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ORIGINAL ARTICLE

Progressive instability of bilateral sacral fragility fractures in osteoporotic bone: a retrospective analysis of X-ray, CT, and MRI datasets from 78 cases

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Abstract

Purpose The pathogenetic mechanism, progression, and instability in geriatric bilateral fragility fractures of the sacrum (BFFSs) remain poorly understood. This study investigated the hypothesis of sequential BFFS progression by analysing X-ray, computed tomography (CT), and magnetic resonance imaging (MRI) datasets.

Methods Imaging data from 78 cases were retrospectively analysed. Fractures were categorized using the CT-based Fragility Fractures of the Pelvis classification. MRI datasets were analysed to detect relevant fracture location information. The longitudinal sacral fracture was graded as stage 1 (bone oedema) on MRI, stage 2 (recent fracture), stage 3 (healing fracture), or stage 4 (non-union) on CT. Ligamentous avulsions at the L5 transverse process and iliac crest were also captured.

Results Contralateral sacral lesions were only recognized by initial bone oedema on MRI in 17/78 (22%) cases. There were 22 cases without and 56 cases with an interconnecting transverse fracture component (TFC) [between S1/S2 ($n=39$) or between S2/S3 ($n=17$)]. With 30/78 patients showing bilateral fracture lines at different stages (1/2: $n=13$, 2/3: $n=13$, 1/3: $n=4$) and 38 at similar stages, Wilcoxon tests showed a significant stage difference ($p<0.001$). Forty cases had a coexistent L5 transverse process avulsion, consistent with a failing iliolumbar ligament. Analysis of variance revealed significant increases in ligamentous avulsions with higher fracture stages ($p<0.001$).

Conclusion Our results support the hypothesis of stagewise BFFS progression starting with unilateral sacral disruption followed by a contralateral lesion. Loss of sacral alar support leads to a TFC. Subsequent bone disruption causes iliolumbar ligament avulsion. MRI is recommended to detect bone oedema.

Keywords Sacrum · Fragility fracture · Insufficiency fracture · Pelvis · Osteoporosis · Sequential progress

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Introduction

The sacrum is the central keystone in axial load transmission from the upper body to the lower extremities. Sacral fractures often occur during pelvic ring injuries with adequate load impacts. Sacral fragility fractures in geriatric patients result from poor bone quality due to progressed osteoporosis [1] with a lack of elastic compensation [2]. However, there are numerous unanswered questions regarding the emergence mechanism, level of instability, progression, and treatment options.

The pattern of sacral fragility fractures was first reported by Lourie in 1982 [3]. Burge et al. reported a 5% incidence of pelvic fracture for the population > 50 years [4]. Weber et al. noted that 2% of women > 65 years with low back pain have a sacral fracture [5]. The standardized incidence rate

of pelvic fractures derived from insurance data in a German population > 60 years was 22.4/10.000 person years and showed strong age and sex effects [6].

Numerous fracture patterns in the osteoporotic pelvis can be ascribed to the altered structure of osteoporotic bone. Such injuries have become increasingly important because of demographic changes in Western countries [7]. Affected individuals show increased mortality, with 1- and 3-year mortality rates of 17.5% and 25.5%, respectively, partially due to pain-related immobility [8]. Therefore, it is important to clarify the underlying causal mechanism. A better understanding of this injury is of fundamental importance to develop adequate conservative and surgical treatment options.

In this study, we hypothesized that in contrast to the one-stage, high-velocity bilateral sacral injuries that occur in good-quality bones, BFFSs follow sequential progression starting with a unilateral vertical sacral lesion. At this point, the overlying ligaments initially remain intact. With time, a contralateral lesion may follow and sometimes become completed by an interconnecting transverse sacral lesion. Subsequent bony avulsions of the L5 transverse process or a shelled iliac avulsion of the posterior sacroiliac ligaments may reflect progressive vertical instability.

Materials and methods

In 2014, we implemented an internal diagnostic imaging protocol for pelvic injuries in geriatric patients [9]. Computed tomography (CT) was performed in patients with evidence of an anterior pelvic ring fracture on standard X-rays or in patients with substantial low back pain without a fracture on pelvic or lumbar X-rays. Magnetic resonance imaging (MRI) was routinely used in cases with fractures on CT to detect the complete injury pattern including CT-silent bone oedema and in cases of pain and no fracture sign on CT. Axial, coronal, and sagittal reconstructions were made from each raw CT dataset (Toshiba® Aquilion, bone reconstruction FC35; Tokyo, Japan). For MRI, the short-tau inversion recovery (STIR) sequence was used in the axial plane and the modified coronal plane in line with the inclination to the sacral body to detect the bone oedema distribution. Additionally, a T1-weighted sequence was routinely used to visualize specific fracture lines. Image data compilation was routinely performed for each patient during the same inpatient treatment period, with a maximum lag time of 5 days.

