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ORIGINAL ARTICLE

Intradiscal vacuum phenomenon matches lumbar spine degeneration patterns in an ageing population

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Abstract

Purpose Intra-Discal Vacuum phenomenon (IDVP) is well-recognised, yet poorly visualised and poorly understood radiological finding in disc degeneration, particularly with regard to its role in spinal alignment. CT analysis of the lumbar spine in an aging population aims to identify patterns associated with IDVP including lumbopelvic morphology and associated spinal diagnoses.

Methods An analysis was performed of an over-60s population sample of 2020 unrelated abdominal CT scans, without acute spinal presentations. Spinal analysis included sagittal lumbopelvic reconstructions to assess for IDVP and pelvic incidence (PI). Subjects with degenerative pathologies, including previous vertebral fractures, auto-fusion, transitional vertebrae, and listhesis, were also selected out and analysed separately.

Results The prevalence of lumbar spine IDVP was 50.3% (955/1898) and increased with age (125 exclusions). This increased in severity towards the lumbosacral junction (L1L2 8.3%, L2L3 10.9%, L3L4 11.5%, L4L5 23.9%, and L5S1 46.3%). A lower PI yielded a higher incidence of IDVP, particularly at L5S1 ($p < 0.01$). A total of 292 patients had IDVP with additional degenerative pathologies, which were more likely to occur at the level of isthmic spondylolisthesis, adjacent to a previous fracture or suprajacent to a lumbosacral transitional vertebra ($p < 0.05$).

Conclusions This study identified the prevalence and severity of IDVP in an aging population. Sagittal patterns that influence the pattern of IVDP, such as pelvic incidence and degenerative pathologies, provide novel insights into the function of aging spines.

Keywords Vacuum · Pelvic incidence · Lumbar lordosis · Disc degeneration · Adult deformity

Introduction

An intradiscal vacuum phenomenon (IDVP) occurs when a cavity opens in an intervertebral disc in the supine position, lowering the intradiscal pressure and generating a nitrogen gas bubble [1]. Historically, it has been observed in 1–3% of spinal radiographs, reaching 20% in elderly individuals [2]. A renewed research interest in this area has shown associations with low back pain and degenerative pathologies [3–6]. Its relevance as a component of lumbar spine morphology has not yet been investigated.

Age-related changes in disc and lumbopelvic morphology are well documented, including reductions in disc height and lumbar lordosis [7]. Most disc degeneration studies and classifications are MRI-based and, therefore, do not include IDVP as part of the pathogenesis. Alternatively, while CT reliably reveals an intradiscal bubble, it is not well documented as an imaging study for degenerative conditions or deformities, even since digital sagittal reconstructions have been made possible. Thus, the relevance and function of IDVP in the degenerative spine remains unclear.

IDVP has not been evaluated in this context, particularly with respect to its role in lumbar spine morphology or the associated degenerative pathologies that affect sagittal balance or spinal compensatory mechanisms. The objective of this study was to identify IDVP prevalence in an ageing

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population, with respect to lumbar spine morphology and associated degenerative pathologies.

Methods and materials

The study design is illustrated in Fig. 1. After approval from the institutional review board, subjects only included historic scans of those over 60 years of age without implication for treatment, without acute or relevant spinal pathology, who underwent CT scans of the abdomen for symptoms unrelated to the spine, with 1–3 mm image cuts. All patient data were anonymized at the source, and image interpretation data were collected in a secure database. The exclusion criteria were as follows: duplicate scans, insufficient quality or detail, pelvic or hip abnormality, acute spinal findings, destructive spinal pathology (tumour or infection), previous neuromodulation, or previous spine instrumentation.

All abdominal CT scans were performed using 64-MDCT scanners, with the subject in a supine position, with digital sagittal and coronal reconstructions (McKesson Radiology™). The selected scans had full visualization of the lumbar spine and pelvis (including the femoral heads), without spinal indications for CT scanning. CT scans were assessed by two experienced musculoskeletal clinicians who underwent IVDP-specific training in a consensus reading for the presence, location, and severity of intervertebral IDVP.

Degenerative pathologies were selected out and analysed separately. These included.

