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Anatomical and histological analysis of a complex structure too long considered as a simple ligament: the *Filum Terminale*

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1 **Anatomical and histological analysis of a complex structure too long considered as a**
2 **simple ligament: the *Filum Terminale***

3
4 **Abstract**

5
6 **Background:** The intradural *Filum Terminale* (iFT) connects the *Conus Medullaris* (CM)
7 with the Dural Sac (DS) and the extradural *Filum Terminale* (eFT) connects the DS to the
8 coccyx. The aim is herein to update the description of the FT and to integrate these data in a
9 physiopathological context.

10 **Methods:** Anatomical measurements and histological investigation were performed on ten
11 human cadavers.

12 **Results:** The mean lengths of the iFT and eFT were 167.13 and 87.59 millimeters,
13 respectively. The mean cranial diameter of the iFT was 1.84 millimeter. It exceeded 2
14 millimeters in two specimens. The mean half and caudal diameters of the iFT were 0.71 and
15 0.74 millimeter, respectively. The cranial diameter of the eFT was correlated with the caudal
16 diameter of the eFT ($\rho=0.94$, $p=.02$). The level of CM-iFT junction was significantly
17 correlated with the iFT length ($\rho=-0.67$, $p=.03$). The mobilization of the iFT was not
18 transmitted to the extra-dural elements and *vice-versa*. The iFT contained axons and
19 ependymal cells which were dense in the first third and then caudally randomly arranged in
20 islets. This could explain why ependymomas can occur all along the iFT. Ganglion cells were
21 abundant around the junction with the DS. The eFT contained smooth muscle cells,
22 adipocytes and axons. A mechanoreceptor was identified in one specimen.

23 **Conclusions:** Consistently with their common embryological origin, there is a real anatomical
24 and histological continuum between the CM and the FT. The FT should therefore no longer
25 be considered as a simple ligament but rather as a complex fibro-cellular structure.

26
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29
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35 INTRODUCTION

36

37 The development of the *Filum Terminale (FT)* results from the dedifferentiation of
38 the caudal part of the embryonic and fetal Spinal Cord (SC).¹⁻⁴ After birth, the FT connects
39 the *Conus Medullaris (CM)* and the coccygeal periosteum.⁵ More precisely, the intradural FT
40 (iFT) is the cranial portion of the FT that lies between the CM and the DS, while the
41 extradural FT (eFT = *Ligamentum Coccygeale*), constitutes the caudal portion of the FT, thus
42 linking the Dural Sac (DS) and the coccyx.^{2,6-8} The anatomical studies dedicated to the FT are
43 relatively scarce and most are not recent.^{6,8-15} Histologically, the adult FT has long been
44 considered as a fibrous structure and the identification of cellular elements in its vicinity is
45 recent.^{2,7} Obviously, malformations or tumors of the FT are likely to generate neurological
46 disorders because of its close relationship with the SC and the *Cauda Equina (CE)*.⁵ The aim
47 of the present study was therefore to update the anatomical and histological description of the
48 FT, and to integrate these data in a physiopathological context.

49

50 MATERIAL AND METHODS

51

52 Ten human cadavers from adults who donated their bodies to science for anatomical
53 purposes were included. For each specimen, demographic characteristics and morphometric
54 parameters were collected. As summarized in Table 1, 50% of specimens were women and
55 50% were men. With the exception of degenerative scoliosis in one specimen, no obvious
56 neural or orthopedic abnormality was noted.

57

58 Dissection protocol

59

60 After prone positioning, a midline dorsal longitudinal skin and aponeurotic incision
61 was performed from the ninth thoracic vertebra to the coccyx. After dissection of the
62 subcutaneous and muscular plans, spinous processes and laminae from the tenth thoracic
63 vertebra to the fifth sacral vertebra and the coccyx were exposed. A laminectomy was
64 performed from the tenth thoracic vertebra cranially to the sacral hiatus caudally in order to
65 expose the DS, the emerging nervous roots, and the eFT. After careful longitudinal opening of
66 the DS from the tenth thoracic vertebra to its termination, the CM, the CM-iFT junction, the
67 iFT and the CE were exposed. By convention, the end of the CM was defined as the level of
68 emergence of the last coccygeal roots^{5,7}.

69

70 **Anatomical study**

71

72 The shape of the FT, its relationships with the arachnoid and the CE were thoroughly
73 examined. Then, the FT was carefully removed “en bloc” with a collar of dura-matter to
74 preserve the FT-DS junction. Caudally, a fragment of coccygeal periosteum was detached to
75 guarantee the integrity of the eFT. The levels of the CM-iFT junction, FT-DS junction, and
76 the insertion of the FT on the coccygeal periosteum were noted thanks to benchmarks
77 precisely set before the removal of the FT. As previously proposed^{2,6,8,11,14,15}, each vertebra
78 was divided into thirds to increase the precision of the description. The lengths of the iFT and
79 eFT, the diameters of the iFT at different points (origin, first quarter, half, third quarter, and
80 termination), and the diameters of the eFT (origin, half, and termination) were determined
81 with a digital Vernier caliper.

82

83 **Histological study**

84

85 The specimens were fixed in zinc formalin. After paraffin embedding, longitudinal
86 4µm-thick sections were made. Sections were stained with hemalum-phloxine-saffron to
87 highlight cellular and fibrous elements. Complementary staining using luxol-fast-blue,
88 neurofilament, NeuN, and actin were performed to highlight myelinated structures, neural
89 structures, Ganglion Cells (GC) and Smooth Muscular Cells (SMC), respectively.