The hospital information system was retrospectively searched for patients with pelvic ring injuries within the 3-year period from 2014 to 2016. A total of 440 were identified, 273 (62%) were aged > 65 years, and 78 had BFFS without known high-energy trauma. Fracture patterns were categorized using the Fragility Fractures of the Pelvis (FFP) classification described by Rommens et al. [10]. MRI images were analysed in the next step to detect bone oedema; for classification purposes, oedema was interpreted as a fracture.

We used the terminus *spino-sacro-iliac junction* for the complex of the L5, sacrum, ilium, and overlying ligaments of one side. Disruption of these structures leads to spinopelvic junction instability. Longitudinal sacral fracture lines were graded following the Denis classification [11] without regard to the transverse sacral fracture. The occurrence of L5 transverse process avulsion or shelled iliac avulsion of the posterior sacroiliac ligaments was also documented. Furthermore, we looked for an additional interconnecting transverse fracture line between sacral bodies S1/2 or S2/3 leading to bony U- or H-shaped spinopelvic disruption. Finally, associated anterior pelvic ring lesions were noted.

Individual bone quality was estimated using Hounsfield units (HUs) calculated from opportunistic CT scans [12, 13]. HUs from regions of interest (ROIs) of five sagittal slices through the L5 vertebra (∅ 129 mm^2) were measured to calculate the mean HU of L5. $A < 100$ HU cut-off was used for lower general bone mass as reported by Wagner et al. [14].

To investigate the chronological BFFS progression, the sacral lesion of each *spino-sacro-iliac junction* (left/right) was estimated with respect to the fracture healing stage using the following grading method defined by the authors (Fig. 1):

- Stage 1: initial stadium (bone oedema on MRI STIR without lesion on CT in the same region)
- Stage 2: recent fracture (distinct fracture line with no signs of bony callus or bony resorption on CT)
- Stage 3: healing fracture (blurred fracture line with signs of bone apposition and resorption on CT)
- Stage 4: non-union (wide sclerotic fracture line with no signs of bone apposition)

This scale follows the image morphology from the initial emergence of the fracture through the pathological progression of the typical stages of secondary bone healing with callus formation [15], thereby providing a rough assessment of chronological fracture progression.

Statistical analysis was performed with SPSS software version 24 (SPSS Inc., Chicago, USA). A confidence interval of 95% was assumed (significance level $p < 0.05$). Chronological differences in longitudinal fracture lines (stage of fracture healing) between both sides were examined with Wilcoxon rank-sum tests. One-way analysis of variance (ANOVA) was performed for side-separated comparison between the subject's 'fracture stage' and the subject's 'occurrence of an L5 transverse process avulsion'. Bonferroni post hoc tests were performed for pairwise subgroup comparisons. Data are reported as the mean and range.

