Rethinking the standard trans-cortical approaches in the light of superficial white matter anatomy

Francesco Latini¹, Mats Ryttlefors

Department of Neuroscience and Neurosurgery, Uppsala University, Uppsala, Sweden

Abstract

A better comprehension of the superficial white matter organization is important in order to minimize potential and avoidable damage to long or intermediate association fibre bundles during every step of a surgical approach. We recently proposed a technique for cadaver specimen preparation, which seems able to identify a more systematic organization of the superficial white matter terminations. Moreover, the use of the physiological intracranial vascular network for the fixation process allowed us to constantly show main vascular landmarks associated with white matter structures. Hence three examples of standard approaches to eloquent areas are herein reanalyzed starting from the first superficial layer. New insights into the possible surgical trajectories and subsequent quantitative damages of both vessels and white matter fibres can help readapt even the most standard and widely accepted approach through the brain cortex. A more detailed study of these fine anatomical details may become in the near future a fundamental part of the neurosurgical training and the preoperative planning.

Key Words: superficial white matter; transcortical approach; white matter vascular architecture; white matter dissection; eloquent areas

Introduction

As widely demonstrated, the plastic potential of the brain strongly depends on the preserved white matter connectivity sub-serving fundamental functional epicentres (Duffau, 2014b). An extensive anatomical knowledge of the major white matter bundles is mandatory in order to tailor the surgical approach and to optimize the resection of various subcortical lesions. However, although white matter (WM) structures seem to share more common anatomical features across individuals at the deep white matter regions (DWM) (Burgel et al., 1997), only a few studies have analyzed the peripheral and more superficially located white matter (SWM), which fills the space between the deep white matter and the cortex. For example, the SWM is known to contain short cortical association fibres, but their locations, number, and trajectories are not sufficiently defined and for this reason their description has never become a crucial part of the neurosurgical training and preoperative planning.

Only recently, with the advent of several new techniques such as MR diffusion tensor tractography (DTT) (Oishi et al., 2008), polarized light imaging (PLI) (Dammers et al., 2012), optical coherence tomography (Magnain et al., 2014) new insights have been provided regarding the organization of the SWM.

The predominant intra-territorial connections within the superficial white matter are likely to be U-shaped association fibres, although neighbouring cortical regions within a territory may be linked at their border by intra-cortical fibres. Tractographic evidence and previous anatomical dissection studies suggest that territories are connected by multiple parallel long and intermediate association fibre pathways (Catani et al., 2005). The direction of these pathways into the subcortical regions should be always considered in order to optimize the surgical approach minimizing the destruction of several WM fibres. Despite its important role for research and educational applications, diffusion tensor tractography has some important limitations. Unexpected artefacts can arise due to the discrete sampled, noisy and voxel-averaged tensor data. Further, errors can occur when attempts to follow incoherently organized tracts are made. The degree of uncertainty in the estimation of the fibre orientation, which is typical of DTI tractography algorithms, may increase variability across subjects in regions containing crossing fibres in which the fractional anisotropy decreases as the confidence intervals in fibre orientation (i.e., “cone of uncertainty”) especially close the cortical endpoints (Jones et al., 2003). A high level of anatomical knowledge and great care must therefore be exercised in obtaining and interpreting the tractography data. Thus this cannot be considered the best tool for presurgical planning when minimal functional damage to the SWM is warranted (Duffau, 2014a).

Even with some limitations, white matter dissection of previously formalin fixed brains still remains one of the most trustable techniques in order to demonstrate white matter connectivity and to acquire a comprehensive three-dimensional orientation during neurosurgical training (Agrawal et al., 2011). Our group has recently proposed an alternative method to the standard Klingler’s technique for cadaver specimen preparation, which seems to improve the three-dimensional orientation of the superficial and deep white matter fibres (Latini et al., 2015). The intra-carotid perfusion process provides a very homogeneous fixation with many fine anatomical details preserved even at the grey/white matter junction. In a
previous article we demonstrated that the cortical terminations of the major associative bundles could be identified until the pial layer with a very good accuracy. The main goal of this paper is to support a perspective renewed role of the white matter dissection for the acquisition of a three-dimensional orientation within the superficial white matter.