- isthmic spondylolisthesis
- degenerative listhesis
- prior lumbar fracture
- lumbosacral transitional vertebrae (LSTV)
- autofused segment(s).

Categorization of IDVP was performed according to the classification of Wilhuber et al. [8], including mild (air/disc ratio l:2, less air than disc tissue), partial (1:1, equal distribution), and total (2:1, with more air than disc tissue) (Fig. 2).

To assess sagittal lumbopelvic morphology, the angle of pelvic incidence (PI) was calculated using the technique previously validated by Baker et al. [9]. The PI eclipses the anteroposterior dimensions of the pelvis, subtended between the lumbosacral and pelvic (hip-sacrum) longitudinal axes, as seen on a lateral profile, and found to be highly correlated with lumbar lordosis (LL). Using the image reconstruction function, the centre of the femoral heads was identified on respective sagittal slices to reveal the bicoxofemoral axis in the midsagittal plane, drawn to the mid-S1 endplate, and

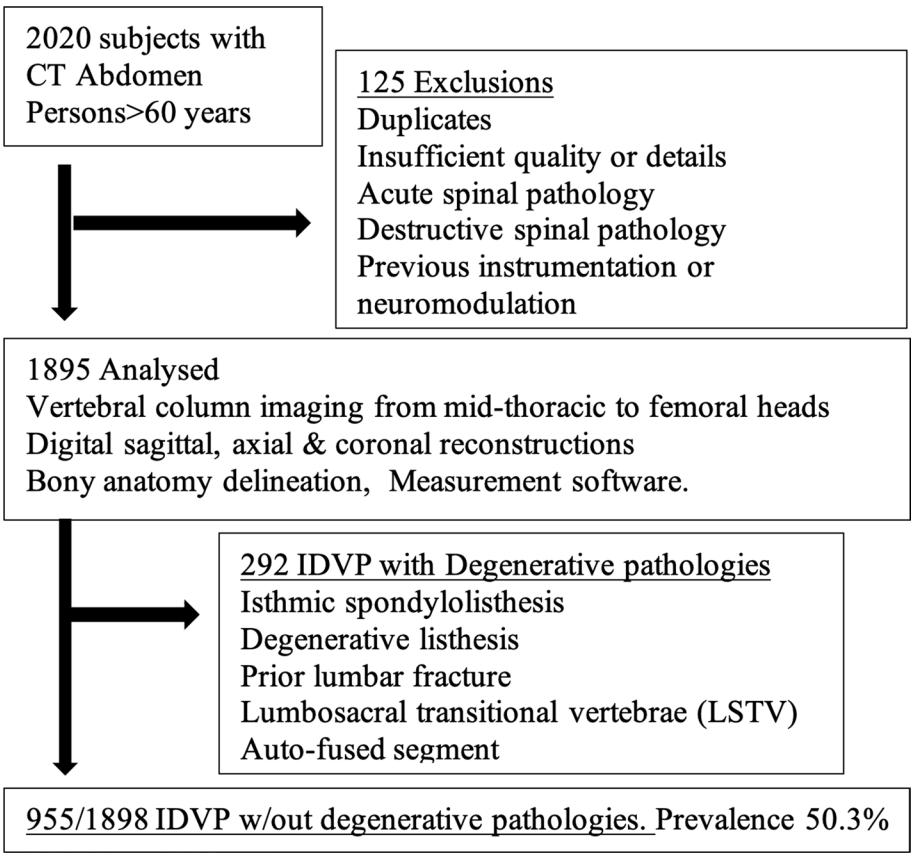

Fig. 1 Study design

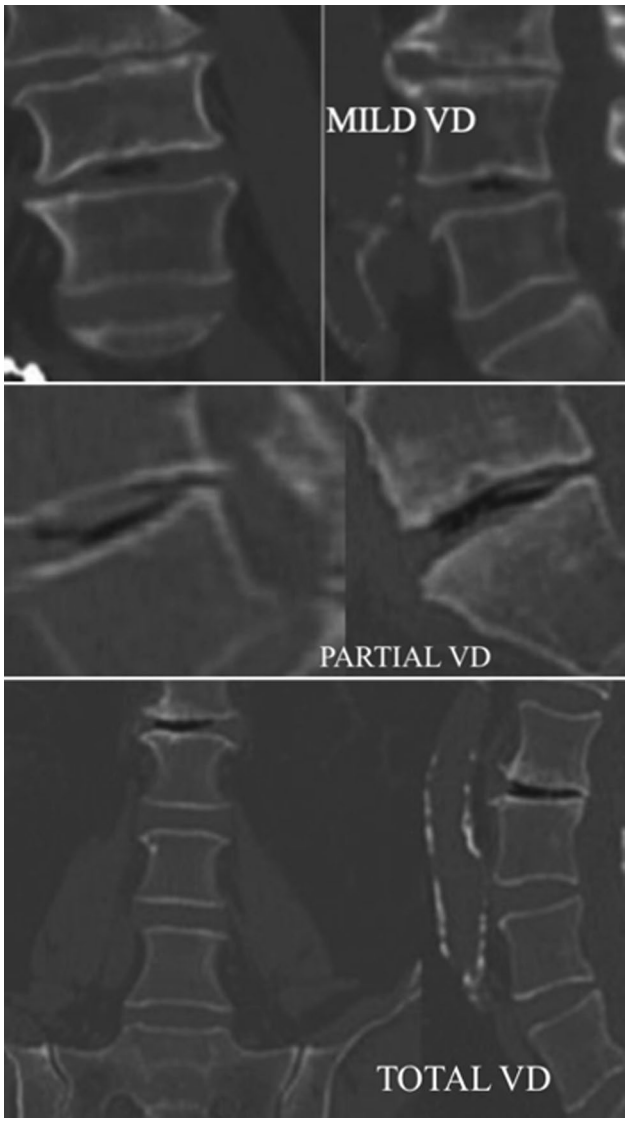

Fig. 2 IDVP classification: mild (air/disc rate of l: 2 in type 1 meaning that there is less air than disc tissue), partial (1:1 in type 2 with equal distribution of air and disc), and total (2:1 in type 3 vacuum, with more air than disc)[12]

an angle was created perpendicular to the mid-S1 endplate [10]. This was checked against the 2D profile scout images.

Statistical analysis

All patient data were analysed using the statistical software R v4.1 [R Core Team 2021, Vienna, Austria]. Demographic and clinical details were compiled and summarized with respect to IDVP. Intra- and inter-observer agreements for the presence of IDVP on CT were assessed. Those with and without degenerative pathologies were selected and analysed using ANOVA.