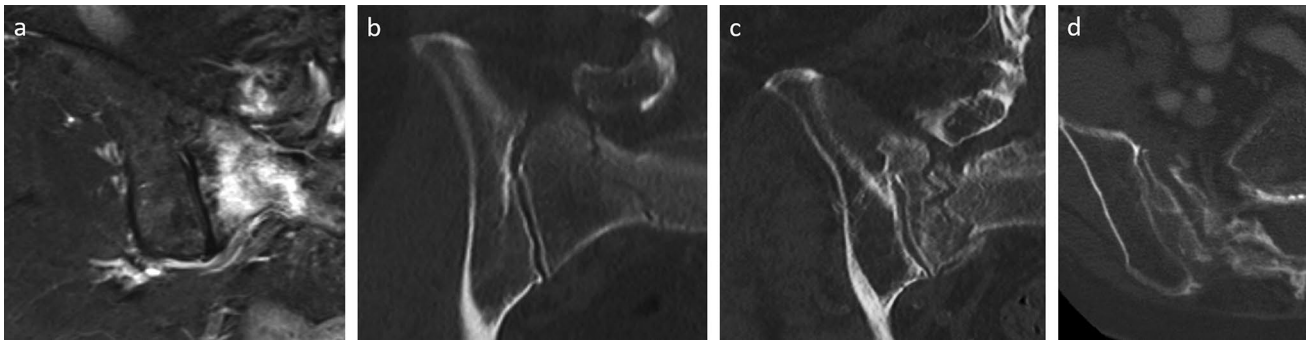

Fig. 1 Chronological BFFS progression in four stages: (**a**) fracture stage 1 with initial bone oedema on MRI STIR, (**b**) stage 2 with a distinct fracture line but no signs of bone callus or resorption on CT, (**c**) stage 3 a healing fracture with a blurred fracture line and signs of bone apposition and resorption on CT, and (**d**) stage 4 with a pseudarthrosis represented by a wide sclerotic fracture line with no signs of callus formation on CT

Results

Within the BFFS cohort of 78 patients, 4 (5%) were male and 74 (95%) were female. The mean age was 79 (range 65–94) years. We found a mean HU value of 66 of L5 (− 5–128).

Based on CT data, 17 of the 78 cases were primarily classified as unilateral sacral lesion. One case showed only an anterior lesion and another no lesion on CT; MRI revealed bilateral sacral oedema in both cases (Table 1). In 43 (55%) patients, bilateral disruption was connected by a TFC. Thirty (70%) were located between sacral bodies 1/2 and 13 (30%) between sacral bodies 2/3.

A bilateral trans-alar longitudinal fracture location (i.e., Denis 1) was observed in 49 of 78 (63%) cases. Bilateral trans-foraminal disruption (i.e., Denis 2) was observed in 16 (20%) sacra. In 13 (17%) pelvises, the sacrum was disrupted trans-alar on one side and trans-foraminal on the other side. The anterior pelvic ring was involved in 48 (62%) cases (40 unilateral and 8 bilateral lesions).

BFFSs with different stages were verified in 30 (38%) patients. In most of these cases ($n = 26$) we found a one-stage difference ($n = 13$ between 1 and 2 and also $n = 13$ between 2 and 3). Four cases had a difference of 2 stages (between 1 and 3). No pseudarthroses (stage 4) were observed in our population. Analysing only the subgroups with different fracture stages between sides ($n = 30$) with Wilcoxon rank-sum tests, the stages differed significantly between both sides ($p < 0.001$). The mean ranks of the first and second fractures were 1.4 ± 0.5 and 2.5 ± 0.6, respectively. Cohen's *d* effect size was 0.92, corresponding to a strong effect [16]. Wilcoxon tests showed stage differences (time delay) between sides ($p < 0.001$) across the entire study population. Cohen's d was 0.59, which was lower despite the higher heterogeneity, but the effect size was still between medium and large. A comprehensive overview of the data distribution is shown in Fig. 2.

An associated bilateral L5 transverse process avulsion was found in 23 (29%) cases, and a unilateral process in 17 (22%). ANOVA revealed a significant influence of fracture stage on L5 transverse process avulsion (left side: $p = 0.016$, right side: $p = 0.014$). Bonferroni post hoc tests showed significant differences between stages 2 (recent fracture) and 3 (healing fracture) for the left ($p = 0.026$) and right sides ($p = 0.024$). Figure 3 depicts the incremental increase in avulsions with stage progression. A shelled iliac avulsion of the strong posterior sacroiliac ligament was found in only three cases. However, no iliac avulsion occurred in stage 1. Four lesions were verified in stage 2, and two lesions were verified in stage 3. Moreover, iliac crest avulsion was always combined with an iliolumbar ligament tear. Tables 2, 3 list an overview of the failure of ligamentous stabilizers.

Table 1 Extent of sacral fracture involvement in all 78 pelvises by additional MRI image information

Sacral lesion	No	Monolateral	Bilateral		
			Transverse fracture component		
			No	Sub S1	Sub S2
CT	2 (2.6%)*	17 (21.8%)	16 (20.5%)	30 (38.5%)	13 (16.6%)
CT + MRI	0 (0.0%)	0 (0.0%)	22 (28.2%)	39 (50.0%)	17 (21.8%)

*Including 1 case without any verifiable lesion on CT and 1 case with just anterior pelvic ring disruption (FFP 1a)

