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REVIEW

Imaging of pelvic ring fractures in older adults and its clinical implications-a systematic review

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Abstract
Identifying the full scope of pelvic fracture patterns in older adults has gained clinical importance since the last decennium. CT is recommended as the golden standard; however, MRI has even greater diagnostic accuracy. Dual energy computed tomography (DECT) is a new and promising imaging technique, but the diagnostic accuracy in the context of pelvic fragility fractures (FFPs) has not been widely established. The aim was to provide insight into the diagnostic accuracy of different imaging techniques and the relevance for clinical practice. A systematic search was performed in the PubMed database. All studies that reported on CT, MRI or DECT imaging techniques in older adults who suffered a pelvic fracture were reviewed and, if relevant, included. Eight articles were included. In up to 54% of the patients, additional fractures were found on MRI compared to CT, and in up to 57% of the patients on DECT. The sensitivity of DECT for posterior pelvic fracture detection was similar to MRI. All patients without fractures on CT appeared to have posterior fractures on MRI. After additional MRI, 40% of the patients had a change of classification. DECT and MRI showed very similar results in terms of diagnostic accuracy. Over a third of all patients appear to have a more severe fracture classification after MRI, the majority changing to Rommens type 4. However, in only a few patients who changed of fracture classification, a change of therapy was advised. This review suggests that MRI and DECT scans are superior in diagnosing FFPs.

Keywords Computed tomography · Dual energy computed tomography · Magnetic resonance imaging · Older adults · Pelvic fragility fracture · Pelvic ring fractures

Introduction

The number of pelvic fractures in the older adult population has been steadily increasing over the past years and is expected to keep rising [1–3]. The consequences of a pelvic fracture in this vulnerable population are significant from both patient and societal perspective. One-year mortality rates have been described up to 27%, there is a high rate of hospital admissions, and only a third of the patients can return to their own home because of loss of functional independence [4, 5]. Pelvic fragility fractures (FFPs) in the older adult are often caused by an inadequate or low-energy trauma, with two-thirds of the patients not able to identify or remember a traumatic event [6]. However, high-energy traumatic pelvic ring injuries also occur in the older adult. Falls from stairs, for example, which are a high-energy accident if they happen from the top of the stairs, also contribute to the burden of serious fractures in older adults [7, 8].

Accurately identifying the full scope of the fracture pattern has gained clinical importance over the last decennium. Recent studies have shown that if a pubic ramus fracture has a concomitant sacral fracture, the fracture pattern is substantially more unstable and if these patients are conservatively treated, they suffer from longer periods of immobility and pain [9]. Surgical fixation, however, reduces pain and improves mobility and physical function in older adults [10]. In addition, surgical techniques have developed over the last years from invasive open procedures, with a high level of soft tissue disruption, to minimally invasive percutaneous

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techniques [11]. These percutaneous techniques are safe and allow for faster rehabilitation, improving 1-year survival and functional independence [12–14].

One challenge in the diagnostic work-up of older adults with a pelvic fracture is visualising fractures of the posterior pelvic ring. It has been well established that pelvic X-rays are highly inaccurate in diagnosing posterior pelvic fractures, missing concomitant posterior pelvic ring lesions in 32–97% of the patients with pubic rami fractures on radiographs [6, 15, 16]. This has resulted in recent literature recommending conventional CT as the golden standard to diagnose the full scope of pelvic fracture patterns. However, conventional CT is not the only option for advanced imaging. The diagnostic accuracy of magnetic resonance imaging (MRI) in identifying occult fractures in the proximal femur is well described [17, 18]. In patients with osteoporotic vertebra fractures, 16% of the patients increased in fracture classification severity after MRI [19]. Similar results have been seen in osteoporotic sacral fractures, where 22% of the patients had bilateral instead of unilateral sacral fractures after MRI, and thus a more severe fracture classification [20]. However, in clinical practice, MRI has several limitations like costs and availability. Dual energy computed tomography (DECT) is a new and promising imaging technique with accessibility similar to CT. The application for clinical practice of this technique and the diagnostic accuracy compared to MRI in pelvic fragility fractures, however, has not been widely established.

To provide insight into the relevance for clinical practice of MRI and DECT imaging in older adults who suffered a pelvic fragility fracture, a systematic review was conducted. The aim of this review was to evaluate if MRI or DECT imaging results in an increase in the detection of additional fractures, and if this has implications for a change in classification of the fracture pattern and therapy.

Methods

Literature search

A systematic search for relevant studies was performed in PubMed/MEDLINE. The search strategy comprised three key elements: CT scan, MRI scan and DECT scan, in relation to pelvic fractures. These three key elements were connected with Boolean operators to form an overarching search. Terms were kept broad and synonyms were used to maximise sensitivity of the search. The details of this literature search are shown in Appendix 1. The search was updated until August 2022. Snowballing was done to identify additional relevant articles. This review fully complies with the PRISMA guidelines [21].