90

91 **Statistical analysis**

92

93 A statistical analysis was performed using R software (R foundation for Statistical
94 Computing, Vienna, Austria, version3.5.1) to investigate correlations using the Pearson
95 correlation coefficient and the Spearman correlation coefficient for quantitative and ordinal
96 variables, respectively. The level of significance was set at 5% ($p < .05$).

97

98

99

100 **RESULTS**

101

102 **Microsurgical anatomy**

103

104 The iFT was easily differentiated from the CE roots (CEr) thanks to its characteristic
105 pearly white color. Conversely, the eFT did not always have the same hue and could also
106 appear greyish or translucent.

107

108 **1. iFT**

109

110 As the very proximal portion of the iFT was anterior to the lumbar and sacro-
111 coccygeal roots, the CM-iFT transition was not directly seen after opening the dura mater
112 (Figure 1A). The exposure of the CM-iFT transition revealed the progressive appearance of
113 fibrous tissue organized in linear spans within the CM. In parallel, the nervous tissue became
114 less abundant and disappeared completely about 1 millimeter below the emergence of the last
115 coccygeal roots. At this level, the fibrous spans converged towards a common origin which
116 should be considered as the starting point of the FT (Figure 1B).

117 The iFT had a close relationship with the CEr and its relative position compared to the
118 roots changed gradually during its intradural course. Its central and distal parts were clearly
119 posterior to the roots. Adhesion of nervous rootlets to the iFT were observed. They were
120 located in the proximal portion of the iFT in three cases (30%) and in the most distal portion
121 of the iFT in five cases (50%). In two cases (20%), a rootlet was intertwined with the FTi.

122 Only the posterior surface of the iFT was in contact with the arachnoid membrane. The
123 contact was direct in three cases (30%) while a film of cerebrospinal fluid was interposed
124 between these two structures in the remaining cases (70%). The iFT was in the same sub-
125 arachnoidal compartment as the CEr except in one specimen in which there was a longitudinal
126 septum isolating the iFT and some CEr from the remaining roots. The iFT was either
127 hourglass shaped (70%) or cone-shaped (30%).

128

129 **2. FT-DS junction**

130

131

132 There was a *continuum* between the FT and the DS (Figure 1C). This fusion area was
133 most frequently centered on the median line (80%) and sometimes lateralized on the right
134 (10%) or left (10%)

135

136 **3. eFT**

137

138 The eFT lay against the posterior vertebral wall, anteriorly to the CE, in an adipose
139 environment until it came out of the sacral channel through the sacral hiatus. Its path
140 continued either in contact with the coccygeal periosteum or with the posterior sacro-
141 coccygeal ligament. The eFT was free of any attachment, except in its last centimeter where
142 osteo-periosteal attachments were inconstantly found.

143 The periosteal insertion of the eFT was located on the posterior surface of the coccyx
144 and was polymorphic. In its most common form, it was Y-shaped and located on the midline
145 (50%) or lateralized on the right (10%). In the remaining cases, there were either a single
146 bundle inserted in a punctual zone (20%, Figure 1D) or several bundles (at least three) that
147 were fan-shaped (20%, Figure 1E). The shape of the eFT was more constant since 9 eFTs
148 (90%) were cone-shaped and one (10%) hourglass-shaped.

149

150 **4. Vascular elements**

151

152 Proximally, the arterial vasculature of the FT was provided by a small artery that was
153 connected to the anterior spinal artery. A bifurcation was sometimes noticed at the proximal
154 part of the iFT but, in this case, one of the two branches was dominant. Distally, the artery of
155 the iFT was connected with several vessels distributed in the iFT.

156 A vein of variable caliber, often thin (80%) but appearing dilated in two specimens
157 (20%), was found posteriorly to the iFT artery. Insofar as this vein had no collateral branches,
158 it seemed improbable that it could provide the venous drainage of the iFT.

159

160 **Morphometric parameters**

161

162 As summarized in Table 2, the mean lengths of the iFT and eFT were 167.13
163 millimeters and 87.59 millimeters, respectively. The mean diameter of the iFT ranged from
164 1.84 millimeter at its origin to 0.74 millimeter at its termination with an intermediate
165 shrinkage. In 2 specimens, the initial diameter of the iFT exceeded 2 millimeters and in one of
166 them, the CM was in a low position (L2L3 disc). The mean diameter of the eFT decreased
167 progressively from 1.05 millimeter to 0.59 millimeter, consistently with the predominant
168 cone-shape.

169

170 The distribution of the CM-iFT junction was Gaussian, centered on the L1L2 in
female specimens and more variable in male specimens. The levels of the iFT-DS-eFT and

171 eFT-coccyx junctions were more constant and centered on the lower third of S2 (60% of
172 cases) and the second coccygeal vertebra (80% of cases), respectively (Figure 2).

173

174 There was no significant correlation between the height of the specimen and the iFT
175 length ($\rho=0.43$, $p=0.21$) or the eFT length ($\rho=0.37$, $p=0.29$). The iFT and eFT lengths were
176 also not correlated ($\rho=0.34$, $p=0.32$). The comparison of the different diameters of iFT and
177 eFT with each other in all possible combinations found only one statistically significant
178 correlation: the proximal diameter of the eFT was correlated with the distal diameter of the
179 eFT ($\rho=.94$, $p=0.02$).

