each pair of the five ROIs, using paired samples t tests for each patient subgroup, and between the two patient subgroups, using two samples t tests for each ROI subgroup. Statistical significance was determined at a false discovery rate adjusted p value of 0.05. Note that statistical inferences for the weight maps were not feasible, as a weight map was acquired for each patient subgroup, not for each patient.

RESULTS

There were no significant differences between CM patients and SC patients in terms of age, gender or affected side. There was no difference in motor function between the two groups, apart from slower Nine-Hole Peg Test times for CM patients compared to those for SC patients (52.3±36.1 s vs 24.9±24.2 s respectively, p=0.02). Lesion likelihood maps for the two patient subgroups are shown in figure 1A, B. CM patients had significantly higher lesion loads than SC patients did, for all ROIs (p value=0.0009 for CST, p value=0.0002 for SM, p value=0.0009 for aSM, p value=0.0160 for GM and p value=0.0001 for WM) (figure 1C). Of the five ROIs, CST showed the greatest lesion load in both patient subgroups. In SC patients, the lesion load was greater in CST than in SM (p value=0.0339) and in GM (p value=0.0014). In CM patients, the lesion load was greater in CST than in GM (p value=0.0005). The full list of comparisons is provided in online supplementary tables S1 and S2.

Weight maps for the two patient subgroups are shown in figure 1D, E. The contribution towards upper limb motor deficit was the greatest (more negative value) in CST for SC patients in terms of age, gender or affected side. There was
**DISCUSSION**

In this study, we examined the contribution to upper limb impairment made by damage in a set of brain regions in two groups of chronic patients with stroke with different lesion types. We showed that (1) the CST was the region most likely to be affected by both, subcortical and combined cortical/subcortical infarcts, and (2) CST damage was the most significant contributor to upper limb impairment in patients with subcortical infarcts, but not in those with combined cortical/subcortical infarcts. Although this result may be expected, it is important when considering how to use brain imaging to predict future motor outcomes after stroke.

The brain regions that contributed most to upper limb motor deficit in patients with subcortical or cortical/subcortical damage, respectively, correspond to the individual findings of previous lesion load studies. However, our study involved several different methodological approaches. First, while these studies examined for lesions within only one ROI of either aSM or CST, we measured and compared the contribution towards upper limb motor deficit of damage in five different ROIs. Second, we estimated probable damage as a voxel-wise lesion likelihood map over the whole brain. These weighted values (ie, likelihood of lesion in each voxel) may be more useful than binary values (‘lesion’ or ‘not lesion’ in each voxel) given the increase in data points, but these two approaches have not yet been directly compared and so empirical data are required to determine the relative utility of each in predictive models in future. Third, previous studies have used univariate approaches such as voxel-based morphometry and voxel-based lesion-symptom mapping to assess the voxel-wise contribution of damage to functional deficits. Whereas we applied a multivariate approach—multivoxel pattern analysis—which allowed us to evaluate the relationship between distributed topographic patterns of brain damage and functional deficit rather than simply the contribution of damage in a single voxel. The current finding obtained with the multivariate approach verified the critical brain regions identified in terms of the voxel-wise contribution of damage to upper limb motor deficit with univariate approaches and, moreover, provided further insights into the influence of lesion location by revealing the ROI-wise contribution of damage to upper limb motor deficit.

In this contribution, we suggest that quantification of anatomical damage could be valuable in future attempts to reliably predict post-stroke motor outcome. However, although quantifying corticospinal damage is a useful first step toward predicting motor deficit, it may be insufficient if the aim is to develop a single automated process applicable to all patients, especially those with additional cortical damage. There are potential limitations in our approach. First, we acknowledge that our separation of patients based on infarct location is, on the face of it, arbitrary. However, the key point is that whether this a priori separation was optimal or not, it allowed us to answer a specific experimental question and to demonstrate a difference in the relationship between the location of stroke-related damage and motor deficit in the two patient subgroups. It is notable that dexterity (but not other motor scores) was more impaired in patients with additional cortical infarcts, indicating a possible concomitant aspect of different lesion topography. Second, we have looked for a relationship between motor deficit and lesion characteristics in a cross-sectional study. The characteristics of lesions may have changed over time, so that the use of brain images acquired in the early post-stroke phase to predict late outcome will need to be explicitly tested. Third, healthy participants from whose brains we derived the ROIs were not perfectly age-matched with patients. However, healthy participants were included to construct ROIs, and not to be directly compared to patients in the current study. Nevertheless, the importance of selecting the most relevant regions for assessing clinically

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**Figure 1** Lesion likelihood maps averaged across patients with subcortical lesions (SC patients) (A) and patients with lesions extending to cortical motor areas (CM patients) (B). In each map, the cross indicates the location of the most probable damage: x=28.5 mm, y=0.0 mm, z=4.5 mm in (A) and x=19.5 mm, y=−9.0 mm, z=28.5 mm in (B) in terms of Montreal Neurological Institute (MNI) coordinates. Comparison of lesion loads between brain regions of interest (ROIs) in SC patients and CM patients (C). Weight maps of SC patients (D) and CM patients (E). In each map, the cross indicates the location of the highest negative weight reflecting the greatest contribution of damage to upper limb motor deficit: x=25.5 mm, y=−9.0 mm, z=24.0 mm in (C) and x=43.5 mm, y=−16.5 mm, z=30.0 mm in (D) in terms of MNI coordinates. Comparison of contribution weights between ROIs in SC patients and CM patients (F). CST, SM, aSM, GM, and WM are ROI labels. For details about ROIs, refer to Online supplementary methods. CST, corticospinal tract; GM, grey matter; WM, white matter.
relevant damage is clear. The five ROIs suggested in this study were hypothetically specified because of their potential for influencing motor deficit. However, in future, systematic approaches for selecting the most informative set of brain regions for predicting motor deficit will need to be performed.15

In summary, we have demonstrated that the brain regions that contribute most to upper limb motor deficit are different depending on lesion location and that one approach does not fit all. We suggest that the anatomy of damage should be considered in models for predicting motor outcome after stroke, but our study also illustrates that these models need to include a wider range of specified brain regions in order to be relevant for a broad range of stroke types.

Acknowledgements The authors thank Mohamed L Seghier for kindly providing the ALI toolbox.

Contributors The following persons have contributed to the present manuscript as authors according to the ICMJE guidelines for authorship: C-hP, NK and NSW.

Funding This work has been supported by The Wellcome Trust (number 088414).

Competing interests None declared.

Ethics approval Joint Ethics Committee of the Institute of Neurology, UCL and National Hospital for Neurology and Neurosurgery, UCL Hospitals NHS Foundation Trust, London, UK.

Provenance and peer review Not commissioned; externally peer reviewed.

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*J Neurol Neurosurg Psychiatry* 2016 87: 1283-1286 originally published online July 22, 2016
doi: 10.1136/jnnp-2015-312738

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