ANATOMICAL DIFFERENCES IN L5 AND L4 PEDICLES: CT AND MRI 3D DIRECT VOLUME RENDERING STUDY OF THE MORPHOMETRY AND OF THE DISTANCE BETWEEN THEM AND NERVOUS STRUCTURE

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ABSTRACT

The Authors expose the results of their anatomic and radio-imaging study on morfometry and direction of vertebral lumbar pedicles.

The study could give the opportunity for improvement of transpedicular screwing in stabi-lizing lumbar spine surgical procedures.

INTRODUCTION

Lumbar vertebrae have the largest bodies and their diameter progressively increase descending down towards sacrum, in particular the transverse diameters as a greater increase compared to the antero-posterior diameter¹. Lumbar region is characterized by wide range of anatomical vari-ations due to greater weight and force that are applied at this level. Pedicles in the lumbar region arise from the rostral aspect of the vertebral body, these processes present important differences among population.

Several researches in current literature based on cadavers, analyzed morphometry of lumbar vertebrae (pedicles, vertebral arches, vertebral body, vertebral foramen, intervertebral space height)¹⁸,¹⁹,²⁰,²¹, Karabekir et Al. (2011)², compared 100 dry lumbar vertebrae from 20 adult cadavers to MRI acquisition of the lumbar vertebrae of 21 healthy control subject; both vertebral body and pedicle morphometry were analyzed. Shiubii lien et Al. (2007)² considered both specimens from 6 cadavers and morphometric analysis extrapolated from CT scan of the thoracic and lumbar spine, to identify a safe region for pedicles screw fixations. However, these works lack in term of number of samples and patients examined. Thus, only few examples in recent literature report data from a conspicuous number of patients. Muhammad M Alam et Al.⁴ analyzed pedicles dimension, canal diameters, and laminae morphometry in 49 patients (two-hundred and twenty vertebrae), Wolf et Al.⁵ made and evaluation of the workspace of the pedicle entry point
the one between the vertebral body and the disk puncture points in 55 patients (Tab. 1).

We analyzed 325 patients and we subdivided this sample into three different categories based on the degree of lateral tilt of pedicle of L5. Then we performed CT and MRI of the lumbar spine, from L1 to the center of the femur head, to evaluate the bone morphometric values of the pedicles and the relation between them and the adjacent nervous structures (Tab. 2).

Pedicle Screw fixation is a common technique used by surgeons in treatment of spine disorders to obtain posterior spinal column fusion\textsuperscript{6,23}. The purpose of pedicle screw fixation is to improve conditions of patients suffering from a wide range of disorders through the stabilization of the “posterior” vertebral column. The main reason that made the surgeons choose the pedicles for screw application comes from anatomical factors. In order to obtain a successful three dimensional fixation the surgeon needs to select the strongest site accessible posteriorly, that is the pedicle. Early anatomical studies underline that the diameter and structure of the pedicle is large enough to allow the insertion of vertebral screw via transpedicular route. The key role played by the pedicles in this procedure is now supported by biomechanical studies and by even more recent morphometry studies that will be discussed in this work.

Pedicle screw fixation in the lumbar region allows a strong anchorage of the screw itself to the vertebral body this leads to a secure three dimensional positional control between the screw and the longitudinal elements. The numerous benefits of the transpedicular fixation explains why this surgical technique is applied in treatment of several pathologies: spinal fractures, Tumors, scoliosis, spondylolisthesis and low back pain among the others. In spinal fractures a better positional control of the anterior column leads to a reduction of displaced and fractured vertebrae moreover: satisfying results are reported in the decompression of the canal of retropulsed bony fragments associated with burst fractures\textsuperscript{13,7,24,25}. Concerning tumors, pedicle screw fixation, allowing a strong fixa-tion and a three dimensional positioning control, determines posterior tumor decompression with subsequent restoration or prevention of paraplegia\textsuperscript{14,15,27}. Recently clinical and radiological results of percutaneous pedicle screw fixation in the management of metastatic tumours have been investigated\textsuperscript{26}. Results of this study are encouraging: patients with spinal tumors and fractures treated with pedicle screw fixation experienced and increased quality of life following their surgery\textsuperscript{28,29}. In scoliosis\textsuperscript{30,31,32}, application of transpedicular screws is apparently a suitable replacement of the classic correction arranged with Harrington instrumentation. Pedicular screw implicates the trasmission of a derotation force to the center of vertebral body allowing a true segmental scoliosis correction. Some complications typical of the Harrington Instrumentation (flatback syndrome) can be solved with the application of screw or hook-rod system. Through pedicle screw fixation an invasive violation of the spinal canal can be avoided\textsuperscript{34}. Spondylolisthesis and spondilopthosis\textsuperscript{33,34} are treated with pedicle screw fixation, this approach attempt to improve the quality of life of patients suffering from high grade spondylolisthesis. Unfortunately single stage approach shows an high rate of implant and fusion failure. Low back pain is often treated with pedicle screw fixation, its advantage consists of an increased stability of vertebral elements that leads to a solid fusion\textsuperscript{17}. Zdeblick TA in his work points out on the improved fusion rate that occurs after the application of transpedicular screws.

