Toward 3D reliable finite element model (FEM) of the spinal cord (SC): Identification of SC morphometric standards based on MR acquisitions

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Introduction: Most of the recent finite element models (FEM) of the human spinal cord (SC) are based on *postmortem* specimens' geometry [1-3], measured on a few vertebral segments.
The present study was undertaken to determine if *post mortem* measurements are likely to significantly represent *in vivo* geometric characteristics of the spinal cord. Based on MR imaging, which allows visualizing *in vivo* geometry of gray and white matter at different spinal levels, the possibility of establishing morphologic standards and identifying recurrent features among individuals was investigated.

Material and methods: Experiments were performed on healthy volunteers (age groups: 29±6 (G1, n=5) and 64±6 (G2, n=4)), on a 3T MR system (Verio, Siemens, Erlangen). Images were acquired perpendicular to the spinal cord axis, at different levels (***Fig.1***), using a multi-echo gradient-echo sequence (MGE) (5 echoes, TR/TE 500/27 ms, in-plane resolution 0.5x0.5 mm², slice thickness 5mm, 3 NEX, ECG synchronization).
Measurements of transverse (T∅) and antero-posterior (AP∅) SC diameters, anterior (AW) and posterior (PW) horn widths and surface percentage of white (WM) and gray (GM) matters (compared to the SC cross-section), were performed for each slice (***Fig.2***) using the SliceOmatic (Tomovision) software. Compressive ratio (AP∅/T∅), antero-posterior ratio (AP∅(segment i) /AP∅(segment C3)), transverse ratio (T∅(segment i) /T∅(segment C3)) and normalized SC surface (S(segment i)/S(C3)) were then calculated. Variability of measurements among the groups was determined for each spinal segment and then averaged (overall variability). Finally, *in vivo* MR measurements were compared to data reported by Kameyama *et al*. [4] from cadaveric specimens, using a Bland-Altman analysis.

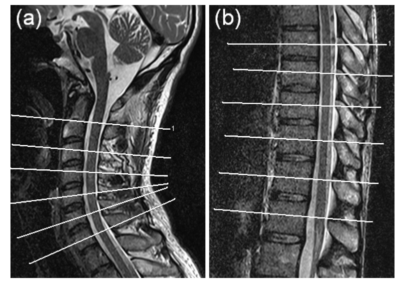

Fig.1 – MGE slice locations (C2 to C7 and T8 to L1 vertebrae).

Results: The main observations resulting from the measurement analyses were: (i) intra-subject morphologic features differ depending on the spinal cord level (e.g. **Fig.3a,b,c**), (ii) inter-subject variations in absolute cord size (T∅, AW, PW) are large (table 1, variability), (iii) *in vivo* MR values are larger than those observed *postmortem* (e.g. **Fig.3a,b**), especially AP diameter, T diameter, compressive ratio and width of the posterior horns (table1, bias), however (iv) normalized surface S(i)/S(C3), AP ratio, T ratio and % of white matter have low variability and are very similar to postmortem values (bias<0.1%, table 1, bold values). These four parameters could thus be considered as good morphometric standards.

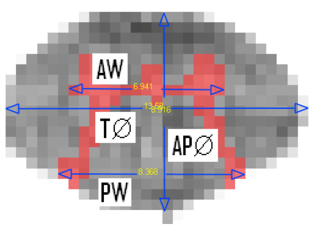

Fig.2 – Description of the main metrics on MGE images.

Table 1	**Overall mean variability (%)**			**Bland-Altman**
	G1 (n=5)	**G2 (n=4)**	**All (n=9)**	**Bias±SD**
T∅	7.9	8.1	8.0	-1.71±1.07 mm
AP∅	4.8	10.7	6.7	-1.89±0.75 mm
AW	17.8	16.8	17.5	-1.55±1.58 mm
PW	9.3	4.6	7.7	-1.99±0.66 mm
WM surface percentage	**3.6**	**2.9**	**3.4**	**0.05±0.04 %**
Compressive ratio	6.3	15.9	9.5	-8.1±8.1 %
S(i)/S(C3)	7.7	8.4	7.4	**0.08±0.09 %**
AP ratio	**4.6**	**6.5**	**5.3**	**0.04±0.05 %**
T ratio	**5.1**	**2.1**	**4.1**	**0.05±0.07 %**

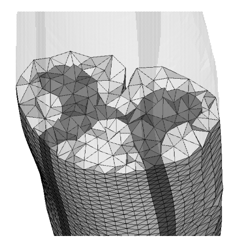

Fig.4 – Lumbar level of spinal cord finite element model

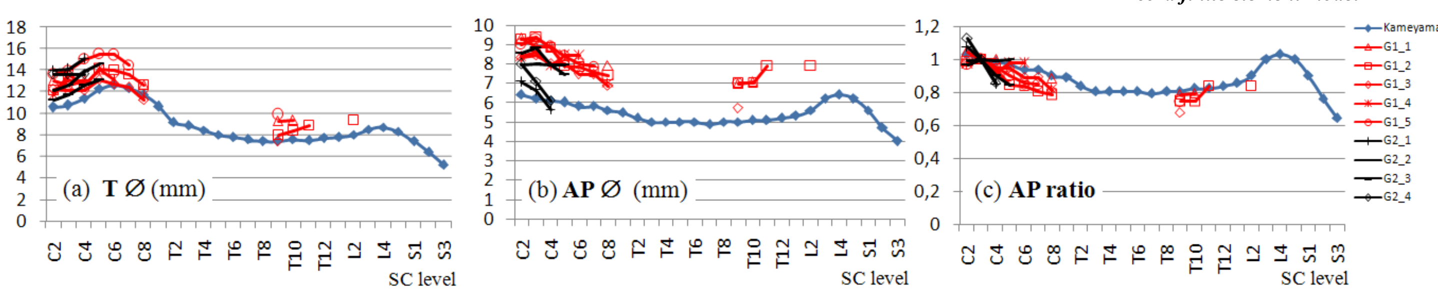

Fig. 3 – Measurements of (a) transverse diameter (mm), (b) anteroposterior diameter (mm) and (c) anteroposterior ratio, on group 1 (G1, red) and group 2 (G2, black) and comparison with post-mortem measurements (Kameyama, blue).

Conclusion: Previous studies have reported important variability among the measurements performed on cadavers [6] and in human [7]. In this study, SC morphometric standards, which can be used to build a reliable 3D FEM of the spinal cord, have been successfully identified. Further investigations and refinements are needed (age influence, relation between DTI measurements and biomechanical properties, etc.). However, this work already opens new perspectives to: (i) study stress distribution patterns and injury mechanisms involved in compressive pathologies and trauma at different levels of the spinal cord, (ii) extrapolate from any MR image of a normal segment what should normally be expected at the level of an individual lesion, and (iii) create patient specific refined virtual models of the central nervous system (e.g. **Fig.4**).

References:[1] Greaves et al., Annals of Biomedical engineering (2008), [2] Kato et al., J Neurosurg Spine (2008), [3] Li et al., Spine (2009), [4] Kameyama et al. Spine (1996), [5] Development of the human spinal cord, ed. Oxford (2001), [6] Kameyama et al., Rinsho Shinkeigaku (1992), [7] Sherman et al., AJNR (1990).