Continuous variables were compared using the Mann–Whitney test, while categorical variables were compared using either the χ^2 or Fisher's exact test, where appropriate. The presence of IDVP was modelled using binary logistic regression to investigate associations with age (years), PI (degrees), and position (upper lumbar, equally upper and lower, and lower lumbar). Univariate models for each of the three predictors and mutually adjusted multivariable regression are presented.

Among those with IDVP, the prevalence and severity (mild/partial/total) within levels (L12, L23, L34, L45, and L5S1) was recorded. The prevalence across positions was assessed using the χ^2 test for association. Severity (mild/partial/total) was modelled using ordinal logistic regression to investigate associations with age (years) and PI (degrees) at each level (L12, L23, L34, L45, and L5S1) separately. Associated degenerative pathologies (as listed above) were selected and analysed using ANOVA.

Results

A total of 2020 CT scans were analysed, all subjects were over 60 years of age, with 125 exclusions (Fig. 1), leaving 1898 subjects in the remaining cohort, including 955 with IDVP, with a prevalence of 50%. This included cohorts of 292 with IDVP and positive degenerative pathologies, and 663 with IDVP but without additional degenerative pathologies. Intra- and inter-observer agreement for the presence/absence of IDVP on CT was 95% for both, and the agreement on the subtype (mild/partial/total) of IDVP was 70.1% and 85.4%, respectively.

The PI was significantly higher in those without IDVP (54°) than in those without IDVP (51°) ($p < 0.01$) (Fig. 3). At 72 years, the age was significantly lower in those without IDVP than in those without IDVP at 76 years (Table 1).