Low back pain represents the most common cause of activity limitation in people younger than 45 years old in United States, the second most frequent reason for visit and the third ranking cause of surgical procedures. In order to obtain correct pedicle screw fixation the angle of the screw has to be equal or at least similar to the lateral tilt of the pedicles. “new leg pain” is a condition that come immediately a lumbar fusion using pedicle screw that may be caused by a screw
breaching the cortex of the pedicle. Thanks to current imaging and diagnostic technique the cause of Failed back spinal surgery (FBSS) may be identified. The main (most frequent) cause of failure is foraminal stenosis followed by recurrent or residual disk erniation (25% to 29%) \textsuperscript{8,35,36}.

The accuracy of the application of Pedicle screw has been investigated in recent literature\textsuperscript{37,38}. These studies point out a large range of wrong fixated screws\textsuperscript{9}. The variation in term of results is probably lead back to the different assessment methods. In recent year new technology has been developed and introduced, for example navigation and computer assisted fluoroscopy\textsuperscript{39,40,41,42}. A comparison can be made between the results from hand free fixation of pedicle screw and the ones from these new techniques. There is a minor incidence of FBSS when the new “guided” techniques are applied. The higher rate of failure that occurs when these new guided techniques can be explained with an anatomical variation of the lumbar spine and especially of the pedicles of L4 and L5.

\section*{MATERIAL AND METHODS}

\textbf{Participants and Radiological acquisitions}

This study include 325 consecutive patients (166 male (51,1\%) and 159 female (49,9\%), mean age of 62 years old (range from 34 to 72 years old), who were visited in our orthopedic ambulatory between January 2015 and December 2015 (Tab. 2). Considering the morphological feature of this study the only exclusion criteria were (I) musculoskeletal congenital abnormalities, (II) fractures at lumbar-sacral region or (III) precedent surgeries at lumbar spine or hip. For each patient that met the inclusion criteria were acquired: (I) antero-posterior and latero-lateral radiography of the lumbo-sacral spine, (II) CT examinations were performed with aSomatom Definition scanner (Siemens) using the following parameters: Kv 120, mAs 400, slice thickness of 0.6 mm, (III) MRI acquisition were taken with a Philips Achieva 3T R2.6 (Best, the Netherlands) was used for generating, firstly, Coherent Gradient Echo in aUltra Fast Echo Sequence so as to acquire T1-weighted isotropic volumes for high resolution scans. All subjects, who were examined for other reasons, gave informed consent and all procedures followed were in accordance with the Declaration of Helsinki of 1975.

\textbf{Sample Subdivision: L5 pedicle lateral tilt}

The sample is divided into three categories based on the lateral tilt of L5 pedicles. The evaluation was made with an axial slice of the CTscan at the level of the rostral part of the vertebral body. The angles evaluations were performed by using a freeware software package (Osirix 3.1.1 64 bit) at L5, placing a line from the middle point of the pedicle to the anterior margin of the vertebral body, and a line from the anterior margin of vertebral body to the center of the spinous process. The same angles were evaluated also for L4, L3, L2, L1.

\textbf{Bone Morphometry measurement}

3D direct volume rendering (3D DVR) of the CT scan were reconstructed using the same software (Osirix 3.1.1 64 bit), three parameters of the bone structure were analyzed: (I) pedicle width (PW), defined as the transverse axis of the pedicle, (II) pedicle height (PH), defined as the vertical axis of the pedicle and (III) interpedicular distance (IPD) defined as the distance between the pedicles at their emergency at the rostral part of the vertebral body. The measurements come from the analysis of the whole lumbar region.
Distance between pedicles and nervous structures

3D direct volume rendering (3D DVR) of the MRI scan were reconstructed using the same software (Osirix 3.1.1 64 bit), four parameters were analyzed: (I) pedicle-inferior root distance (PIRD), (II) pedicle-superior root distance (PSRD), (III) root-exit angle (REA) and (IV) nerve root diameter. The measurements came from the whole lumbar region.