180 The level of CM-iFT junction was significantly correlated with the iFT length ($\rho=-$
181 0.67 , $p=0.03$) but neither with the specimen height ($\rho=-0.12$, $p=0.73$) nor the length of the
182 eFT ($\rho=0.23$, $p=0.51$). The level of iFT-DS-eFT junction was neither correlated with the
183 specimen height ($\rho=-0.22$, $p=0.52$), the length of the iFT ($\rho=-0.22$, $p=0.53$), the length of the
184 eFT ($\rho=-0.56$, $p=0.09$), nor the level of CM-iFT junction ($\rho=-0.06$, $p=0.85$).

185

186 **Mobilization of the FT**

187

188 Although cranial and caudal tractions of the iFT resulted in concomitant mobilization
189 of the CM and DS, respectively, the movements were neither transmitted to the eFT nor to the
190 CEr. Reciprocally, cranial and caudal tractions of the eFT were transmitted to all the CEr in
191 their extradural portion. Whereas very few movements were transmitted to the DS, the iFT
192 and the CM remained static.

193

194 **Histological structure**

195

196 As macroscopically observed, the CM-iFT transition is progressive since there is a
197 gradual depletion of glial and neuronal cell elements with a strong enrichment in connective
198 tissue. Peripherally, the pia mater was thickened. At this level, included axons, myelinated or
199 not, were found in all specimens (Figure 3A). The iFT-CM junction was also enriched in
200 ependymal cells organized in tubes or rosettes (Figure 3B). The persistence of ependymal
201 cells, randomly arranged in islets, beyond the first third of the iFT, was noted in five
202 specimens (50%). NeuN-immunopositive GC were randomly distributed within the CM-iFT
203 junction (Figure 3C and insert) and in the first half of the iFT (Figure 3D) in five specimens
204 (50%). In nine specimens (90%), amyloid bodies were present within the cellular areas of the

205 proximal part of the iFT (Figure 3E). Nervous elements were abundant at the close periphery
206 of the iFT (Figure 3F) and were sometimes myelinated, as highlighted by luxol-fast-blue
207 staining (Figure 3G), but also within the iFT (Figure 3H, 3I).

208 In five specimens (50%), the iFT-DS junction was particularly enriched in GC which
209 were anarchically disposed (Figure 3J).

210 In the eFT of one specimen, a structure composed of a circular cluster of neuronal
211 cells organized in sheets was found (Figure 3K) and probably corresponded to a
212 mechanoreceptor. The proximal eFT contained included axons (Figure 3L) and calcospherites
213 within connective tissue areas (Figure 3M). SMC were constantly present in the whole eFT
214 (Figure 3L and 3N) as highlighted by the immunostaining for actin (Figure 3N insert).
215 Adipocytes were found around the eFT and within the most distal portion of the eFT (Figure
216 3O), as was fibrous tissue (Figure 3P).

217

218

219 **DISCUSSION**

220

221 **Anatomical considerations**

222

223 The definition of the iFT origin remains elusive.^{5,7} *In fine*, the CM-iFT junction is not
224 punctual but instead corresponds to a transition zone where the nervous tissue of the CM is
225 progressively replaced by fibrous tissue spans converging at a point that seems to relevantly
226 and objectively define the origin of the iFT.

227

228 The iFT-DS-eFT junction has been very rarely studied.² It has either been described as
229 a "perforation" of the DS by the iFT¹⁶ or as a "fusion", given the *continuum* between the FT
230 fibrous stroma and the dura-mater.^{2,6,7} The description herein is in accordance with this
231 second term and remains consistent with the embryological data. Indeed, the FT originates
232 from the dedifferentiated distal portion of the embryonic SC which fuses with the dura-mater
233 that previously covered it.^{1,7} In series reported herein, the iFT-DS-eFT junction was located
234 outside the sagittal medial line in 20% of cases while it was so in 11% of cases in the study
235 reported by Hansasuta *et al.*⁶ This anatomical data must be kept in mind when looking for the
236 iFT in its distal portion through a restricted surgical approach.

237

238 The termination of the eFT has been considered as a blend of the eFT fibers and the
239 coccygeal periosteum.⁷ The polymorphism of this termination with one or several bundles
240 described in the present study is original.

241

242 **Analysis of morphological and biomechanical parameters**

243

244 The mean lengths of the iFT and eFT herein are approximately 10 mm longer than the
245 values previously published^{2,7,9,10,12,17} (Table 3) probably because the specimens were not
246 fixed with formaldehyde that is responsible for retraction and restriction of the measured
247 lengths.¹⁸ We confirmed the absence of correlation between the specimen height and the iFT
248 length.^{2,12,17} Conversely, the correlation between the specimen height and the eFT length
249 previously described by De Vloo *et al.*², Pinto *et al.*¹² and Nasr *et al.*¹⁷ was not found. The
250 diameters of the iFT and the eFT are comparable to those obtained in other studies^{2,9,12,17}
251 (Table 3). However, the correlation between the 4 most caudal diameters of the iFT and
252 between the 3 diameters of the eFT, identified by De Vloo *et al.*² were not validated in this
253 series.