Inclusion and exclusion criteria

All studies that reported on imaging in patients who suffered a pelvic fracture were reviewed by two authors (AM, AB). All English prospective and retrospective cohort studies, case–control studies and case series that reported on diagnosing pelvic fractures using a CT scan, MRI scan or DECT scan were included in this review. To be eligible for inclusion, all relevant study participants should be 50 years or older, or have a mean age of > 60 years. Studies were excluded if the additional CT scan, MRI scan or DECT scan was performed postoperatively. Studies that focused on pelvic or sacral fractures in patients with a known malignancy or metastatic bone disease, studies in which the MRI was not performed additional to conventional CT imaging but in a separate cohort, and studies of which the age distribution in the relevant cohort of patients was unknown were excluded. Case report, systematic and narrative reviews were excluded. A flowchart of the selection process is presented in Fig. 1.

Data extraction

Data was collected by two authors (AM, AB). The following outcomes were reviewed: additional fracture detection per patient and per fracture, the distribution of the additional fractures, the diagnostic accuracy overall and of the posterior ring only, the classification and how this changed after additional imaging, the provided therapy and change of therapy. If one study made comparisons of multiple imaging modalities, the results of these comparisons were separated and grouped with the other studies that noted these modalities. The classifications used in the articles were noted; the Rommens and Hofmann classification for fragility fractures and AO classification when referring to pelvic fractures as a result of high-energy trauma [22, 23]. Details of the Rommens and Hofmann classification, hereafter referred to as the Rommens classification, can be found in Fig. 2.

Methodological quality assessment

A methodological quality assessment was done on the included studies using the critical appraisal tools of the Joanna Briggs Institute [24]. For each study design, the appropriate critical appraisal tool was used. Answers that could be given were yes, no, unclear and not applicable. If the answer was 'yes', two points were assigned and 'no or unclear' resulted in no points. A minimum of 12 points was the lower bound to be included in the review. The details of the critical appraisal of the included articles are presented in Table 6 of Appendix 2.

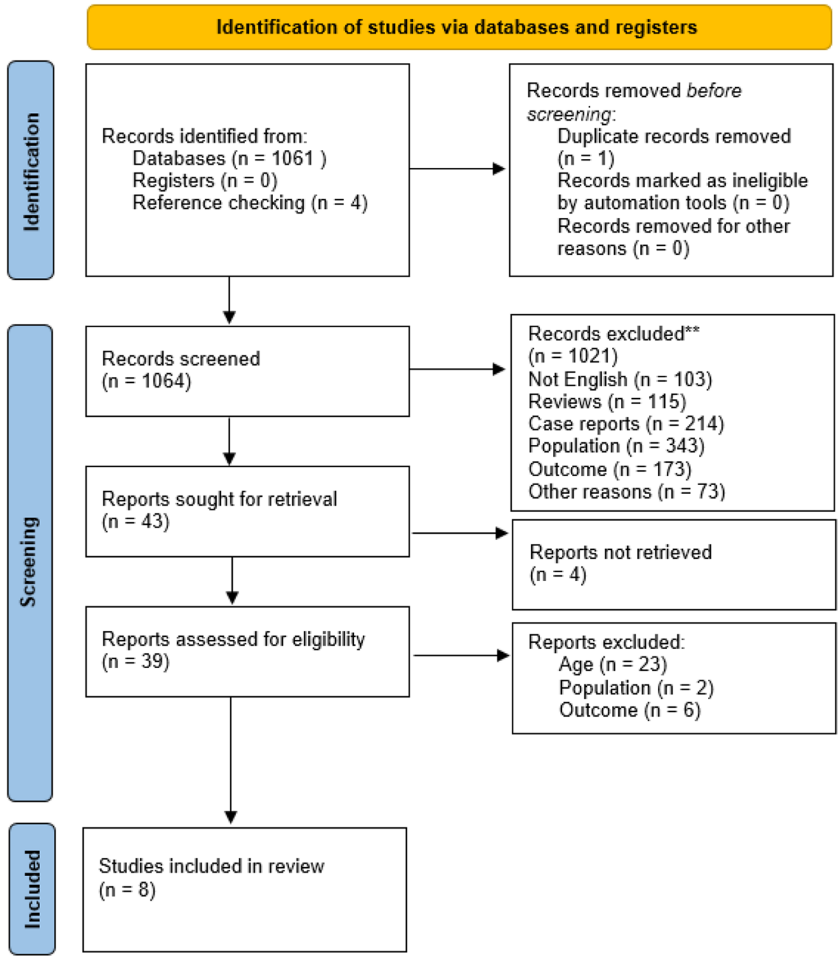

Fig. 1 PRISMA 2020 flow diagram for systematic reviews [36]

Results

A total of 1062 articles were identified, of which 8 articles met the eligibility criteria (see Fig. 1). Only two studies were prospective cohort studies [25, 26]; all other were retrospective cohort studies [27–32]. The number of patients included in these studies differed from 31 to 145 per study. Overall, 512 patients were included. In the included patients, 871 pelvic fractures were detected in 392 patients. Most of the included patients were female ($n = 391$, 76%). The mean age of the patients included in the articles ranged from 61 to 81. Almost all fractures were caused by a low-energy trauma ($n = 311$, 95%). Details of the patient population in the included studies can be found in Table 1.

Additional fracture detection

CT vs. MRI

All eight articles reported on the incidence of additional pelvic fractures found on MRI compared to conventional CT (Table 2). In 10–54% of the patients, additional fractures were found on MRI. This resulted in an increase of 21–40% of the total number of fractures. These additional fractures were almost all fractures in the posterior pelvic ring ($n = 156$, 84%).