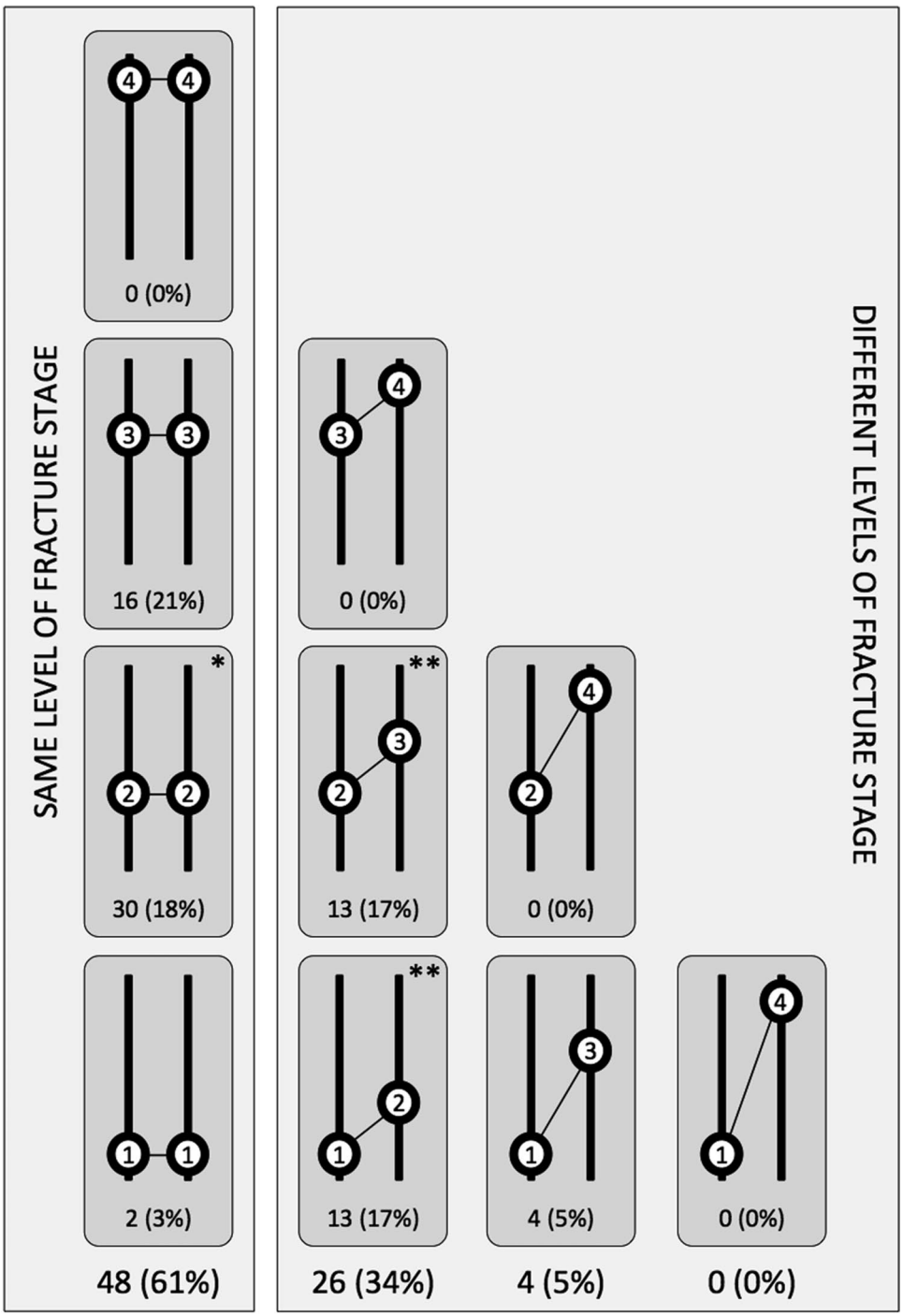

Fig. 2 Relationship of age-related stages of right and left sacral fracture lines (most cases with: *same stages or **different stages)

In the review of the 78 cases, we found 5 (6%) with sequential imaging. These patients where readmitted after initial conservative treatment of a unilateral fracture. MRI and CT imaging were repeated at readmission due to the patients' severe pain. In all of these 5 cases, we found a one-stage upgrade of the known fracture side and a newly appeared fracture on the contralateral side. Figure 4 shows a typical case of sequential BFFS emergence.

Discussion

In a 3-year period, we treated five cases showing a chronological progression of sacrum fractures. These patients initially presented with a unilateral fracture and were treated conservatively. A few weeks later there was exacerbation, and a second fracture appeared on the contralateral side.