254

255 The median level of the CM-iFT junction is concordant with those of other
256 cadaveric^{2,6,8,11-15} and remnologic series¹⁹ (Table 4). While this junction is usually lower in
257 men than in women^{15,19}, we observed the converse (L1L2 disc in women, T12L1 disc in men).
258 The median level of the iFT-DS junction corresponded to the lower third of S2, which is one-
259 third vertebra lower than in the other studies^{2,6,12,13,19} (Table 4) and did not vary according to
260 the sex, contrary to what has been observed by Mac Donald *et al.*¹⁹ These conflicting data
261 could suggest that the level of the CM-iFT and iFT-DS-eFT junctions are gender independent.
262 The eFT ended at the second coccygeal vertebra in 80% of cases, which confirms that its
263 termination level is more stable than the levels of the CM-iFT and iFT-DS-eFT junctions.²

264

265 The level of the CM-iFT junction was correlated with the length of the iFT, which is
266 consistent with the relatively low variability of the iFT-DS junction level. This correlation had
267 already been demonstrated by Pinto *et al.*¹² but is not consensual.² Besides, we do not confirm
268 the significant correlation between the level of the iFT-DS junction and the length of the
269 eFT², nor the correlation between the levels of the CM-iFT and the iFT-DS-eFT junctions.¹²

270

271 These discordant results could be related to statistical power and a larger sample may
272 be required to conclude. Ethnical differences may also have contributed as not all previously
273 published data were obtained in European specimens. Nevertheless, no correlation has been
274 constantly found in the other studies. Subsequently, the clinical application of these results
275 requires caution because of several biases including measurements after removal, in old
276 specimens and overestimation of nervous structures in cadavers.²⁰

277

278 The tractions performed during the dissections highlighted the damping role played by
279 the FT, since its mobilization in one of its compartments (iFT or eFT) was not transmitted to
280 the elements of the other compartment. Accordingly, Tubbs *et al.* noticed that the traction of
281 the eFT induced no movement of the iFT⁷. The application of increasing loads demonstrated
282 that the FT loses its elasticity more rapidly than the SC in animals and in humans, which
283 confirms that the FT protects the SC against mechanical stress.^{2,5,21,22} The identification of a
284 multicellular structure, that may correspond to a mechanoreceptor, close to SMC in one
285 specimen, could suggest that the eFT is able to self-regulate its tension. For some authors, the
286 loss of FT elastic properties is linked to histological changes²³⁻²⁶, results in a lowering of the
287 CM-iFT junction (below L2 body^{2,5}), and could lead to myelopathy development described as
288 tethered cord syndrome.^{5,9,12,27,28}

289

290

291

292 **From embryology to histology and histopathology**

293

294 During secondary neurulation, the FT originates from the SC located downstream of
295 the 31st metameric segment.¹ Vacuolization and apoptotic phenomena^{2,23,29} are responsible for
296 the dedifferentiation of this structure that is redifferentiated into fibrous tissue.^{1,4,5}
297 Microscopic examination of human fetal SC reveals GC, ependymal and neuroblastic or
298 neuronal cell bodies that are or not subjected to degenerative processes.^{1,24,30} Subsequently,
299 the adult FT is likely to contain the same tissue elements as the SC.^{4,10} Furthermore, the recent
300 identification of neuronal and glial stem cells in rat and human FT³¹ confirms that this
301 structure is far more complex than a simple ligament.

302

303 The performance of longitudinal sections is original. Neuronal bodies, axons that were
304 sometimes myelinated and ependymocytes were identified within the iFT, as previously
305 described^{3,7,30,32} This could explain the development of ependymomas within the iFT⁷.

306 Nevertheless, the decreasing frequency of these elements following a cranio-caudal gradient
307 usually described^{3,7,32}, needs to be nuanced; even though the cell density is higher
308 proximally, islands of ependymocytes are identifiable all along the iFT and are rather
309 randomly distributed.

310

311 Consistent with the only description of the iFT-DS junction², we also observed that the
312 outer fibrous layer of the DS blends almost imperceptibly into the fibrous stroma of the FT.
313 Strikingly, we noted that the density of GC was particularly high at this level, that would
314 explain the occurrence of gangliocytomas, paragangliomas^{33,34} and ganglioneuroblastomas.³⁵

315

316 Examination of the eFT found axonal structures, SMC, and adipose tissue. The
317 absence of ependymal cells, as previously described⁷, indicates that coccygeal ependymomas
318 would more probably arise from subcutaneous coccygeal ependymal residues rather than from
319 the eFT.⁷ Contrary to Tubbs *et al.*, we did not find residues of meningotheial tissue or GC
320 within the eFT.⁷ The presence of adipose and meningotheial tissue within FT is sometimes
321 considered as pathological.^{24,36} This remark should consequently only apply to the iFT.

322

323 CONCLUSIONS

324

325 In accordance with their common embryological origin, there is a true anatomical and
326 histological *continuum* between the CM and the FT. The biomechanical role played by the FT
327 is particularly important and the identification of a mechanoreceptor, thanks to longitudinal
328 sections, suggests potential self-regulatory mechanisms. Subsequently, this study definitively
329 confirms that the FT should no longer be considered as a simple ligament but rather as a
330 complex fibro-cellular structure.