The Superficial WM Architecture and its Neurosurgical Implications

A more systematic organization of the white matter terminations underneath the sulcal or gyral surface can be demonstrated with this technique as shown in Figure 1. While short intra-cortical U fibres interconnect territories that share the same sulcus, the adjacent gyri shares U fibres with a variable length and seem disposed in a constant disposition between the gyrus and the sulcus. In this organization, the gyral surface seems sub-served preferentially by a high number of long association fibres terminations, which present an oblique/vertical direction from the deep territories to the pial surface (Figure 1A, B). As demonstrated by other techniques, a higher density of axonal terminations run underneath the gyral region, while the cortices that share the same sulcus present mostly very short U-fibres at least at the most superficial layer (Nie et al., 2012).

The full comprehension of this superficial white matter organization is important in order to minimize potential and avoidable damage to long or intermediate association fibre bundles during every step of a surgical approach.

In this light, several studies report the impossibility to completely resect areas with lower potential of compensation by plasticity phenomena (Ius et al., 2011; Sarubbo et al., 2015). These areas include for instance the primary motor and somatosensory areas which are mainly uni-modal and probably organized serially, sub-served preferentially by projection fibre bundles (Duffau, 2014b). The balance between extent of resection and functional outcome is still very crucial in this area. In a recent series 75% of patients operated with the use intra-operative monitoring because for pre/post central sulcus lesions had residual tumours (Noell et al., 2015). The rate of postoperative permanent deficits in rolandic area is reported between 4, 8 and 16% (Keles et al., 2004; Carraba et al., 2007; Noell et al., 2015).

The absence of parallel alternative pathway may explain the impossibility to efficiently restore their function after damage. However, it is also well known that patients with WM lesion may improve, even if the recovery is rarely complete. Several mechanisms related to the integrity of the perilesional WM pathways (latent parallel networks, accessory pathways, additional relays, parallel long association pathways) have been hypothesized as supporting some level of functional compensation (Duffau, 2009). Hence according to the new insights into the intracortical WM fibres, standard approaches to such eloquent areas may be carefully reanalysed starting from the first superficial layer in order to minimize avoidable damage to SWM able to support a post-operative functional compensation.

New Insights into the Neurosurgical Training with WM Dissection

One of the limitations of the white matter dissection is that it is hard to merge the three-dimensional orientation acquired in the laboratory with the intraoperative experience because of the obvious differences between the prepared specimens and the living tissues. On the other hand vascular structures can be identified constantly during operations, guiding the strategy and the surgical approach to subcortical lesions. An advantage of our specimens is the use of the physiological intracranial vascular network for the fixation process, which preserves vascular landmarks at each stage of WM dissection. These fine and constant details allow correlation between vessels and white matter structures with the obvious advantage in three-dimensional orientation that can be employed during any standard neurosurgical procedure.

Despite in clinical practice is the nature/location of the lesion that often dictates the surgical strategy; a transcortical approach is always the first step in many neurosurgical procedures.

In these cases, the corticotomy is mostly based on the lesion's features, the vascular architecture of the region and the personal experience of the neurosurgeon.

The possibility to observe with a different and more detailed anatomical view the WM architecture from the first cortical layer encouraged us to reconsider some of the standard trans-cortical approaches with the aim of minimizing the quantitative damage to the superficial white matter.

Three examples of trans-cortical approaches in the post central gyrus are herein demonstrated, showing how the different layers of white matter fibres can be identified since the sub-pial surface is associated with almost constant vascular landmarks.

In all the approaches a balance between the vascular damage and the quantitative damage to the white matter fibres have been considered. The classical subcortical vascular architecture described by Yasargil (1987) was adopted as reference and confirmed during the dissection. A trans-gyral trans-cortical approach was the first to be tested (Figure 3, yellow square, approach n°1). This dissection showed several technical disadvantages. The number of vascular structures encountered from the pial layer underneath the central area of the gyrus was abundant, with vessels located only approximately 2 mm apart. This organization forces the neurosurgeon to an inconvenient trajectory with a prolonged manipulation or retraction of long association fibres underneath the gyral grey/white matter junction. According to the data provided on the density of axonal terminations, even for small subcortical lesions this approach may be considered the least recommended because of the inescapable vascular and WM damage.