In the multivariable model, the odds of upper compared to lower IDVP were reduced by 66% (OR 0.34, 95% CI, 0.16, 0.76; $p = 0.007$). For every year of age, the odds of IDVP increased by 7% (OR 1.07, 95% CI 1.02, 1.12; $p = 0.003$), and for every degree of PI, the odds of vacuum decreased by 4% (OR 0.96, 95% CI 0.94, 0.99; $p = 0.015$). The results were similar with and without adjustment.

The prevalence of IDVP increased with caudal progression from the L1L2 to the L5S1 junction (L1L2 8.3%, L2L3 10.9%, L3L4 11.5%, L4L5 23.9%, and L5S1 46.3%) (χ^2 p-value < 0.001) (Table 2 and Fig. 4).

The prevalence of degenerative pathologies (including fracture, lumbosacral transitional vertebra, isthmic spondylolisthesis, adjacent collapsed fused disc, and degenerative listhesis) was significantly higher in patients with IDVP, 207/940 (22%) of IDVP negative had degenerative pathologies, versus 292/955 (30.5%) of IDVP positive with

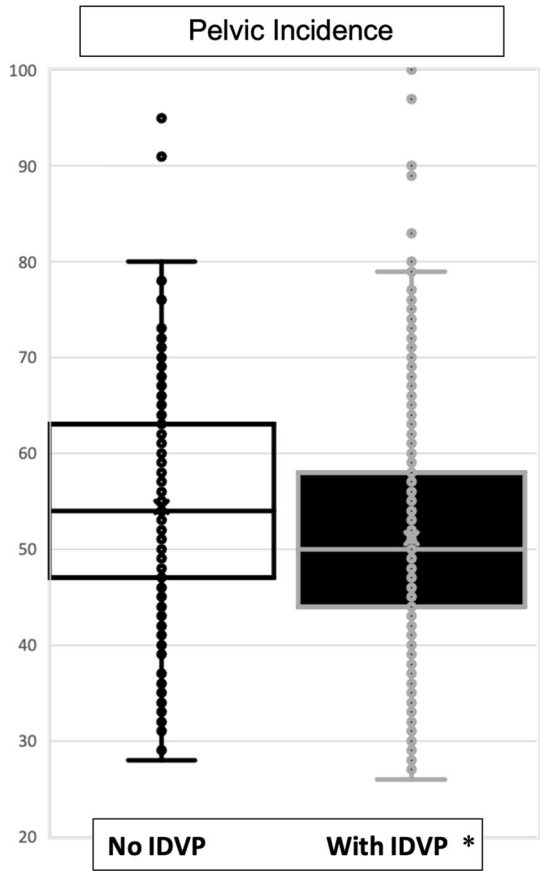

Fig. 3 Box plot/histogram for categories of no IDVP v with IDVP. *p < 0.05

degenerative pathologies. Where they were to occur, the IDVP was more likely to occur at the level of the degenerative pathology, including L45 for LSTV (sacralized L5), at L5S1 for isthmic spondylolisthesis, and adjacent to the level of the previous fracture ($p < 0.05$) (Table 3 and Fig. 5). Examples of IDVP with typical characteristics are shown in Fig. 6.

Discussion

Analysis of over 2000 subjects revealed novel insights regarding IDVP. While it is accepted that IDVP is associated with advanced disc degeneration, this study further characterizes this. IDVP occurs in 50% of adults over 60 years of age, significantly higher than previous cohorts. This may reflect the increasing prevalence of degenerative disc disease, or the superior diagnostic ability of CT to radiograph, whose recent digital sagittal reconstructions post-date the invention of MRI. Where an IDVP occurs, it is more likely to occur at more than one level. It is expected that disc degeneration is increased in the lower lumbar spine, and this pattern has also been demonstrated with IDVP. Furthermore, this is particularly evident at L5S1 with a lower mean pelvic incidence (PI) and in association with degenerative pathologies, such as at L45 with sacralized L5S1 (LSTV), at L5S1 with isthmic spondylolisthesis, or adjacent to the level of a previous fracture.