CT vs. DECT

Only two studies reviewed the incidence of additional pelvic fractures on DECT compared to conventional CT (Table 3). They found that 10–57% of the patients showed additional sacral fractures on DECT imaging compared to conventional CT imaging. This resulted in an increase of 23–65% of the number of pelvic fractures.

MRI vs. DECT

The same two studies reviewed the incidence of additional pelvic fractures seen on DECT imaging compared to MRI (Table 3). Palm et al. found no difference between MRI and DECT. Booz et al. reported one additional patient with bone marrow oedema found on DECT [29, 31]. A minimum of 43 and maximum of 52 zones with bone marrow oedema were found on DECT compared to 39 zones on MRI. Booz et al. considered all areas

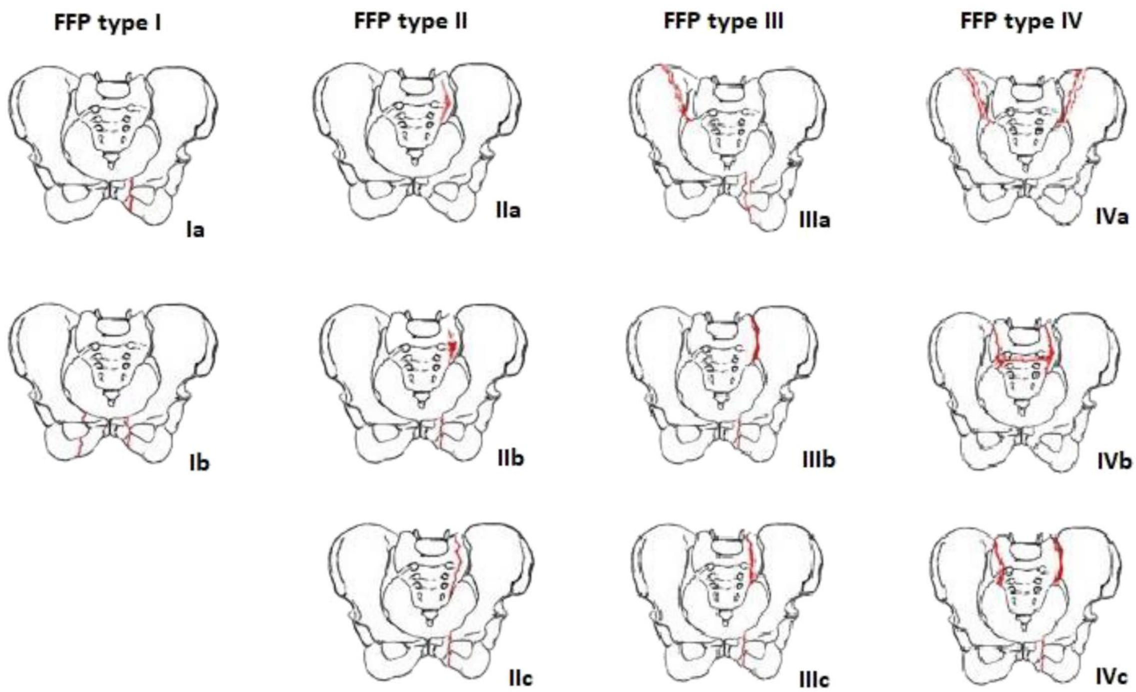

Fig. 2 Rommens and Hofmann classification [22]

with bone marrow oedema detected in their series to be sacral insufficiency fracture (SIF) associated bone marrow oedema. Palm et al. regarded all bone marrow oedema sites as fractures.

Diagnostic accuracy

The overall sensitivity of conventional CT imaging for pelvic fracture detection compared to the standard of reference ranged from 71 to 90%, and for fractures of the posterior ring between 67 and 88% (see Table 4). The overall sensitivity of DECT compared to the standard of reference was 93–100%, which is similar to MRI (96–100%). Compared with conventional CT imaging, DECT and MRI had greater diagnostic accuracy in detecting posterior pelvic ring fractures.

Change of classification

Four studies report on how an additional MRI after a conventional CT would influence the Rommens classification of these fracture patterns (see Table 5). Overall, in 61 patients (29%), this resulted in a change of classification. On conventional CT imaging, the most common fracture pattern was Rommens type 2, which is a unilateral fracture. After MRI, we see a decrease in the incidence of isolated anterior ring fractures (Rommens type 1) and increase of bilateral combined posterior and anterior fractures (Rommens type 4) to 50% (see Fig. 3).

Three articles report in detail on how the fracture patterns changed after additional MRI in 45 patients in total [27, 29, 30], as shown in Table 4. The six patients without fractures on conventional CT all appeared to have posterior fractures on MRI: 4 unilateral (Rommens type 2) and 2 bilateral (Rommens type 4). All the 17 patients with isolated anterior fractures (Rommens type 1) on CT appeared to have additional posterior fractures on MRI, of which 76% ($n=13$) were unilateral and 24% ($n=4$) bilateral. The 15 patients who were classified as type 2 prior to MRI all had bilateral posterior injuries (Rommens type 4) instead of unilateral.