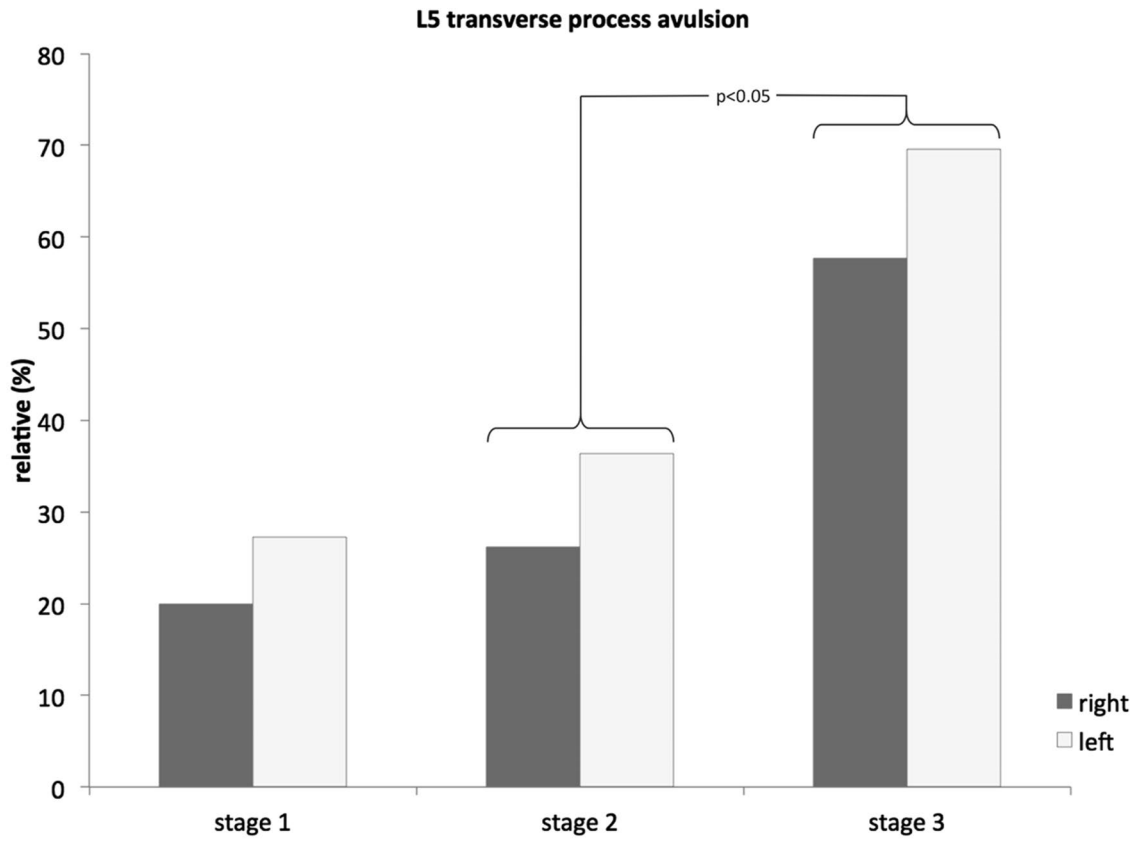

Fig. 3 Correlation of L5 transverse process avulsion with progressing fracture stage

Table 2 Distribution of associated ligamentous avulsions as a function of fracture stage on the right side

Spino-sacral-iliac junctions – right side							
	Stage 1		Stage 2		Stage 3		Total
	Absolute	Relative	Absolute	Relative	Absolute	Relative	
L5 transverse process avulsion							
Yes	2	20.0%	11	26.2%	15	57.7%	28
No	8	80.0%	31	73.8%	11	42.3%	50
Posterior iliac crest avulsion							
Yes	0	0.0%	2	4.8%	1	3.8%	3
No	10	100.0%	40	95.2%	25	96.2%	75
Combined avulsions							
Yes	0	0.0%	2	4.8%	1	3.8%	3
No	10	100.0%	40	95.2%	25	96.2%	75

This study was designed to test the hypothesis that bilateral insufficiency fractures take a sequential course.