RESULTS

Classification according to lateral tilt of L5

Sample has been divided considering lateral tilt of L5 into three different groups (Fig. 1).

The name of each category is referred to the letters W, U, V:
- W reminds the widest degree of lateralization,
- U an intermediate degree,
- V the narrowest one.

The first one or W-Type (WT) exhibited a lateral tilt of L5 larger than 36° (min. 36°, max. 44.7° and mean of 37.3°); 123 patients, 41.8% of the whole, belong to this group.

The second group or V-Type exhibited a lateral tilt of L5 from 30° to 36° (min. 30.8°, max 35.8° and mean of 33.4°); 141 patients, 48% of the whole, belong to this group.

The third group or U-type exhibited a lateral tilt of L5 smaller than 30° (min. 27.5°, max. 29.9° and a mean of 28.6°); 30 patients, 10.2% of the whole, belong to this group (Tab. 3).

Focusing attention on 144 women (Tab. 2), which represented 48% of the whole sample, we observe that 57 women, indeed 41.3% of total women, belong to the first group or W-Type; 69 women, indeed 50% of total women, belong to the second one or V-type, while 12 women, indeed 8.7% of total women, belong to the U type. On the other hand taking into consideration 156 men (Tab. 3), 53% of the whole sample, we notice that 66 men, so 42.3% of all men, belong to the first group or W type; while 72 men, that means 46.2% of all men, belong to the second group of V type; Finally the 6 left (11.5% of all men) belong to the third group.

Lateral tilt of L4

In this study the lateral tilt of L4 pedicle is calculated with the same method described in the previous paragraph. The average that we obtained calculating the degree of lateral tilt of the pedicle in each of the three categories in L4 depends on the one of L5: Patients that exhibited a W-type (41.8%) show a degree of lateralization of the pedicle of L4 of 28.4° (+/- 3.8°). Patients that exhibited a U-type (48%) show a degree of lateralization of the pedicle of L4 of 25.1° (+/- 3.5°). Patients that exhibited a V-type (10,8%) show a degree of the lateralization of the pedicle of the L4 of 22.2° (+/-3.3°) (Tab. 3) (Fig. 2).

Lateral tilt of L3, L2, L1

According to the lateralization of the pedicles in the first three lumbar vertebrae, data appear almost overlapping with the measurements that several works in recent literature reported. There is no variations based on the positioning of L5 in the three categories. The Average degree of lateralization in L3 is 22.2° (+/-1.8°), for L2 and L1 pedicles this degree is 21.2° (+/-1.5) and 20.7° (+/-1.5°) respectively.

Morphometric Values of Pedicles

Thanks to the 3D DVR of the CT scan it was possible to study the 3D morphometry of the
Pedicle structure.

Concerning L5: PW has a mean value of 18.5 mm in WT, 17.2 mm in VT and 15.8 mm for UT; PH has a mean value of 13.4 mm in WT, 12.8 mm (VT) and 11.2 mm in UT; IPD has a mean value of 29.2 mm in WT, 27.3 mm in VT and 25.8 mm in UT.

Concerning L4: Pedicle width: 13.6 mm (WT), 12.6 mm (VT) e 11.8 mm (UT). Per il Pedicle Height: 13.3 mm (WT), 12.6 mm (VT) 11 mm (UT).

Interpedicular Distance: 27.2 mm (WT), 26.6 mm (VT) and 25.6 (UT). Even from the morphometric point of view there are not substantial differences in pedicles of the proximal lumbar vertebrae (L1, L2, L3) according to our proposed classification (Tab. 4) (Fig. 3).

Pedicles and adjacent nerve roots

Thank to 3D DVR of the MRI we analyzed the correlation between the pedicles and the adjacent nervous structures, especially with nerve roots. We analyzed four parameters and then we compared the results obtained in the three different categories.

Concerning L5: PSRD has a mean value of 4.9 mm in WT, 4.6 mm in VT and 4.4 mm in UT; PDSD has a mean value of 1.9 mm in WT, 1.5 mm in VT and 1.3 mm in UT; REA has a mean value of 43° in WT, 40.2° in VT and 37.8° in UT. No differences were observed for PIRD (with a mean value of 1.5 mm) and NRD (with a mean value of 4 mm).

Concerning L4: PSRD has an average value of 4.9 mm in WT, 4.8 mm in UT, 4.5 mm in VT; PDSD has an average value of 2.0 mm in WT, 1.8 mm in UT and 1.5 mm in VT. REA has an average value of 40.2° in WT, 38.8° in UT, 36.4° in VT. PIRD has the same value in WT and UT (1.8 mm) while in VT the average value is 1.6 mm. No differences were observed for NRD.