Palm et al. reported on how an additional DECT after conventional CT would influence a change of the Rommens classification [29]. Of the patients, 35% ($n=16$) changed to a more severe type, which is similar to the results of the patients who received an MRI in the same study [29] (see Fig. 4). Of these patients, two (13%) changed from no fracture or isolated anterior fracture to bilateral posterior fractures (Rommens type 4), and eight (50%) changed from unilateral posterior to bilateral posterior fracture patterns (Rommens type 4).

Change of therapy

Graul et al. and Hackenbroch et al. reported on the number of patients that had a change of therapy after additional MRI (Table 3) [27, 30]. Of the patients who had a change of classification, only 22–33% received a different type of treatment. Graul et al. reported that 6 of the 21 patients

Table 1 Details of included studies and study population

Author, year	Comparison	Study design	Imaging interval	Population	Overall (M/F)	Pt with Fx	Fx	Mean age	LET	HET
Cabarrus et al. 2008 [32]	CT vs. MRI	RCS	CT + MRI < 3 m	Pelvic insufficiency fractures	145 (41/104)	64	103	66	NA	NA
Graul et al. 2020 [27]	CT vs. MRI	RCS	MRI < 4w after CT	Fragility fracture of the pelvis and no adequate trauma	67 (13/54)	67	165	80	67	0
Graul et al. 2021 [28]	CT vs. MRI	RCS	CT + MRI < 6 m	Sacral fracture and no adequate trauma	77 (14/63)	77	182	76	77	0
Hackenbroch et al. 2020 [30]	CT vs. MRI	RCS	MRI < 3w after CT	Acetabular and/or pelvic ring fracture	31 (9/22)	31	NA	81	22	9
Henes et al. 2012 [25]	CT vs. MRI	PCS	MRI < 1w after CT	Acute pelvic fracture	38 (7/31)	38	122	75	NA	NA
Nüchtern et al. 2015 [26]	CT vs. MRI	PCS	MRI < 1w after CT	Anterior pelvic fracture on Xray	56 (7/49)	56	170	75	47	9
Booz et al. 2020 [31]	CT vs. MRI vs. DECT	RCS	MRI + DECT < 1w	Acute low back pain and no adequate trauma	52 (24/28)	28	52	61	52	0
Palm et al. 2020 [29]	CT vs. MRI vs. DECT	RCS	MRI + DECT < 2w after CT	Suspected fragility fracture of the pelvis	46 (6/40)	31	77	79	46	0

M = male, F = female, Pt = patient, Fx = fracture, LET = low energy trauma, HET = high energy trauma, RCS = retrospective cohort study, PCS = prospective cohort study, m = month, w = weeks, NA = data not available

whose classification changed switched from conservative to operative treatment, and one patient switched from unilateral to bilateral surgical fixation. Both patients reported by Hackenbroch et al. switched from conservative to operative treatment [30]. There was no information available on the influence of DECT on the change of therapy.

Discussion

This review suggests that MRI and DECT scans are superior in diagnosing FFPs compared to conventional CT and have similar diagnostic accuracy for posterior pelvic fracture detection.

Compared to conventional CT imaging, in up to 54% of the patients additional pelvic fractures can be found on MRI and 57% on DECT. Almost all additional fractures were vertical sacral fractures. It is noteworthy that 63% of all the patients that changed classification changed to Rommens type 4 after MRI or DECT. Fifty percent of the patients who changed classification after MRI or DECT went from unilateral to bilateral posterior fracture patterns (Rommens type 4), and 13% even went from no fracture or isolated anterior fracture to Rommens type 4. This suggests that the incidence of pelvic fragility fractures and the extent of the fracture patterns are underestimated in current practice.

After additional MRI, 21–36% of the total number of patients appeared to have a more severe fracture pattern. A change of therapy was advised in 22–33% of these patients. The reason for not changing therapy despite the increase in severity of the fracture pattern was not provided by the included articles.

Although MRI appears to be superior to conventional CT in terms of diagnostic accuracy, it is unlikely that MRI will become the gold standard in clinical practice. MRI is more expensive to use on a daily basis, may not be available at all times when needed, and there is less patient comfort because of longer scanning times. In addition, MRI is contraindicated in patients who have implants or other medical devices which are incompatible with the MRI, which is more prevalent in older adult patients. However, if a physician decides to use MRI specifically to detect FFPs, they should consider using an abbreviated MRI protocol comprising only coronal T1 and coronal short tau inversion recovery (STIR) images. In older adults, an abbreviated MRI protocol has a sensitivity of 92% and a specificity of 98%, and saves 20 min of scanning time compared to the complete protocol [33]. The reduced time in the scanner may result in less motion artefacts in patients with acute pain and provide images that better correspond to reality [33]. Furthermore, if an occult pelvic fracture is suspected and MRI is not readily available, it is beneficial to perform region-of-interest-based Hounsfield units (HU)

Table 2 Details of additional fracture detection by MRI compared to conventional CT