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338

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REFERENCES

1. Streeter GL. Factors involved in the formation of the filum terminale. *Am J Anat.* 25(1):1-11. doi:10.1002/aja.1000250102
2. De Vloo P, Monea AG, Sciort R, van Loon J, Van Calenbergh F. The Filum Terminale: A Cadaver Study of Anatomy, Histology, and Elastic Properties. *World Neurosurg.* 2016;90:565-573.e1. doi:10.1016/j.wneu.2015.12.103
3. Jang HS, Cho KH, Chang H, Jin ZW, Rodriguez-Vazquez JF, Murakami G. The Filum Terminale Revisited: A Histological Study in Human Fetuses. *Pediatr Neurosurg.* 2016;51(1):9-19. doi:10.1159/000439284
4. Pearson AA, Sauter RW. Observations on the caudal end of the spinal cord. *Am J Anat.* 1971;131(4):463-469. doi:10.1002/aja.1001310406
5. Saker E, Henry BM, Tomaszewski KA, et al. The Human Central Canal of the Spinal Cord: A Comprehensive Review of its Anatomy, Embryology, Molecular Development, Variants, and Pathology. *Cureus.* 2016;8(12):e927. doi:10.7759/cureus.927
6. Hansasuta A, Tubbs RS, Oakes WJ. Filum terminale fusion and dural sac termination: study in 27 cadavers. *Pediatr Neurosurg.* 1999;30(4):176-179. doi:10.1159/000028790
7. Tubbs RS, Murphy RL, Kelly DR, Lott R, Salter EG, Oakes WJ. The filum terminale externum. *J Neurosurg Spine.* 2005;3(2):149-152. doi:10.3171/spi.2005.3.2.0149
8. Reimann AF, Anson BJ. Vertebral level of termination of the spinal cord with report of a case of sacral cord. *Anat Rec.* 88(1):127-138. doi:10.1002/ar.1090880108
9. Fontes RBV, Saad F, Soares MS, de Oliveira F, Pinto FCG, Liberti EA. Ultrastructural study of the filum terminale and its elastic fibers. *Neurosurgery.* 2006;58(5):978-984; discussion 978-984. doi:10.1227/01.NEU.0000210224.54816.40
10. Harmer JW. The normal histology of the intradural filum terminale. *Arch Neurol Psychiatry.* 1933;29(2):308-316. doi:10.1001/archneurpsyc.1933.02240080098008
11. McCotter. Regarding the length and extent of the human medulla spinalis. *Anat Rec.* 1916;10. doi:10.1002/ar.1090100902
12. Pinto FCG, Fontes RB de V, Leonhardt M de C, Amodio DT, Porro FF, Machado J. Anatomic study of the filum terminale and its correlations with the tethered cord syndrome. *Neurosurgery.* 2002;51(3):725-729; discussion 729-30.
13. Trotter M. Variations of the sacral canal; their significance in the administration of caudal analgesia. *Curr Res Anesth Analg.* 1947;26(5):192-202.

- 379 14. Needles JH. The caudal level of termination of the spinal cord in american whites and
380 american negroes. *Anat Rec.* 1935;63(4):417-424. doi:10.1002/ar.1090630409
- 381 15. Thomson A. Fifth Annual Report of the Committee of Collective Investigation of the
382 Anatomical Society of Great Britain and Ireland for the Year 1893-94., Fifth Annual
383 Report of the Committee of Collective Investigation of the Anatomical Society of Great
384 Britain and Ireland for the Year 1893-94. *J Anat Physiol J Anat Physiol.* 1894;29, 29(Pt
385 1, Pt 1):35, 35-60.
- 386 16. Moore GE, Peyton WT. The clinical use of sodium fluorescein and radioactive
387 diiodofluorescein in the localization of tumors of the central nervous system. *Minn Med.*
388 1948;31(10):1073-1076.
- 389 17. Nasr AY, Hussein AM, Zaghoul SA. Morphometric parameters and histological Study
390 of the Filum Terminale of Adult human cadavers and MR images. *Folia Morphol.* May
391 2018. doi:10.5603/FM.a2018.0041
- 392 18. Benet A, Rincon-Torroella J, Lawton MT, González Sánchez JJ. Novel embalming
393 solution for neurosurgical simulation in cadavers. *J Neurosurg.* 2014;120(5):1229-1237.
394 doi:10.3171/2014.1.JNS131857
- 395 19. Macdonald A, Chatrath P, Spector T, Ellis H. Level of termination of the spinal cord and
396 the dural sac: a magnetic resonance study. *Clin Anat N Y N.* 1999;12(3):149-152.
397 doi:10.1002/(SICI)1098-2353(1999)12:3
- 398 20. Choi D, Carroll N, Abrahams P. Spinal cord diameters in cadaveric specimens and
399 magnetic resonance scans, to assess embalming artefacts. *Surg Radiol Anat SRA.*
400 1996;18(2):133-135.
- 401 21. Tani S, Yamada S, Fuse T, Nakamura N. [Changes in lumbosacral canal length during
402 flexion and extension--dynamic effect on the elongated spinal cord in the tethered spinal
403 cord]. *No To Shinkei.* 1991;43(12):1121-1125.
- 404 22. Tani S, Yamada S, Knighton RS. Extensibility of the lumbar and sacral cord.
405 Pathophysiology of the tethered spinal cord in cats. *J Neurosurg.* 1987;66(1):116-123.
406 doi:10.3171/jns.1987.66.1.0116
- 407 23. Selçuki M, Vatansever S, Inan S, Erdemli E, Bağdatoğlu C, Polat A. Is a filum terminale
408 with a normal appearance really normal? *Childs Nerv Syst ChNS Off J Int Soc Pediatr*
409 *Neurosurg.* 2003;19(1):3-10. doi:10.1007/s00381-002-0665-1
- 410 24. Tehli O, Hodaj I, Kural C, Solmaz I, Onguru O, Izci Y. A comparative study of
411 histopathological analysis of filum terminale in patients with tethered cord syndrome and
412 in normal human fetuses. *Pediatr Neurosurg.* 2011;47(6):412-416.
413 doi:10.1159/000338981
- 414 25. Liu F-Y, Li J-F, Guan X, Luo X-F, Wang Z-L, Dang Q-H. SEM study on filum
415 terminale with tethered cord syndrome. *Childs Nerv Syst ChNS Off J Int Soc Pediatr*
416 *Neurosurg.* 2011;27(12):2141-2144. doi:10.1007/s00381-011-1414-0