Concerning L1, L2, L3 no differences were observed in the four parameters into the three categories (Tab. 5) (Fig. 4).

DISCUSSION

We hypothesized that high rate of failed Surgical treatment concerning the application of interpedicular screw in the pedicles of the lumbar region and in particular at the level of L4 and L5, is due to anatomical differences present among population. Our results underline the necessity of implement a classification of the distal lumbar vertebrae (L4-L5) according to the lateral tilt of the pedicles (Fig. 5).

We can assume that our results based on CT and MRI scan of 325 patients can supply a definitive evidence that the degree of lateral tilt assumes three main morphometric features (W-Type 41%, U-Type 48% and 12% V-Type from the largest to the narrowest) among populations. About 48% of the population present degree of lateralization of U-Type L5 between 30° and 36° degrees, Subjects that presents a pedicle of L5 shows a lateralization of L4 pedicle of 25.1° (+/- 3.5°). Our results underline that L4 lateralization depends directly from L5 one [Tab.6], not only in U-Type but also in W-Type (L5 mean PLT 37.3° +/− 2.8°, L4 mean PLT of 28.4° +/− 3.8°), and V-type (L5 mean PLT 28.6° L4 mean PLT 22.2°).

Morphometric features follow the variations of the lateral tilt. Our results point out that both longitudinal diameter (PH) and trasverse diameter (PW) decrease with low values of PLT, poeple belonging to the W-type category show an average values of PW of 18.5 mm while V-type subjects have a mean of 15.8 mm (14% less than W-Type). The same conclu-
sions can be assumed for pedicle height (PH), 13.3 mm in W-type subjects and 11 mm in V-type subjects. This data suggests that less is PLT the lesser is the area of the pedicle. For this reason during a pedicle screw fixation will be easier to damage medial wall. Concerning other values that vary with the PLT, IPD shows wide variations passing from an average value of 27.2 mm to a mean of 25.6 mm in W-type and V-type respectively. It’s correct to suppose that a variation of IPD is associated with a reduction of the transverse diameter of vertebral canal making itself more vulnerable to foraminal stenosis.

The distance of the pedicle from the nerve roots depends on PLT too. In this work we consider five points but three of them show sensible difference. No differences are evident for PIRD and for NRD on the other hand the slight reduction has been observed concerning PSRD and PDSD. The parameter REA shows a sensible variation with an average value of 40.2° in W-Type, 38.8° in U-Type and 36.4° in V-Type. From an overall analysis of data obtained into these studies we can assume that differences among population exist and could have clinical resonance. Our analysis is endorsed by a sample that was previously classified into three categories.

This lead us to the assumption that our results are more accurate than the ones that are inferred without considering the differences among the pedicles. This classification could help the surgeons to apply interpedicular screws, this could imply the decrease of surgical risk. From a strictly surgical point of view, our measurements show that V-type Lumbar Vertebrae is linked to greater incidence FBSS. Unfortunately we can only suppose a possible relation between cause and effect because our sample studied in this papers is based on patients that came in our ambulatory for hip, knee or back disorders. It would be better to have the opportunity of evaluate morphometry of the lumbar region in healthy subjects, following our classification. Once this point is achieved it would be easier to establish a possible predisposition to Lumbar spine pathologies (Low back pain, Scholiosis) thus would enhance prevention. Similar data can be referred also to L4 but we think that its relevance is not worth an extended discussion.

On the endorsement of epidemiological studies we assume that lumbar region pathologies have a significant social impact. A wide range of studies in literature confirm that almost 80% of all people experienced back pain during one’s own life. Back pain in its mildest way has an annual incidence in the adult population of 10-15%; the percentage increases in older subjects. A study con-ducted by Rossignol et Al. on a large sample of 2341 patients establish that is way more probable for the lumbar symptoms than thoracic symptoms to become chronic. In the USA, back pain is even the main reason of activity limitation in people younger than 45 years and one of the most common causes for people to be hospitalized. Data from other western countries are similar. Data coming from the surveys conducted by Praemer et Al assess that, from 1985-1988, back and spine disorders led to 185 million days of restricted activity (21x0 impairment) which included 83 million days confined to bed. Several studies made an attempt to link low back pain with psychological factors in-cuding (anxiety, depression, somatisation, negative body image). The experience of stress, anxiety and especially depression follows sometimes low back pain. However more studies are needed to demonstrate a connection between low back pain and various psychological factors. Volinn et al examined the US national hospital discharge survey from time trends to investigate the rate of surgical operations from 1979 to 1987. Taylor and colleagues later extended the study to including data up through 1990. During the 11 years considered operations among adults increased by 55%. The Perspective for Conditions of patients that recover over three months while for individuals who did not recover within this time the recovery process is slower, and
ther treatment is more difficult. These data suggest that a better knowledge of the anatomical structure of the pedicles is necessary to improve both surgical techniques and health care system for patients with spine disorders.