Author, year	Comparison	Additional fracture detection by MRI			
		per Pt	per Fx	Distribution per Pt	Distribution per Fx
Cabarrus et al. 2008 [32]	CT vs. MRI	30/64 (47%)	29/103 (28%)	NA	Sacrum: 17/29 (59%)
					Os Ilium: 2/29 (7%)
					Os pubis: 10/29 (34%)
Graul et al. 2020 [27]	CT vs. MRI	NA	45/165 (27%)	NA	Sacrum: 38/45 (84%)
					Os pubis: 7/45 (16%)
Graul et al. 2021 [28]	CT vs. MRI	9/77 (12%)	48/182 (26%)	NA	Sacrum: 48/48 (100%)
Hackenbroch et al. 2020 [30]	CT vs. MRI	9/31 (41%)		NA	NA
Henes et al. 2012 [25]	CT vs. MRI	NA	25/122 (21%)	NA	Sacrum: 12/25 (48%)
					Anterior ring: 13/25 (52%)
Nüchtern et al. 2015 [26]	CT vs. MRI	8/48 (17%)*	NA	Posterior ring: 8/48 (17%)	NA
Booz et al. 2020 [31]	CT vs. MRI	15/28 (54%)	21/52 (40%)	Sacrum: 15/15 (100%)	Sacrum 21/21 (100%)
Palm et al. 2020 [29]	CT vs. MRI	3/31 (10%)	18/77 (23%)	Sacrum: 3/3 (100%)	Sacrum: 18/18 (100%)

Pt = patient, Fx = fracture, NA = data not available

*only data on posterior fractures available

Table 3 Details of additional fracture detection by DECT compared to conventional CT and MRI

Author, year	Comparison	Additional fracture detection by MRI			
		per Pt	per Fx	Distribution per Pt	Distribution per Fx
Booz et al. 2020 [31]	CT vs. DECT	16/28 (57%)	34/52 (65%)	Sacrum: 16/16 (100%)	Sacrum: 34/34 (100%)
	MRI vs. DECT	1/28 (4%)	13/52 (25%)	Sacrum: 1/1 (100%)	Sacrum: 13/13 (100%)
Palm et al. 2020 [29]	CT vs. DECT	3/31 (10%)	18/77 (23%)	Sacrum: 3/3 (100%)	Sacrum: 18/18 (100%)
	MRI vs. DECT	No difference	No difference	No difference	No difference

Pt = patient, Fx = fracture

measurements on conventional CT to improve fracture detection. Henes et al. found that quantitative HU measurements achieved a diagnostic accuracy of 93.9% compared to visual evaluation for the depiction of occult sacral insufficiency fractures [34].

This review shows that DECT is a promising new imaging modality for the detection of pelvic fractures. By combining two separate X-ray photon energy spectra, this imaging modality has similar sensitivity and specificity as MRI for fracture and bone marrow oedema detection. The potential of DECT has already been recognised for other fractures, like spine fractures, where DECT showed an accuracy of 89% in detecting bone marrow and disc oedema [35]. Furthermore, DECT is fast and availability is less of an issue than in MRI scanning. One pitfall of DECT is that it does not differentiate between oedematous bone marrow and haematopoietic bone marrow, which might be problematic in young patients with 'blood-rich' bone marrow but should not lead to false positives on our older adult patient population with pelvic fragility fractures [36]. Although dual energy spectral imaging might not currently be available in all hospitals, this imaging modality is expected to be more widespread available when hospitals need to replace their old CT scanners.

Strengths and limitations

This is, to the best of our knowledge, the first review to provide clinically relevant information on the value of different advanced imaging modalities in the detection of pelvic fractures in older patients.

Based on the results of this review, further cross-sectional research is necessary to determine how MRI and DECT influence the classification and treatment of pelvic fractures in the elderly. Since the threshold for

Table 4 Details of the standard of reference and diagnostic accuracy of the different imaging modalities

Author, year	Comparison	Standard of reference	Diagnostic accuracy	
			Overall	Posterior ring
Cabarrus et al. 2008 [32]	CT vs. MRI	Clinical Hx, findings from all imaging studies, and F/U imaging	CT: 75% sens	CT: 67% sens
			MRI: 100% sens	MRI: 100% sens
Graul et al. 2020 [27]	CT vs. MRI	Positive screening in at least one of the imaging modalities	CT: 73% sens	NA
			MRI: 100% sens	
Graul et al. 2021 [28]	CT vs. MRI	Positive screening in at least one of the imaging modalities	NA	CT: 88% sens
				MRI: 100% sens
Hackenbroch et al. 2020 [30]	CT vs. MRI	Unavailable	NA	NA
Henes et al. 2012 [25]	CT vs. MRI	Clinical Hx, findings from all imaging studies, and F/U imaging	MRI: 96% sens, 99% spec	MRI: 99% sens, 100% spec
Nüchtern et al. 2015 [26]	CT vs. MRI	Consensus meeting with radiologists and orthopaedic surgeons	CT: 71% sens	CT: 83% sens, 92% spec
			MRI: 99% sens	MRI: 99% sens
Booz et al. 2020 [31]	CT vs. MRI vs. DECT	SIF-associated bone marrow oedema on MRI	DECT: 93% sens, 95% spec	NA
Palm et al. 2020 [29]	CT vs. MRI vs. DECT	SIF-associated bone marrow edema on MRI	CT: 90% sens, 100% spec	CT: 68% sens, 100% spec
			MRI: 100% sens, 100% spec	MRI: 100% sens, 100% spec
			DECT: 100% sens, 100% spec	DECT: 100% sens, 100% spec

**Hx = history, F/U = follow-up, SIF = sacral insufficiency fracture, sens = sensitivity, spec = specificity, NA = data not available*