- 417 26. George TM, Bulsara KR, Cummings TJ. The immunohistochemical profile of the
418 tethered filum terminale. *Pediatr Neurosurg*. 2003;39(5):227-233.
419 doi:10.1159/000072866
- 420 27. Filippidis AS, Kalani MY, Theodore N, Rekate HL. Spinal cord traction, vascular
421 compromise, hypoxia, and metabolic derangements in the pathophysiology of tethered
422 cord syndrome. *Neurosurg Focus*. 2010;29(1):E9. doi:10.3171/2010.3.FOCUS1085
- 423 28. Yamada S, Won DJ, Pezeshkpour G, et al. Pathophysiology of tethered cord syndrome
424 and similar complex disorders. *Neurosurg Focus*. 2007;23(2):E6. doi:10.3171/FOC-
425 07/08/E6
- 426 29. Hertzler DA, DePowell JJ, Stevenson CB, Mangano FT. Tethered cord syndrome: a
427 review of the literature from embryology to adult presentation. *Neurosurg Focus*.
428 2010;29(1):E1. doi:10.3171/2010.3.FOCUS1079
- 429 30. Gamble HJ. Electron microscope observations upon the conus medullaris and filum
430 terminale of human fetuses. *J Anat*. 1971;110(Pt 2):173-179.
- 431 31. Chrenek R, Magnotti LM, Herrera GR, Jha RM, Cardozo DL. Characterization of the
432 Filum terminale as a neural progenitor cell niche in both rats and humans. *J Comp
433 Neurol*. 2017;525(3):661-675. doi:10.1002/cne.24094
- 434 32. Choudhary KK, Bhytani A, Agarwal R, Madan VS. Extradural myxopapillary
435 ependymoma with sacral osteolysis--a case report. *Indian J Pathol Microbiol*.
436 2002;45(3):363-365.
- 437 33. Pytel P, Krausz T, Wollmann R, Utset MF. Ganglioneuromatous paraganglioma of the
438 cauda equina--a pathological case study. *Hum Pathol*. 2005;36(4):444-446.
439 doi:10.1016/j.humpath.2005.01.024
- 440 34. Shankar GM, Chen L, Kim AH, Ross GL, Folkerth RD, Friedlander RM. Composite
441 ganglioneuroma-paraganglioma of the filum terminale. *J Neurosurg Spine*.
442 2010;12(6):709-713. doi:10.3171/2009.12.SPINE09482
- 443 35. Okudera Y, Miyakoshi N, Sugawara T, et al. Ganglioneuroblastoma of filum terminale:
444 case report. *J Neurosurg Spine*. 2014;21(2):270-274. doi:10.3171/2014.4.SPINE121002
- 445 36. Pang D, Zovickian J, Wong S-T, Hou YJ, Moes GS. Limited dorsal myeloschisis: a not-
446 so-rare form of primary neurulation defect. *Childs Nerv Syst ChNS Off J Int Soc Pediatr
447 Neurosurg*. 2013;29(9):1459-1484. doi:10.1007/s00381-013-2189-2

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452 **FIGURE CAPTIONS**

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Fig. 1 Anatomical study of the different portions of the Filum Terminale.

456 *The orientation is the same for all pictures (left = cranial, right = caudal). Pictures were*
457 *taken with a digital camera (A - x4 magnification) or a surgical microscope (B and C - x40*
458 *magnification) (D and E – x10 magnification).*

459 *The very cranial portion of the iFT is anterior to the lumbar and sacro-coccygeal roots and is*
460 *subsequently not visible immediately after opening the dura mater (A). The interface between*
461 *the CM and the iFT corresponds to a progressive transition zone marked by a progressive*
462 *disappearance of the nervous tissue that is replaced by fibrous tissue organized in linear*
463 *spans (B). The space delimited by black arrows highlights the continuum between the iFT and*
464 *the DS. The term “fusion” seems appropriate to describe the FT-DS junction, both in the*
465 *intra-dural and extra-dural spaces (C). Example of eFT caudal periosteal insertion with a*
466 *single bundle marked with a black arrow (D). Example of eFT caudal periosteal insertion*
467 *with several bundles, marked with black arrows, that were fan-shaped (E).*

468 *CM = Conus Medullaris, DS = Dural Sac, eFT = extradural Filum Terminale, iFT =*
469 *intradural Filum Terminale*

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473 **Fig. 2** *Representation of vertebral projections of:*

474 - *the Conus Medullaris – intradural Filum Terminale junction (*),*

475 - *the Filum Terminale – Dural Sac junction (#), and*

476 - *the extradural Filum Terminale - coccyx junction (-).*

477

478 **Fig. 3** *Schematic representation of the Filum Terminale with pictures corresponding to the*
479 *different levels (x400).*

480 *The CM-iFT junction contains small rootlets included in the iFT stroma (A), ependymal cells*
481 *organized as a rosette (B) and ganglion cells randomly distributed at the CM-iFT junction*
482 *(C) which display positive immunostaining for NeuN (insert).*

483 *The First half of the iFT contains isolated ganglion cells (D) and amyloid bodies which are*
484 *frequently found in cellular areas (E). Nervous rootlets are directly contiguous to the iFT (F).*

485 *The second half of the iFT is also contiguous to myelinated rootlet, as highlighted by luxol-*
486 *fast-blue coloration (G). Groups of axons are included in the iFT (H), as attested by the*
487 *immunopositivity for neurofilament (I).*