While the associated diagnoses above cause disc degeneration from different biomechanical forces, the resulting IDVP fits with an extension moment on the spine in all cases. The acute lordotic angle at L5S1 in the setting of low PI is recognized as a significant risk factor in disc degeneration and also outlined above. Similarly, Kanna et al. noted in their series, where L5S1 had the highest prevalence of IDVP, that angular instability was the most important predictive factor in the pathogenesis of IDVP, more than translation [5]. The anterior shear forces associated with isthmic spondylolisthesis reflect correlative findings of disc degeneration and degree of slip [11]. LSTV has previously shown degenerative effects at the suprajacent level for the disc and facet, and spinal stenosis [12]. The degenerative effects of a fracture on

Table 1 Demographic details and IDVP regions

Characteristic	N	Not seen, N = 940[a]	Vacuum seen, N = 663[a]	p-value[b]
PI	832	54 (11)	51 (11)	< 0.001
Age	1592	72 (8)	76 (9)	< 0.001
Position	689			0.010
Lower lumbar			412 (63%)	
Equal (upper and lower)			131 (20%)	
Upper lumbar			106 (16%)	
Involvement	1551			< 0.001
None		847 (95%)		
Unilevel			305 (46%)	
Multilevel			346 (52%)	

*p < 0.05. [a]n (%); mean (SD). [b]Fisher's exact test; Pearson's Chi-squared test; and Wilcoxon rank-sum test

Table 2 Prevalence and severity of IDVP across levels

Level	Total	Partial	Mild	None
L1L2	18 (8.3%)	51 (8.6%)	80 (16.0%)	674 (24%)
L2L3	22 (10.1%)	67 (11.4%)	86 (17.2%)	648 (23.1%)
L3L4	25 (11.5%)	104 (17.6%)	87 (17.4%)	607 (21.6%)
L4L5	52 (23.9%)	157 (26.6%)	107 (21.4%)	507 (18.1%)
L5S1	101 (46.3%)	211 (35.8%)	139 (27.9%)	372 (13.3%)

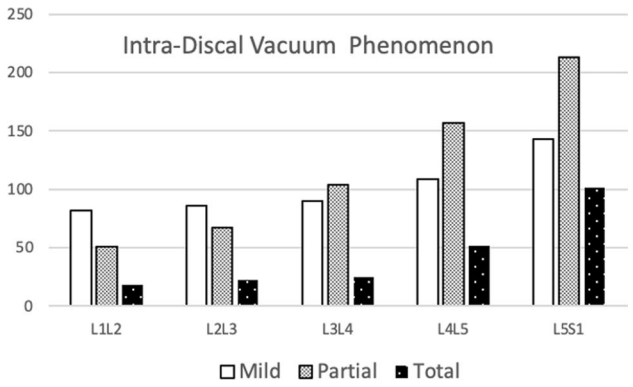

Fig. 4 IDVP for each lumbar segment, with increases in prevalence and severity from L1L2 to L5S1 ($p < 0.001$)

a disc are significant, regardless of the level. This has been studied at the thoracolumbar junction, in high-velocity cases, and considered more so in burst fractures involving the end plate [13, 14]. IDVP in fracture cases has been considered as a result of nutritional supply disturbances via the vertebral endplate [15], but given the biomechanical causes of IDVP, all associated with disc degeneration, this may be a secondary phenomenon. This would preferentially support the negative pressure theory over the endplate degeneration theory of IDVP [5]. The former relates to constant extension and distraction of the spine which creates micromotion between adjacent vertebrae, low-solubility nitrogen within the negative pressure area and cavity expansion. The latter theory relates to endplate sclerosis which blocks the transfer of nutrients and metabolites to the inner disc, leading to disc degeneration and entrapment of gases.

Spinal CT studies for the purpose of research in asymptomatic populations do not exist. In contrast, retrospective analysis of subjects undergoing unrelated CT scanning was considered appropriate, as previously shown [16–18]. Using CT spine for this study was not considered wise as most CT spine scans are either indicated for trauma evaluation or for pre-surgical planning, both of which would skew results. Nonetheless, recent studies of CT scans have shown considerable insight on IDVP, including that of Murata et al. [4], who outlined increased severity of IDVP with worsening grade of disc degeneration, particularly with central ("island") IDVP that also involved the anterior annulus. We effectively consider their three-level grading of severity (spot-linear-island) to be similar to that of Kanna's (dot-linear-dense) [5] or Wilhuber's CT classifications (above) [8].