Table 5 Details of the change of classification and change therapy of the different imaging modalities

Author, year	Comparison	Change of classification		Change of therapy
		Rommens	AO	
Cabarrus et al. 2008 [32]	CT vs. MRI	NA	NA	NA
Graul et al. 2020 [27]	CT vs. MRI	MRI: 21/67 (31%)	NA	7/21 (33%)
Graul et al. 2021 [28]	CT vs. MRI	MRI: 16/77 (21%)	NA	NA
Hackenbroch et al. 2020 [30]	CT vs. MRI	MRI: 8/22 (36%)	MRI: 1/9 (11%)	2/9 (22%)
Henes et al. 2012 [25]	CT vs. MRI	NA	MRI: 7/38 (18%)	NA
Nüchtern et al. 2015 [26]	CT vs. MRI	NA	NA	NA
Booz et al. 2020 [31]	CT vs. MRI vs. DECT	NA	NA	NA
Palm et al. 2020 [29]	CT vs. MRI vs. DECT	MRI: 16/46 (35%)	NA	NA
		DECT: 16/46 (35%)		

** NA = data not available*

surgical intervention of pelvic fragility fractures has been lowered the last few years, this might affect the current findings of this review.

The included studies used different CT, MRI and DECT scanners and protocols, which may have caused information bias. In addition, the retrospective data collected in

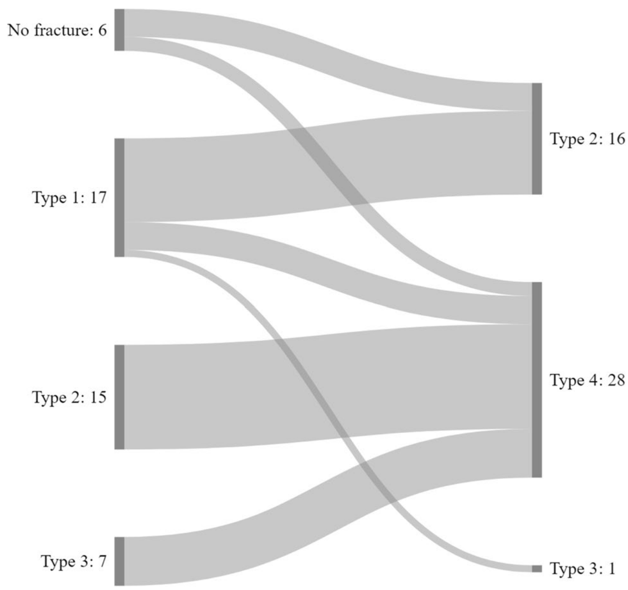

Fig. 3 How does the Rommens classification on conventional CT change after additional MRI

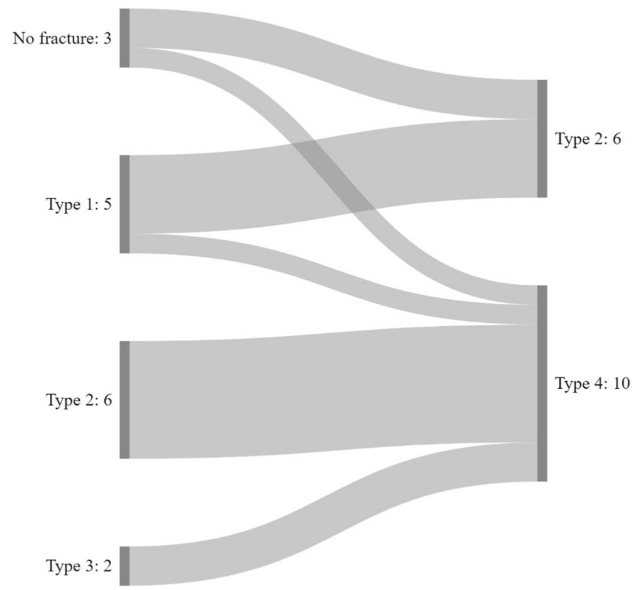

Fig. 4 How does the Rommens classification on conventional CT change after additional DECT

different type of populations makes this review vulnerable for selection bias. Although our primary goal was to evaluate the value of CT, MRI and DECT in the diagnosis of pelvic fragility fractures, we included two studies that described 18 fractures in older adults caused by high-energy trauma, which are not specifically fragility fractures [26, 30]. Two of the included articles allow a relatively long interval of several months between imaging modalities [28, 32]. Fracture progression, e.g. a progress of instability due to increased fracture displacement or the appearance of additional fractures, is reported in 14% of all conservatively treated FFPs [37]. Taking this into consideration, some of the additional fractures detected on the advanced imaging in these two studies might be due to fracture progression and not a lack of diagnostic accuracy of the imaging modalities, resulting in false positives.

Conclusion

Comparing DECT and MRI to conventional CT scanning, additional fractures in rates up to 57% and 54% can be found, respectively. DECT and MRI showed very similar results in terms of sensitivity and specificity for posterior pelvic fracture detection. After additional MRI, up to 36% of the patients appear to have a more severe fracture pattern, of which 63% changed to the most severe fracture pattern type (Rommens type 4). In 30% of the patients who changed of fracture classification, a change of therapy was advised. This review suggests that MRI and DECT scans are superior in diagnosing FFPs compared to conventional CT scan; however, cross-sectional studies are warranted to evaluate the clinical implications.