**Tab. 1** Recent findings in concerning vertebrae morphometry

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<th>Study</th>
<th>Number of Patients/Cadavers</th>
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<tr>
<td>Karabekir et al. (2011)</td>
<td>21</td>
<td>Pedicle Width, Pedicle Height, Vertebral Body a/p and lateral diameters</td>
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<tr>
<td>Shiu Bi Lien (2007)</td>
<td>6</td>
<td>Pedicle Height, safe zone width, sagittal and trasversal pedicle’s angle, root exit angle</td>
</tr>
<tr>
<td>Muhammad M Alam (2014)</td>
<td>49</td>
<td>Morphometry of Laminae, Morphometry of pedicles, canal diameters, Morphometry of vertebral Bodies</td>
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<tr>
<td>Wolf (1976)</td>
<td>51</td>
<td>Pedicle entry point, Morphometry of Vertebral Body, Morphometry of Pedicles, Disc Entry points</td>
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**Tab. 2** Patients demographics. BMI: body mass index

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<tr>
<td>Number of patient</td>
<td>325</td>
</tr>
<tr>
<td>Age</td>
<td>62 y.o. +/- 12 (from 34 to 72)</td>
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<tr>
<td>Male</td>
<td>166/51,7%</td>
</tr>
<tr>
<td>Female</td>
<td>159/49,3%</td>
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<tr>
<td>BMI (kg/m²)</td>
<td>29.4 +/- 6.2</td>
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</table>

**Tab. 3**

Orientation of L5 (3a) and L4 (3b) lateral tilt in the three categories (W-Type, V-Type, U-Type).

L5: (WT mean value 37.3°, VT mean value 33.3°, UT mean value 28.6°).
Tab. 4 Morphometric Features of the pedicles of L5 in the three categories

L5 PW: 18.5 mm in WT, 17.2 mm in VT, 15.8 mm UT
L5 PH: 13.4 mm in WT, 12.8 mm in VT, 11.2 mm UT
L5 IPD: 29.2 mm in WT, 27.3 mm in VT, 25.8 mm UT

L4 PW: 13.6 mm (WT), 12.6 mm (VT), 11.8 mm (UT)
L4 PH: 13.3 mm (WT), 12.6 mm (VT), 11 mm (UT)
L4 IPD: 27.2 mm (WT), 26.6 mm (VT) and 25.6 (UT)

Tab. 5a Distance between the pedicles of L5 and the adjacent nervous structures (PSRD, PDSD, PIRD, NRD)

L5: PSRD (WT mean value of 4.9 mm, VT mean 4.6 mm, mean value UT 4.4 mm)
PDSD (WT mean value of 1.9 mm, VT mean value 1.5 mm, UT mean value 1.3 mm)
PIRD (mean value of 1.5 mm)
NRD (mean value of 4 mm)
Tab. 5b Distance between the pedicles of L4 and the adjacent nervous structures
L4:  PSRD (WT mean value of 5.0 mm, VT mean 5.0 mm, UT mean 42 mm)
     PDSD (WT mean 20 mm, VT mean value 18 mm, UT mean 16 mm)
     PIRD (WT mean 18 mm, VT mean value 18 mm, UT mean 17 mm)
     NRD (WT mean 38 mm, VT mean 38 mm, UT mean 38 mm)

Tab. 5c Measurements of REA for L5 and L4 in the three different categories
L5: Root exit angle (WT mean value 43°, VT mean value 40.2°, UT 37.8° mean value).
L4: Root exit angle (WT mean value 40.2°, VT mean value 38.8°, UT mean value 36.4°).
Fig. 1 - Mean value of pedicle lateral tilt at L5 in the three categories.

Fig. 2 - Mean value of pedicle lateral tilt at L4 in the three categories.

Fig. 3 - Mean value of morphometric values of L5 pedicle.
Fig. 4 - Mean value of morphometric values of L4 pedicle.

Fig. 5 - Instruments orientation during pedicle screw fixation.
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