In accordance with the literature, most trans-sacral fracture lines were typically located in the alar region (Denis 1) and resulted from bone rarefaction within the alar voids [14, 17]. Notably, an associated anterior ring lesion could only be verified in 62% of cases. Na et al. reported anterior ring involvement in 13 of 15 cases [18]. Our data emphasize the different emergence of BFFS compared to traumatic B- or C-type pelvic injuries in which simultaneous anterior and posterior lesions are caused by a single-stage external force impact to the pelvic ring.

In 2013, Rommens et al. published a comprehensive CT-based FFP classification based on a study of 245 CT datasets that allowed assessment of the degree of fracture instability [10]. Our results underscore the important role of MRI in

Table 3 Distribution of associated ligamentous avulsions as a function of fracture stage on the left side

Spino-sacral-iliac junctions – left side							
	Stage 1		Stage 2		Stage 3		Total
	Absolute	Relative	Absolute	Relative	Absolute	Relative	
L5 transverse process avulsion							
Yes	3	27.3%	16	26.4%	16	69.6%	35
No	8	72.7%	28	63.6%	7	30.4%	43
Posterior iliac crest avulsion							
Yes	0	0.0%	2	4.5%	1	4.3%	3
No	11	100.0%	42	95.5%	22	95.7%	75
Combined avulsions							
Yes	0	0.0%	2	4.5%	1	4.3%	3
No	11	100.0%	42	95.5%	22	95.7%	75

detecting the stage of initial bone oedema from an incipient fracture, which may not be visible on CT. In our cohort, a contralateral sacral lesion could only be identified on MRI in 17 of 78 (22%) cases. Furthermore, the initial CT did not show any sacral fracture involvement in two pelvises; only MRI revealed BFFSs. In summary, CT-based assessment underestimated the magnitude of pelvic injury in > 20% of our cases. Nüchtern et al. and Henes et al. emphasized the superiority of MRI for detecting undislocated fractures in osteoporotic pelvises and reported that 17% of fractures of the posterior pelvic ring would have been missed [19, 20]. Based on this and our results, we recommend routinely performing MRI if there is an osteoporotic pelvic fracture. This allows the entire extent of the injury to be displayed. However, in patients with complete bilateral sacral disruption (FFP 4b) on CT, additional MRI diagnostics may not be needed.

From our results, we can confirm that sacral fragility fractures follow an incremental and progressive loss of bone integrity. This is caused by a repetitive physiological vertical shear load leading to fatigue disruption of the osteoporotic sacrum at the vulnerable rarefied alar bone mass, or the so-called alar voids [17, 21]. The 38% of cases with different fracture stages between sides indicate that a contralateral fracture follows after the unilateral injury. There are other publications in the literature that generally support the hypothesis of pelvic fragility fracture progression [22, 23]. In nearly two-thirds of our patients, we observed sacrum fragility fractures of the same stage. This suggests that bilateral fractures may occur simultaneously due to a direct traumatic load on the sacrum. On the other hand, stage classification based on radiological imaging is only roughly possible. It is also conceivable that the fractures appear so shortly one after the other that a distinction based on the division is not possible.

The role of the anterior pelvic ring remains unclear. However, analysis of CT and MRI data did not allow any reliable conclusion with respect to the chronology of the overall individual injuries. It is clear that an additional anterior lesion increases overall ring instability. Hence, the relevance of associated anterior disruptions needs to be newly debated, and further investigations are necessary to answer this question.

Linstrom et al. stated in their biomechanical analysis that bilateral loss of the sacral alar support causes the entire weight of the upper body to be transferred down to the inclined sacral body, resulting in interconnecting transverse fractures in 61% of cases [21]. This finding corresponds to our results, with 72% of all cases falling into this category.

The initial degree of instability is quite mild, since the overlying ligaments are primarily intact. Although sacral fragility fractures can show an equivalent U- or H-shaped pattern, as in so-called suicidal jumpers' fractures, spinopelvic integrity is maintained for a long time because of the intact ligamentous repression. Therefore, the ligamentous structures need to withstand increased forces under perpetual loading. Pathological overload leads to secondary failure of the iliolumbar ligament due to avulsion of the L5 transverse process and/or shelled bony disruption of the posterior sacroiliac ligament complex. Our results show that the occurrence of ligamentous avulsions significantly increases the transition of fracture stage 2 (recent fracture) to fracture stage 3 (healing fracture). Collectively, our results support the hypothesis of sequential failure of the spino-sacro-iliac junction in fragility fractures of the sacrum that begins with bone disruption and is followed by failure of the overlying ligamentous stabilizers. The proportion increased from only 20% of patients with an initial sacral fracture stage 1 (bone marrow oedema) up to 57.7% in patients with advanced fracture healing (stage 3). As a result of the lesions on L5 and the ilium as an expression of ligamentous decompensation, it must be assumed that the instability widens from vertical to translational.