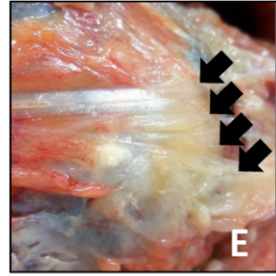
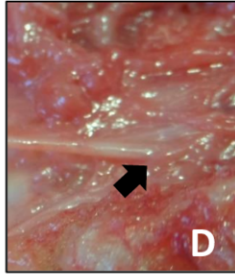
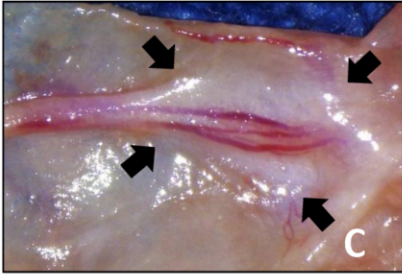
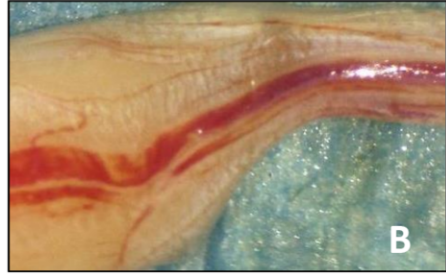
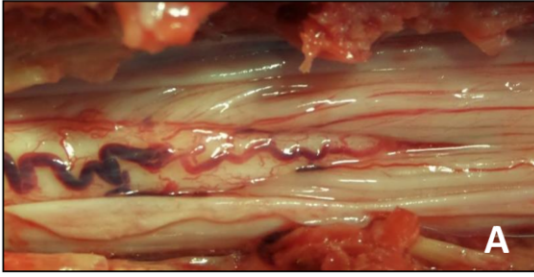
488 *In the FT-DS junction, the density of ganglion cells is particularly high (J).*

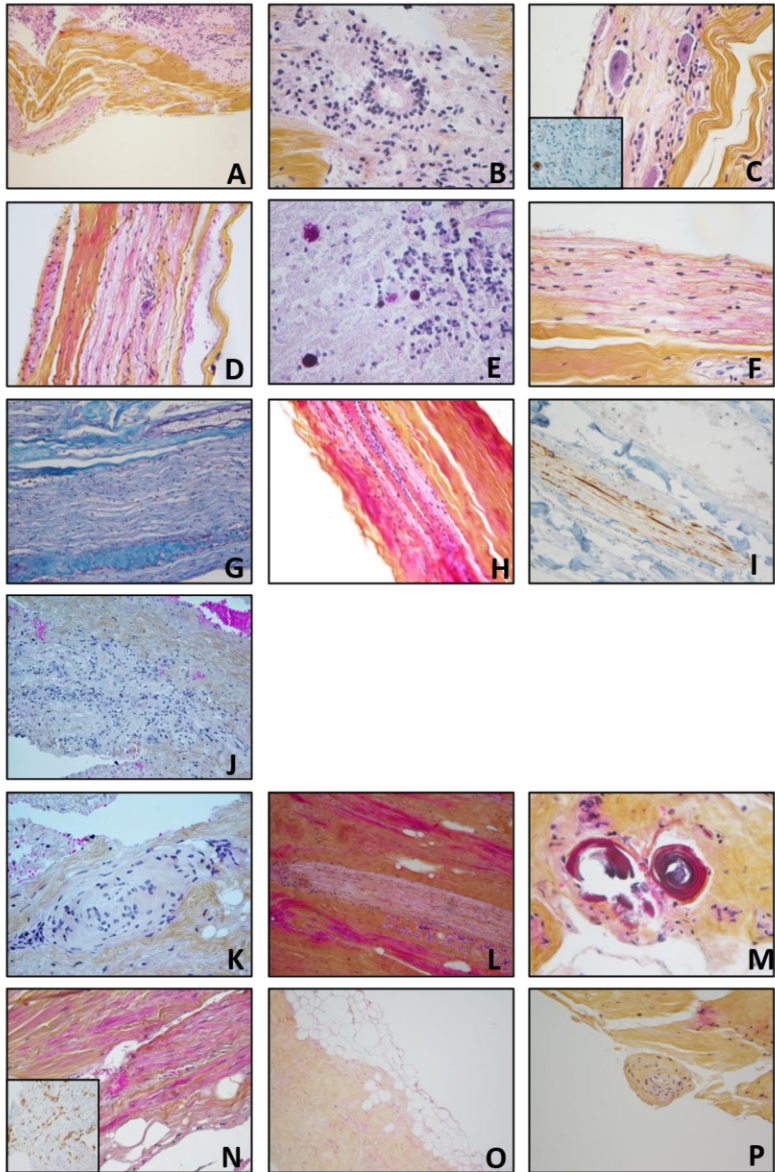
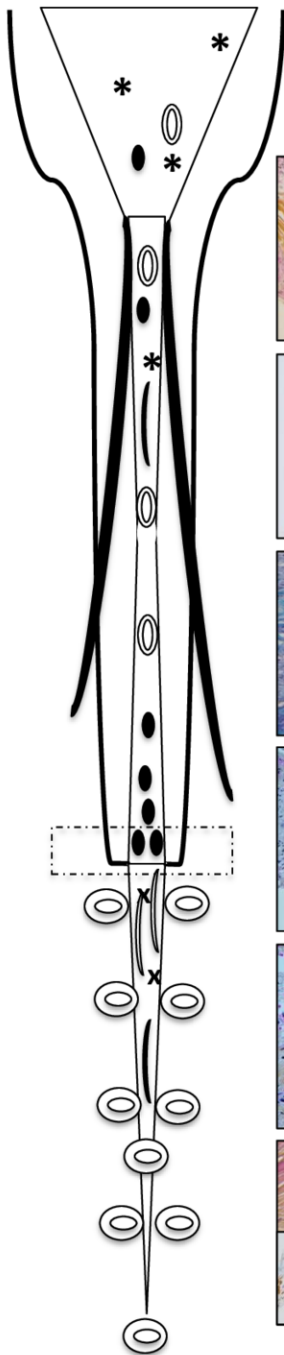
489 In the first half of the eFT, a structure composed of a circular cluster of neuronal cells
490 organized in sheets was found and probably corresponded to a mechanoreceptor (K). Group
491 of axons are surrounded by linear groups of smooth muscle cells (L). Calcospherites (one of
492 which is partially broken) are found in connective tissue (M).