The second approach was defined "parasulcal" through (according to Figure 1) the junction between the long/intermediate (Figure 1, black arrows) and short U-fibres (Figure 1, red arrows). According to Nie et al. (2012), a lesser density of white matter terminations was reported, which was confirmed by our dissection. Moreover, a single artery coming from the lateral wall of the sulcus is often encountered at a 90° angle from the sulcus leading to the deep WM underneath the gyral-sulcal transitional zone (Figure 3 orange square, approach number 2). This trans-cortical artery often joins the deep arterial Anastomosis at the level of the deep white matter and for this reason should be preserved (Figure 2B, Figure 3 orange square, approach number 2). Following
this artery within the deep WM, the microsurgical dissection should be adapted to the longitudinal direction of the fibres of superior longitudinal fasciculus (SLF) and arcuate fasciculus (AF) (Figure 2B). The minimal manipulation of vascular structures (basically only a single vessel) and the tangential trajectory in respect to the long and intermediate fibres may lead to a reduced damage to both vascular and WM structures in the grey/WM junction.

The third approach (trans-sulcal) (Figure 3, red square, approach number 3) has already demonstrated a potential to lead to a safe surgery for the limited amount of vascular structures encountered (Yasargil, 1987; Mikuni et al., 2006).

Once the sulcal artery has been dissected in the subarachnoid space no other visible crucial vascular structures are present until the deep arterial and venous anastomosis (Figure 2B) (Latini et al., 2015). According to previous data (Nie et al., 2012) and confirmed by our dissections, the sulcal areas present a lower density of associative fibres. However the commonly accepted cortical incision during trans-sulcal approach is generally in accordance with the sulcal direction. The dissection of the superficial white matter showed on the other hand that the direction of the U-fibres underneath the sulcal area is actually perpendicular to the sulcal direction. In case of eloquent areas like the somatosensory cortices, a more
extended disconnection of the closer intra-cortical territories can lead to significant post-operative deficits. The incision of the sulcal cortex should rather follow the direction of the fibres as showed in Figure 3 (red square, approach 3, red arrow). This longitudinal direction should be maintained within the deep white matter as well. The fibres of superior longitudinal fasciculus (SLF) and the horizontal segment of the AF run in a longitudinal direction (Figure 2B) and so even for a limited trans-sulcal approach this modified subcortical dissection may be suggested in order to minimize the WM damage and the disconnection between functional epicentres.

All the described exemplary approaches have limitations. For instance the vascular manipulation of the parasulcal (approach n°2) or the sulcal artery (approach n°3) as well as the related arterioles can lead to vascular/WM damage. Thus we cannot claim that one approach is safer than the other based on these anatomical results. Moreover the microvasculature of the subcortical grey and grey-white interface with short-to-intermediate-length arterioles and arteries (that form a dual source of blood supply) is much more complex than the one visible during white matter dissection (Moody et al., 1990). Many factors should be taken into consideration in order to possibly predict the functional outcome after standard neurosurgical procedures.

Therefore, the main aim of this study is not to suggest the best transcortical approach for a certain region but to support the role of a more detailed WM comprehension during the neurosurgical training and presurgical planning.

Summary and Conclusion

We believe that besides the superficial vascular architecture and the widely described major associative WM bundles, a more comprehensive knowledge of the superficial white matter should be mandatory nowadays in order to tailor cortical and subcortical resection with the least invasive possible surgical trajectories even at the most superficial layers. Our dissection technique showed how the main vascular landmarks could be constantly associated with each respective layer of white matter structures. A more widely use of this presurgical training can give to every neurosurgeon a more comprehensive orientation of the peripheral and more superficially located white matter (SWM), which fills the space between the deep white matter and the cortex. These important insights into the possible surgical trajectories and subsequent quantitative damages of both vessels and white matter fibres (associative, projection, intermediate or short fibres) can help readapt even the most standard and widely accepted approach trough the brain cortex.

A more detailed study of these fine anatomical details (with also new DTI techniques, study of the microvascular architecture, study of micronetworks etc.) may become in the near future a fundamental part the neurosurgical training and the preoperative planning. The ideal goal would be to direct new attention to the architecture of this poorly understood region, minimizing avoidable damage to SWM and improving the functional outcome in the daily neurosurgical practice.

Author contributions: FL designed the research, wrote the paper and acquired the data. FL and MR analyzed and interpreted the data, critically reviewed the paper and approved the final version of the article.

Conflicts of interest: None declared.

References

Agrawal A, Kaphammer JP, Kress A, Wichers H, Deep A, Feindel W, Sontag VK, Speitzer RF, Preul MC (2011) Josef Klüngger's models of white matter tracts: influences on neuroanatomy, neurosurgery, and neuroimaging. Neurosurgery 69:238-252.