This study was designed not to identify clinical correlations or associated symptoms as those studies exist [3], but to establish morphological-based patterns in an ageing population. Established disc degeneration affects sagittal alignment, even at a young age [19]. It is especially correlated with low PI [20], lower arc lordosis, and axial-type compressive forces [21]. Conversely, high PI values tended to indicate shear force degeneration at the L3L4 and L4L5 discs [22]. Both PI patterns were reflected in this population, occurring at the level of challenges to sagittal alignment. The associated degenerative pathologies also accelerated disc degeneration at the affected level(s).

The flexible nature of IDVP may explain between how one interprets lumbopelvic parameters in the fused as opposed to the unfused spine, particularly in the context of the surgical scores or decision-making algorithms [23]. IDVP may explain how despite suboptimal parameters, PROM is not as bad in a conservatively managed spine where one can employ intra-spinal compensatory measures, as it is in an instrumented fixed kyphotic spine with the same parameters [24]. IDVP may also respond to more nuanced emerging techniques such as cement discoplasty [25].

However, this study had some limitations. This series would provide a more comprehensive analysis as a prospective series with a detailed analysis of symptomatology. Retrospective symptomatology in a population over 60 years of age may yield little, given the potential for exclusion and

Table 3 Cohort of IDVP with associated degenerative pathologies, which had a higher incidence of IDVP than those without associated degenerative pathologies

292 IDVP with lumbar degenerative pathologies	PI	Associated IDVP level
31 Isthmic spondylolisthesis (IDVP within level)*	62.6	L5S1
19 Degenerative listhesis (IDVP within level)	55.9	L45
89 Prior fracture (IDVP at adjacent level)*	51.5	Level of fracture
94 Lumbosacral transitional vertebrae (adjacent)*	61.4	L4L5
52 Adjacent autofused segment (adjacent)	50.3	-
7 Multiple diagnoses	61.5	-

PI did not influence this. *$p < 0.05$

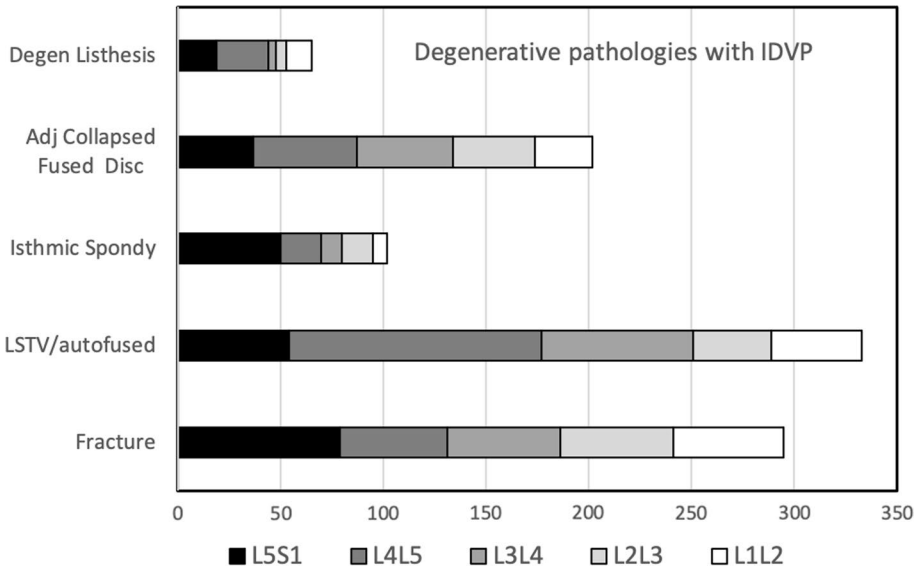

Fig. 5 A total of 292 subjects IDVP with degenerative pathologies, outlined at each different level and with weighted severity scoring. Isthmic spondylolisthesis, while invariably occurring at L5S1, displayed associated IDVP mostly at L5S1 but also at additional or other levels, similarly for lumbosacral transitional vertebrae at L45 and similarly for IDVP adjacent to fracture at the affected level. *$p < 0.05$