Appendix 1

Literature search

"Osteoporotic Fractures/diagnostic imaging"[MAJR] OR (pelvic fragility fracture*[tiab] OR pelvic fracture*[tiab]) OR fragility fracture of the pelvis*[tiab] OR fragility fracture of the pelvi*[tiab] OR pelvic ring trauma[tiab] OR sacral insufficiency fracture*[tiab] OR osteoporotic pelvic fracture*[tiab] OR pelvic fracture in the elderly*[tiab] OR diagnostic imaging of osteoporotic fracture*[tiab].

AND

"Tomography, X-Ray Computed"[Mesh] OR (X-Ray Computed Tomography*[tiab] OR CT Scan*[tiab] OR Computed X-Ray Tomography*[tiab] OR CT X Ray*[tiab].

OR

"Radiography, Dual-Energy Scanned Projection"[Mesh] OR "Absorptiometry, Photon"[Mesh] OR (dual energy CT*[tiab] OR dual energy computed tomograph*[tiab] OR dual energy scanned projection*[tiab].

OR

"Magnetic Resonance Imaging"[Mesh] OR (Imaging, Magnetic Resonance*[tiab] OR Image, Magnetic Resonance*[tiab] OR MRI Scan*[tiab].

Appendix 2

Table 6 JBI critical appraisal tool for cohort studies for use in systematic reviews [37]

Author	Design	Score based JBI appraisal											Overall appraisal
		1	2	3	4	5	6	7	8	9	10	11	
Henes et al. 2012 [25]	PCS	Y	Y	Y	Y	Y	Y	Y	N	U	U	Y	Included
Nüchtern et al. 2015 [26]	PCS	Y	Y	Y	N	N	Y	Y	N	U	U	Y	Included
Booz et al. 2020 [31]	RCS	Y	Y	Y	Y	N	Y	Y	N	U	U	Y	Included
Cabarrus et al. 2008 [32]	RCS	Y	N	Y	Y	Y	Y	Y	N	U	U	Y	Included
Graul et al. 2020 [27]	RCS	Y	N	Y	Y	Y	Y	Y	N	U	U	Y	Included
Graul et al. 2021 [28]	RCS	Y	Y	Y	Y	N	Y	Y	N	U	U	Y	Included
Hackenbroch et al. 2020 [30]	RCS	Y	N	Y	Y	N	Y	Y	N	U	U	Y	Included
Palm et al. 2020 [29]	RCS	Y	Y	Y	N	N	Y	Y	N	U	U	Y	Included

Data Availability The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Declarations

Conflicts of interest AHM Mennen received the Amsterdam UMC Doctoral School PhD Scholarship. AS Blokland, M Maas and D van Embden declare that they have no conflict of interest.