Burgel U, Mecklenburg I, Blohm U, Zilles K (1997) Histological visualization of long fiber tracts in the white matter of adult human brains. J Hirnforsch 38:397-404.

Carrabba G, Fava E, Giussani C, Acerbi F, Portaluri F, Songa V, Stocchetti N, Branca V, Gaini SM, Bello L (2007) Cortical and subcortical motor mapping in Rolandic and perirolandic glioma surgery: impact on postoperative morbidity and extent of resection. J Neurosurg Sci 51:45-51.

Catani M, fytche DH (2005) The rises and falls of disconnection syndromes. Brain 128:2224-2239.

Dammers J, Breuer L, Aker M, Kleiner M, Elben B, Grässel D, Dickisch T, Zilles K, Amunts K, Shah NJ, Pietrzyk U (2012) Automatic identification of grey and white matter components in polarized light imaging. Neuroimage 59:1338-1347.

Duffau H (2009) Does post-lesional subcortical plasticity exist in the human brain? Neurosci Res 65:131-135.

Duffau H (2014a) Diffusion tensor imaging is a research and educational tool, but not yet a clinical tool. World Neurosurg 82:e43-45.

Duffau H (2014b) The huge plastic potential of adult brain and the role of connectomics: New insights provided by serial map pings in glioma surgery. Cortex 58:325-337.

Ius T, Angelini E, Thiebaut de Schotten M, Mandonn et E, Duffau H (2001) Evidence for potentials and limitations of brain plasticity using an atlas of functional resectability of WHO grade II gliomas: towards a “minimal common brain”. Neuroimage 56:992-1000.

Jones DK (2003) Determining and visualizing uncertainty in estimates of fibre orientation from diffusion tensor MRI. Magn Reson Med 49:7-12.

Keles GE, Lundin DA, Lamborn KR, Chang EF, Ojemann G, Berger MS (2004) Intraoperative subcortical stimulation mapping for hemispherical peritumoral gliomas located within or adjacent to the descending motor pathways: evaluation of morbidity and assessment of functional outcome in 294 patients. J Neurosurg 100:369-375.

Latini F, Hjortberg M, Aldskogius H, Ryttele rs M (2015) The use of a cerebral perfusion and immersion-fixation process for subsequent white matter dissection. J Neurosci Methods 235:161-169.

Magannin C, Augustinack JC, Reuter M, Wachinger C, Frosch MP, Ragan T, Akkin T, Wened VJ, Boas DA, Fischl B (2014) Blockface histology with optical coherence tomography: a comparison with Nissl staining. Neuroimage 84:524-533.

Mikuni N, Hashimoto N (2006) A minimally invasive transsulcal approach to the paracentral inner lesion. Minim Invasive Neurosurg 49:291-295.

Moody DM, Bell MA, Chall a VR (1990) Features of the cerebral vascular pattern that predict vulnerability to perfusion or oxygenation deficiency: an anatomic study. AJNR Am J Neuroradiol 11:431-439.

Nie J, Guo L, Li K, Wang Y, Chen G, Li L, Chen H, Deng F, Jiang X, Zhang T, Huang L, Faraco G, Zhang D, Guo C, Yap PT, Hu X, Li G, Yuan Y, Zhu D, et al. (2012) Axonal fiber terminations concentrate on gyri. Cereb Cortex 22:2831-2839.

Noelle S, Feigl GC, Naros G, Barking S, Tatagiba M, Ritz R (2015) Experiences in surgery of primary malignant brain tumours in the primate sensori-motor cortex clinical practical recommendations and results of a single institution. Clin Neurosurg 136:41-50.

Oishi K, Zilles K, Amunts K, Faria A, Jiang H, Akhter K, Hua K, Woods R, Toga AW, Pike GR, Rosa-Neto P, Evans A, Zhang J, Huang H, Mill er MI, van Zijl PC, Mazzotti J, Mori S (2008) Human brain white matter atlas: identification and assignment of common anatomical structures in superficial white matter. Neuroimage 43:447-457.

Sarubbo S, De Benedictis A, Merler S, Mandonn et E, Balbi S, Granieri E, Duffau H (2015) Towards a functional atlas of human white matter. Human Brain Mapp 36:3117-3136.

Yasarlig MG (1987) Microneurosurgery vol IIIA: AVM of the brain, history, embryology, pathological considerations, hemodynamics, diagnost ic studies, microsurgical anatomy. New York: Thieme Medical Publishers Inc.