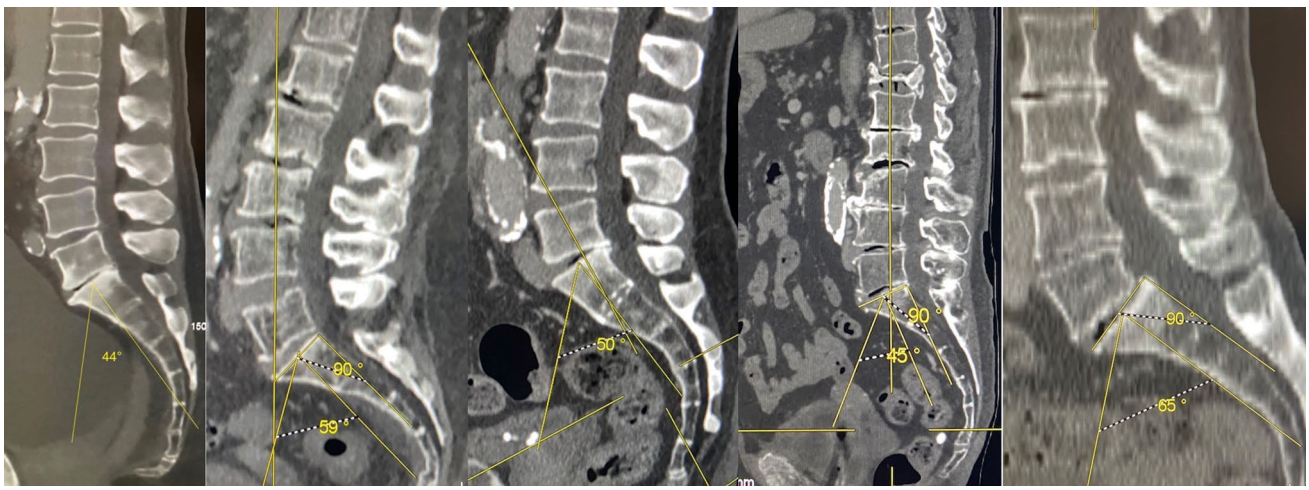

Fig. 6 IDVP findings indicative of lumbar spinal morphology and associated degenerative pathologies. A: low PI° (44°) with IDVP L5S1, B: high PI (59°) with IDVP L1L2L3L4, C: lumbosacral transitional vertebra with IDVP L4L5, D: fracture L3, T12 and autofusion L3L4, each with adjacent IDVP, and E: isthmic spondylolisthesis with IDVP L5S1

inclusion (α and ß) errors–memory decay regarding historical back-related symptoms and a high incidence of an episode of back pain, respectively. It is also possible that despite efforts to normalize the cohort, these subjects may not be as healthy as those who would not avail of health services. The use of contrast was not controlled for and may have affected results. A comparison with erect imaging would provide further insight into the IDVP. No erect CT exists, but this would best analyse this. Further research is ongoing regarding the IDVP patterns in patients with scoliosis.

Finally, it is worth noting a well-recognized high prevalence of disc degeneration in asymptomatic patients aged over 60 years. To further differentiate those with pathological versus age-related changes, correlative studies of both MRI and CT would provide valuable insights, work that is ongoing. The reasons why a significant minority do not develop IDVP go beyond the remit of this research, which is based on yet unknown genetic elements and associated phenotypes. Nonetheless, this study highlights those who with IDVP potentially display an adaptive mechanism as a result of suboptimal spinal biomechanics.

Conclusions

This analysis of IDVP in an ageing population provides novel insights on advanced disc degeneration and associated degenerative risk factors. CT provides a highly sensitive

analysis of prevalence and patterns, revealing IDVP in 50%, particularly at L5S1 with a lower PI or isthmic spondylolisthesis, at L45 with sacralized L5S1, or adjacent to the level of a previous fracture, all of whom encompass features of sagittal malalignment.

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Declarations

Conflicts of interest and source of funding There are no conflicts of interest regarding financial, consultant, institutional, or any other relationships on behalf of any authors. No funding was received for this study.

IRB approval/research ethics committee Approved.

Data access statement All data were anonymized at the source and maintained for the purpose of research as an electronic database available for scrutiny.

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