493 The Second half of the eFT contains smooth muscle cells (N), as attested by the positive
494 immunostaining for actin (insert). A huge amount of adipose cells is found around the distal
495 eFT. Adipose cells are also present within the eFT (O). Winding-up of fibrous tissue are
496 observed (P).

497 CM = Conus Medullaris, DS = Dural Sac, eFT = extradural Filum Terminale, iFT =
498 intradural Filum Terminale

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Legend:

○ Ependymocyte

⌒ Smooth muscle cell

x Calcospherite

● Ganglion cell

⌒ Axon (partially represented)

* Amyloid body

○ Adipose cell

	Mean	Minimum	Maximum
Age (years)	85.2	59	96
Height (cm)	160.2	145	175
Weight (kg)	58.1	40	83
Body Mass Index (kg/m ²)	22.4	18.8	27.1
Time since death (days)	19.4	10	32

Table 1: Demographic characteristics of the specimens

	Mean	SD	Minimum	Maximum
iFT length (mm)	167.13	21.69	135	190
Cranial iFT diameter (mm)	1.84	0.34	1.40	2.57
First quarter iFT diameter (mm)	0.88	0.20	0.56	1.16
Half iFT diameter (mm)	0.71	0.22	0.44	1.14
Third quarter iFT diameter (mm)	0.67	0.30	0.30	1.38
Caudal iFT diameter (mm)	0.74	0.24	0.44	1.12
eFT length (mm)	87.59	17.46	71.11	127
Cranial eFT diameter (mm)	1.05	0.38	0.48	1.72
Half eFT diameter (mm)	0.77	0.22	0.42	1.15
Caudal eFT diameter (mm)	0.59	0.24	0.36	1.02

Table 2: Morphometric parameters of the different segments of the intradural Filum Terminale and extradural Filum Terminale in the present series (expressed in millimeters)

eFT = extradural Filum Terminale, iFT = intradural Filum Terminale, SD = Standard Deviation

	Number of specimens	Mean length	Cranial diameter	1 st quarter diameter	Half diameter	3 rd quarter diameter	Termination diameter
iFT							
Pinto <i>et al</i> , 2002 ¹²	41	156.44	1.38		0.76		
Fontes <i>et al</i> , 2006 ⁹	20	155.4	1.56		1.03		
De Vloo <i>et al</i> , 2016 ²	20	158.75	1.93	0.99	0.85	0.71	0.69
Nasr <i>et al</i> , 2018 ¹⁷	25	162.3	1.7		0.74		
Present series	10	167.14	1.84	0.87	0.71	0.68	0.74
eFT							
Harmeier, 1933 ¹⁰	Not specified	+/- 80					
Tubbs <i>et al</i> , 2005 ⁷	15	+/- 80			+/- 1		
De Vloo <i>et al</i> , 2016 ²	20	69.33	1.07		0.75		1.03
Nasr <i>et al</i> , 2018 ¹⁷	25	74.8			0.48		
Present series	10	87.59	1.05		0.77		0.59

Table 3: Comparison of the length and diameter of the intradural Filum Terminale and extradural Filum Terminale (expressed in millimetres), according to other published series^{2, 7, 9, 10, 12, 17}

eFT = extradural Filum Terminale, *iFT* = intradural Filum Terminale

	Type of study	Number of specimens	Median level of CM-iFT junction	Range of CM-iFT junction	Median level of FT-DS junction
Thomson, 1894 ¹⁵	Unspecified	198	Inferior third of L1	Middle third of T12 Superior third of L3	
Mc Cotter, 1916 ¹¹	Unspecified	234	Inferior third of L1	Inferior third of T12 Superior third of L3	
Needles, 1935 ¹⁴	Unspecified	240	Superior third of L2	Middle third of T12 Inferior third of L3	
Reimann, Anson, 1944 ⁸	Unspecified	129	L1-L2 disc	Inferior third of T12 Middle third of L3	
Trotter, 1947 ¹³	Bone	1227			Middle of S2
Hansasuta <i>et al</i> , 1999 ⁶	Unspecified	27			Middle of S2
Mac Donald <i>et al</i> , 1999 ¹⁹	MRI	136	Middle third of L1	Middle third of T11 Middle third of L3	Middle third of S2
Pinto <i>et al</i> , 2002 ¹²	Cadaveric (fresh)	41	Middle of L1		Superior part of S2
De Vloo <i>et al</i> , 2016 ²	Cadaveric (fresh and embalmed)	20	Inferior third of L1	Middle third of T12 Superior third of L3	Middle of S2
Present series	Cadavers (fresh)	10	Inferior third of L1 and L1L2 disc	Inferior third of T12 L2L3 disc	Inferior third of S2

Table 4: Comparison of the levels of Conus Medullaris -intradural Filum Terminale and Filum Terminale-Dural Sac junctions according to other published cadaveric and MRI series^{2, 6, 8, 11, 12, 13, 14, 15, 19}

CM = Conus Medullaris, iFT = intradural Filum Terminale, DS = Dural Sac