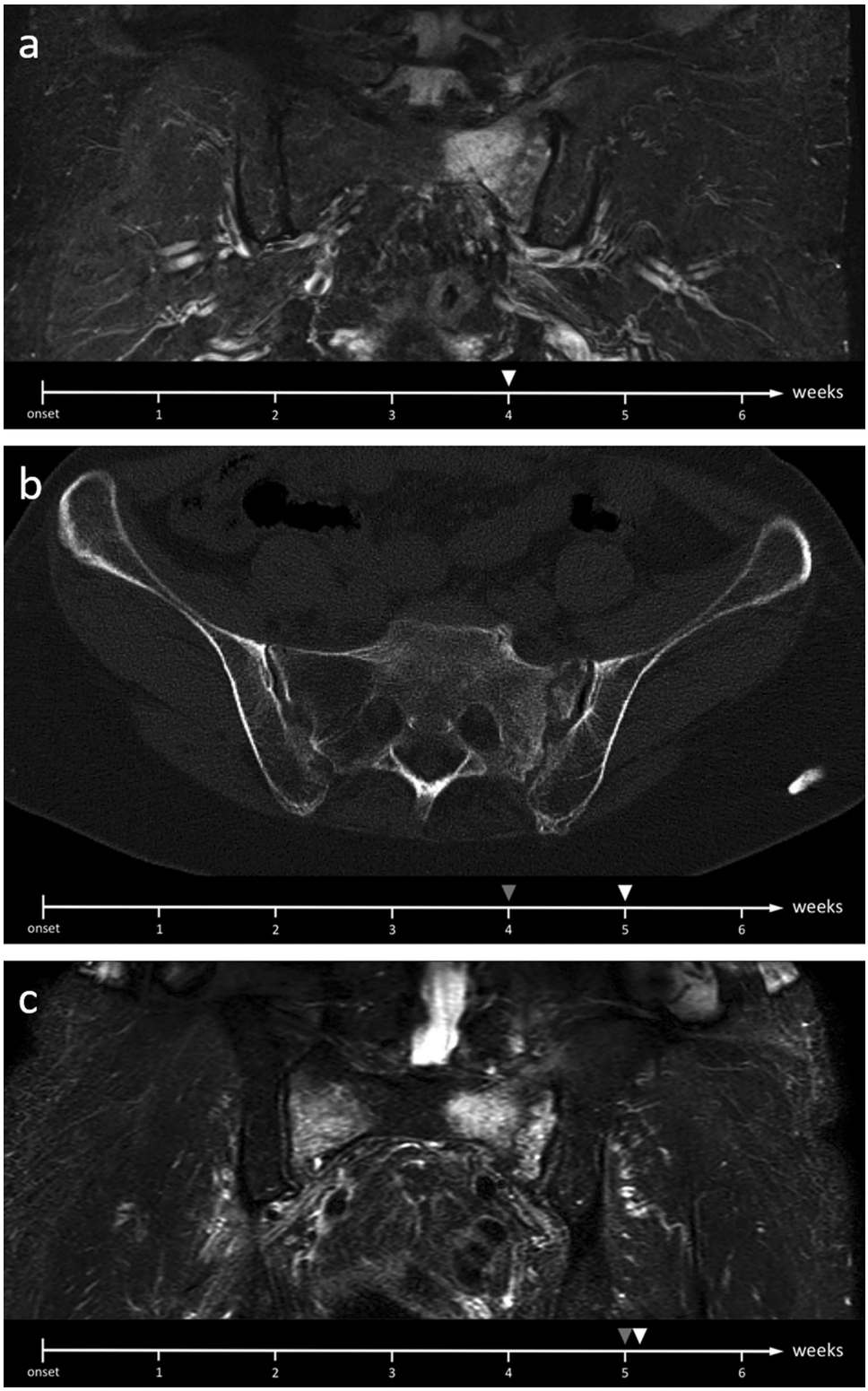

Fig. 4 Typical case of the sequential emergence of BFFS in a 73-year-old female with a 4-week history of low back pain without any trauma: (**a**) Bone oedema of the left sacral ala on coronal MRI STIR without any changes on the right side. **b** Axial CT imaging taken 1 week later because of exacerbating pain showed a stage 3 injury on the left side but still no fracture signs on the contralateral ala. **c** Coronal MRI STIR taken immediately after CT revealed alar oedema on the right side corresponding to a stage one injury