References

1. Kannus P et al (2000) Epidemiology of osteoporotic pelvic fractures in elderly people in Finland: sharp increase in 1970–1997 and alarming projections for the new millennium. Osteoporos Int 11(5):443–448
2. Boufous S et al (2005) The increasing burden of pelvic fractures in older people, New South Wales. Australia Injury 36(11):1323–1329
3. Behanova M et al. (2022) Pelvic fractures-an underestimated problem? Incidence and mortality risk after pelvic fracture in Austria, 2010–2018. J Clin Med 11(10)
4. Breuil V et al (2008) Outcome of osteoporotic pelvic fractures: an underestimated severity. Survey of 60 cases. Joint Bone Spine 75(5):585–8
5. Wilson DGG, Kelly J, Rickman M (2021) Operative management of fragility fractures of the pelvis - a systematic review. BMC Musculoskelet Disord 22(1):717
6. Wagner D et al (2015) Fragility fractures of the sacrum: how to identify and when to treat surgically? Eur J Trauma Emerg Surg 41(4):349–362
7. Hemenway D et al (1994) The incidence of stairway injuries in Austria. Accid Anal Prev 26(5):675–679
8. Startzell JK et al (2000) Stair negotiation in older people: a review. J Am Geriatr Soc 48(5):567–580
9. Studer P et al (2013) Pubic rami fractures in the elderly—a neglected injury? Swiss Med Wkly 143:w13859
10. Booth A et al (2019) Effectiveness of surgical fixation for lateral compression type one (LC-1) fragility fractures of the pelvis: a systematic review. BMJ Open 9(5):e024737
11. Rommens PM, Wagner D, Hofmann A (2017) Minimal invasive surgical treatment of fragility fractures of the pelvis. Chirurgia (Bucur) 112(5):524–537
12. Qoreishi M, SeyyedHosseinzadeh HR, Safdari F (2019) Clinical results of percutaneous fixation of pelvic and acetabular fractures: a minimally invasive internal fixation technique. Arch Bone Jt Surg 7(3):284–290
13. Eckardt H et al (2017) Good functional outcome in patients suffering fragility fractures of the pelvis treated with percutaneous screw stabilisation: assessment of complications and factors influencing failure. Injury 48(12):2717–2723
14. Chen JP et al (2022) Percutaneous iliosacral screw and trans-iliac trans-sacral screw with single C-arm fluoroscope intensifier is a safe treatment for pelvic ring injuries. Sci Rep 12(1):368
15. Scheyerer MJ et al (2012) Detection of posterior pelvic injuries in fractures of the pubic rami. Injury 43(8):1326–1329
16. Schicho A et al (2016) Pelvic X-ray misses out on detecting sacral fractures in the elderly - importance of CT imaging in blunt pelvic trauma. Injury 47(3):707–710
17. Verbeeten KM et al (2005) The advantages of MRI in the detection of occult hip fractures. Eur Radiol 15(1):165–169
18. Haubro M et al (2015) Sensitivity and specificity of CT- and MRI-scanning in evaluation of occult fracture of the proximal femur. Injury 46(8):1557–1561
19. Marongiu G et al (2018) The impact of magnetic resonance imaging in the diagnostic and classification process of osteoporotic vertebral fractures. Injury 49(Suppl 3):S26–S31
20. Mendel T et al (2021) Progressive instability of bilateral sacral fragility fractures in osteoporotic bone: a retrospective analysis of X-ray, CT, and MRI datasets from 78 cases. Eur J Trauma Emerg Surg 47(1):11–19
21. Moher D et al (2010) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Int J Surg 8(5):336–341
22. Rommens PM, Hofmann A (2013) Comprehensive classification of fragility fractures of the pelvic ring: recommendations for surgical treatment. Injury 44(12):1733–1744
23. Marsh JL et al (2007) Fracture and dislocation classification compendium - 2007: Orthopaedic Trauma Association classification, database and outcomes committee. J Orthop Trauma 21(10 Suppl):S1-133
24. Institute JB (2020) Critical appraisal tools. [cited 2022 10 october]; Available from: https://jbi.global/critical-appraisal-tools
25. Henes FO, Nüchtern JV, Groth M, Habermann CR, Regier M, Rueger JM, Adam G, Großterlinden LG (2012) Comparison of diagnostic accuracy of magnetic resonance imaging and multidetector computed tomography in the detection of pelvic fractures. Eur J Radiol 81(9):2337–2342. https://doi.org/10.1016/j.ejrad.2011.07.012
26. Nüchtern JV, Hartel MJ, Henes FO, Groth M, Jauch SY, Haegele J, Briem D, Hoffmann M, Lehmann W, Rueger JM, Großterlinden LG (2015) Significance of clinical examination, CT and MRI scan in the diagnosis of posterior pelvic ring fractures. Injury 46(2):315–319. https://doi.org/10.1016/j.injury.2014.10.050
27. Graul I, Marintschev I, Hackenbroch C, Palm HG, Friemert B, Lang P (2020) Modified therapy concepts for fragility fractures of the pelvis after additional MRI. PLoS One 15(10):e0238773. https://doi.org/10.1371/journal.pone.0238773
28. Graul I, Vogt S, Strube P, Hölzl A (2021) Significance of lumbar MRI in diagnosis of sacral insufficiency fracture. Global Spine J 11(8):1197–1201. https://doi.org/10.1177/2192568220941821
29. Palm HG, Lang P, Hackenbroch C, Sailer L, Friemert B (2020) Dual-energy CT as an innovative method for diagnosing fragility fractures of the pelvic ring: a retrospective comparison with MRI as the gold standard. Arch Orthop Trauma Surg 140(4):473–480. https://doi.org/10.1007/s00402-019-03283-8
30. Hackenbroch C, Merz C, Palm HG, Friemert B, Stuby F, Lang P; AG Becken III der DGU® (2020) Magnetic Resonance imaging in pelvic fractures - part 2: gaining information and clinical therapeutic relevance. Z Orthop Unfall 158(4):360–368. English, German. https://doi.org/10.1055/a-0965-7686
31. Booz C, Nöske J, Albrecht MH, Lenga L, Martin SS, Bucher AM, Huizinga NA, Wichmann JL, Vogl TJ, Yel I (2020) Diagnostic accuracy of color-coded virtual noncalcium dual-energy CT for the assessment of bone marrow edema in sacral

insufficiency fracture in comparison to MRI. Eur J Radiol 129:109046. https://doi.org/10.1016/j.ejrad.2020.109046
32. Cabarrus MC, Ambekar A, Lu Y, Link TM (2008) MRI and CT of insufficiency fractures of the pelvis and the proximal femur. AJR Am J Roentgenol 191(4):995–1001. https://doi.org/10.2214/AJR.07.3714
33. Ross AB et al (2019) Diagnostic accuracy of an abbreviated MRI protocol for detecting radiographically occult hip and pelvis fractures in the elderly. Skeletal Radiol 48(1):103–108
34. Henes FO et al (2012) Quantitative assessment of bone marrow attenuation values at MDCT: an objective tool for the detection of bone bruise related to occult sacral insufficiency fractures. Eur Radiol 22(10):2229–2236
35. Bäcker HC et al (2021) Dual-energy computed tomography in spine fractures: a systematic review and meta-analysis. Int J Spine Surg 15(3):525–535
36. Hackenbroch C et al (2017) Dual energy CT - a novel technique for diagnostic testing of fragility fractures of the pelvis. Z Orthop Unfall 155(1):27–34
37. Rommens PM et al (2019) Progress of instability in fragility fractures of the pelvis: an observational study. Injury 50(11):1966–1973