Our study has some limitations. The presented grading system is based only on generally accepted radiographic morphological changes in indirect bone fracture healing. It, therefore, does not claim to be a statistically validated classification. Although the results of our study seem to support the hypothesis of a stadium-like fracture progression of BFFS. However, the analysis is not based on a structured follow-up protocol. Only in five patients image data were found at different treatment times, all of which confirmed a sequential fracture progression. Ultimately,

our thesis remains a conjecture, which must be confirmed in subsequent statistical analyses with higher case numbers and structured follow-up. Furthermore, dual energy X-ray absorptiometry (DEXA) is typically used to diagnose and follow-up patients with osteoporosis. DEXA was not performed routinely in our population. However, Pickhardt et al. assessed 1867 abdominal CT datasets and showed a distinct correlation of HUs and DEXA values measured in the lumbar spine [13]. Schreiber et al. proposed a reliable cut-off value of 100 HU for osteoporotic bone mineral density in the lumbar spine, with an intra- and inter-observer reliability scores > 0.9 [12]. Hence, HUs can be applied as a reliable quantitative parameter to investigate bone quality. Two of the included patients had HUs > 100, but both cases were included as there was no history of trauma and other causes of the fracture (e.g., malignant disease, radiation, or chemotherapy) were excluded.

This study focused on a cohort of 78 patients with radiological manifestations of BFFSs, so no conclusion can be drawn regarding the proportion of patients who developed BFFSs within the entire population of initial unilateral fragility lesions of the sacrum. It is unknown which unilateral fractures merge into a bilateral one and which heal without successive contralateral fracture. The retrospective design cannot provide this answer. Prospective studies are necessary to follow-up patients with unilateral fractures.

Sacral insufficiency fractures are often missed or diagnosed with a mean delay of 23–55 days because of nonspecific symptoms such as low back pain or buttock pain mimicking lumbar spine pathology [24–26]. Among other reasons, the lack of diagnosis is caused by the insensitivity of first-line medical imaging. BFFSs can only be identified in 20–38% of planar radiographs [25, 27]. For CT scans, the sensitivity of BFFS detection is reportedly 60–75% [26]. In contrast, MRI enables verification of an early fracture stage by allowing visualization of bone marrow oedema, with a sensitivity of 100% [26, 27]. Based on our results, in the case of evidence of a unilateral trans-alar fracture on X-ray or CT, STIR MRI [18, 25] should be performed to detect a possible contralateral lesion based on evidence of bone marrow oedema (stage 1). This step is essential for selecting an appropriate fixation technique. Whereas evidence of an additional contralateral sacral fracture plays a rather subordinate role for conservative treatment, knowledge of bilateral fracture involvement is of critical importance for adequate surgical stabilization. We prefer two-level transsacral screw fixation whenever two transsacral corridors can be occupied to avoid transfixation of the lumbo-pelvic hinge. However, for U- or H-shaped BFFS with a TFC below the S1 corpus, we prefer the minimally invasive spinopelvic fixation. In summary, both techniques ensure adequate stability and allow early full loading, even in the presence of an additional L5 transverse process tear. Nevertheless, with knowledge of the chronological fracture progression a straightforward prophylactic bilateral fixation must be discussed even when a contralateral fracture involvement is primarily excluded, to obviate secondary contralateral disruption.

Conclusions

Finally, the following hypotheses can be stated:

- Bilateral fragility fractures of the sacrum seem to follow a sequential progression starting with unilateral sacral disruption.
- An interconnecting transverse fracture line appears in approximately 50–61% of cases, resulting from the bilateral loss of sacral alar support. At the onset, the ligamentous integrity of the posterior ring remains intact.
- Repetitive loading may lead to incremental failure indicated by avulsion of the L5 transverse process and/or posterior sacroiliac ligaments in late fracture stages.
- MRI should be recommended to distinguish initial bone oedema from an incipient fracture, which may not be visible on CT.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with animals performed by any of the authors. The study was approved by the independent Medical Ethics Committee of the Medical Council of Saxony-Anhalt, Germany, and confirmed under approval no. 78/17.

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