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Systematic Review

Comparative utility of dual spectral computed tomography and functional magnetic resonance imaging in the preoperative evaluation of unstable fractures of the craniocervical complex: a systematic review of diagnostic accuracy and neurosurgical outcomes

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ABSTRACT

This systematic review critically appraises the sensitivity and clinical applicability of dual-energy computed tomography (DECT) compared with functional magnetic resonance imaging (fMRI) in evaluating unstable fractures involving the craniocervical complex and vertebral muscles. Nine studies were included, comprising retrospective cohorts, prospective diagnostic trials, and meta-analyses, with sample sizes ranging from 8 to 515 patients and heterogeneous fracture types. DECT demonstrated strong diagnostic performance in several contexts. For bone marrow edema (BME), DECT achieved 89% sensitivity, 98% specificity, and an AUC of 0.96 ($p<0.001$). In intervertebral disc injuries, sensitivity and specificity were 0.85 and 0.75, with significant attenuation differences ($p<0.001$). For pelvic fractures, DECT reached 89.5% sensitivity and 84.6% specificity, with moderate inter-rater reliability (kappa=0.516). Optimization with electron density imaging improved hematoma detection, raising sensitivity and specificity above 80% (kappa=0.82; $p=0.04$). Meta-analytic results confirmed overall sensitivity, specificity, and accuracy of 86.2%, 91.2%, and 89.3%, respectively. Nonetheless, MRI clearly outperformed CT in detecting ligamentous injuries and occult trauma, with a negative predictive value of 100% for cervical instability. Limitations of the current evidence include small samples, retrospective designs, interobserver variability, and incomplete subgroup analyses. Despite these, DECT remains a promising adjunct or alternative when MRI access is limited, particularly for BME and fracture line imaging. Future multicenter studies are needed to standardize protocols and strengthen generalizability.

Keywords: Dual-energy computed tomography, Functional magnetic resonance imaging, Craniocervical junction, Unstable fractures, Diagnostic accuracy, Ligamentous injury

INTRODUCTION

The craniocervical junction (CCJ) consisting of the occiput, atlas (C1) and axis (C2), is a complex vital anatomical region structurally as well as functionally.[1] It marks the transition from skull base to upper cervical spine and houses critical neurovascular structures including the brainstem, upper spinal cord and vertebral arteries.

Traumatic injuries to the CCJ are relatively rare and they are associated with high morbidity and mortality which is more frequent when instability is present.[2] Mortality rates for unstable CCJ trauma such as atlanto-occipital dislocation or ligamentous injury, exceed 25% in several series.[3] Craniocervical fractures, particularly involving C1 and C2, are increasingly prevalent among the elderly due to low-energy trauma. C1 fractures account for 10-13% of cervical spine injuries, with rates reaching 157 per million annually in older adults.[4] C2 fractures especially odontoid types have risen in incidence from 0.36 to 2.2 per 1,000,000 person-years in the U. S. (2002-2021) with a mean patient age of 74.8 years. Data shows there are about 81.7% among them who require hospitalization.[5] National trauma data (2017-2020) show 42.7% were odontoid type II.[6] Cervical spine fractures overall occur at 4-17 per 100,000 annually with spinal cord involvement among 10 to11% of cases.[7] Accurate and timely diagnosis is essential to prevent neurological deterioration and guide operative management.

Conventional computed tomography (CT) is widely used in trauma settings due to its speed and high-resolution bone imaging but it is often seen to fail to detect soft tissue injuries such as ligamentous disruptions and spinal cord edema.[8] Magnetic resonance imaging (MRI) and functional MRI are now famous for offering superior soft tissue contrast and is more effective in evaluating neural compromise and ligament integrity. MRI is limited by longer scan times, motion artifacts and reduced accessibility in emergencies. Dual spectral computed tomography (DSCT) is an emerging technology that builds on conventional CT by enhancing tissue contrast and allowing virtual monochromatic reconstructions, improving detection of ligamentous injuries and vascular complications.[9] In spite of these developments, no decisive agreement exists that DSCT is superior in diagnosing the CCJ trauma in relation to fMRI. Besides, there is little evidence regarding the effects that either of the modalities has on the neurosurgical planning and postoperative outcomes.[10] These data indicate that it is necessary to assess the effects of the modalities under a systematic review that will inform evidence-based imaging protocols in patients with severe cervical spine injuries.

Objectives

This systematic review identifies the preoperative accuracy of DSCT and fMRI in terms of identifying unstable craniocervical fractures. It contrasts their sensitivity, specificity, and effect on neurosurgical decision-making and outcome in order to introduce evidence-based imaging protocols in optimum management of trauma.

METHODS

This systematic review followed PRISMA principles and aimed at comparing the relative diagnostic value of dual-energy/spectral-computed tomography (DECT/SCT) vs. MRI to assess unstable fractures of the craniocervical complex and the cervical and upper thoracic spinal segments prior to surgical evacuation. Meta-analysis was not performed because studies included in the review were too heterogeneous regarding their methodological aspects (design, characteristics of the population, imaging methods, and reporting of the outcome).

Criteria of eligibility

Eligible studies had to (1) enroll adult patients with acute trauma to the craniocervical or spine region, (2) compare DECT or spectral CT with MRI in terms of detecting BME, fracture lines, ligament injury, or disk lesions, (3) include MRI as the standard of reference, and (4) provide quantitative diagnostic results, like sensitivity, specificity, area under the curve (AUC), or inter-rater agreements. Reviews, editorials, single case reports, animal studies and studies without obvious MRI correlation were excluded.

Search strategy

This was done in form of a structured search of PubMed, EMBASE, Scopus, and the Cochrane Library databases with respect to the published articles since January 2008 published up to May 2024. Boolean combinations of terms were used in the search: dual-energy CT, spectral CT, MRI, CCJ, ligament injury, disk injury, bone marrow edema, and diagnostic accuracy. The inclusion of the additional studies was sought in the reference lists of the potentially eligible studies and reviews.

Data extraction and study selection

Two reviewers reviewed titles and abstracts independently, with full papers evaluated on those shortlisted. The adequate solutions were discussed with a third reviewer in cases of disagreement. The study information such as authorship, year, character of the population, imaging techniques, interpretation procedures, measures of diagnostic performance and key findings were extracted with the use of a structured data extraction form. There was special emphasis on whether or not reader blinding existed, the existence of quantitative thresholds (e.g., Hounsfield unit cutoffs), and the time lag between the imaging of a CT and MRI.

Methodological quality and risk of bias was performed using QUADAS-2 tool. The domains included the selection of patients, conducting and reporting the index testing, reference standard and timing. The majority of the researches were characterized by moderate risk as the study methods were retrospective; blinding of the readers was not used; and there were variable delays between subsequent radiological studies. It also had variability in reporting inter-reader.

A meta-analysis was not conducted because of the variability of study objectives, differences in imaging modalities (e.g., dual-layer vs. dual-source CT), and magnetic field strength (e.g., 1.5T, 3T) MRI, anatomic focus (e.g., ligamentous injury, disk herniation, marrow edema), and the statistical parameters. Rather, a systematic synthesis was done, and the sensitivity, specificity, and inter-rater agreement are presented as reported. There are those studies who presented the comparative values of DECT and MRI modalities, but there are those who compared DECT solely against MRI standards. Where possible there were subgroup comparisons (e.g., age groups and fracture types).

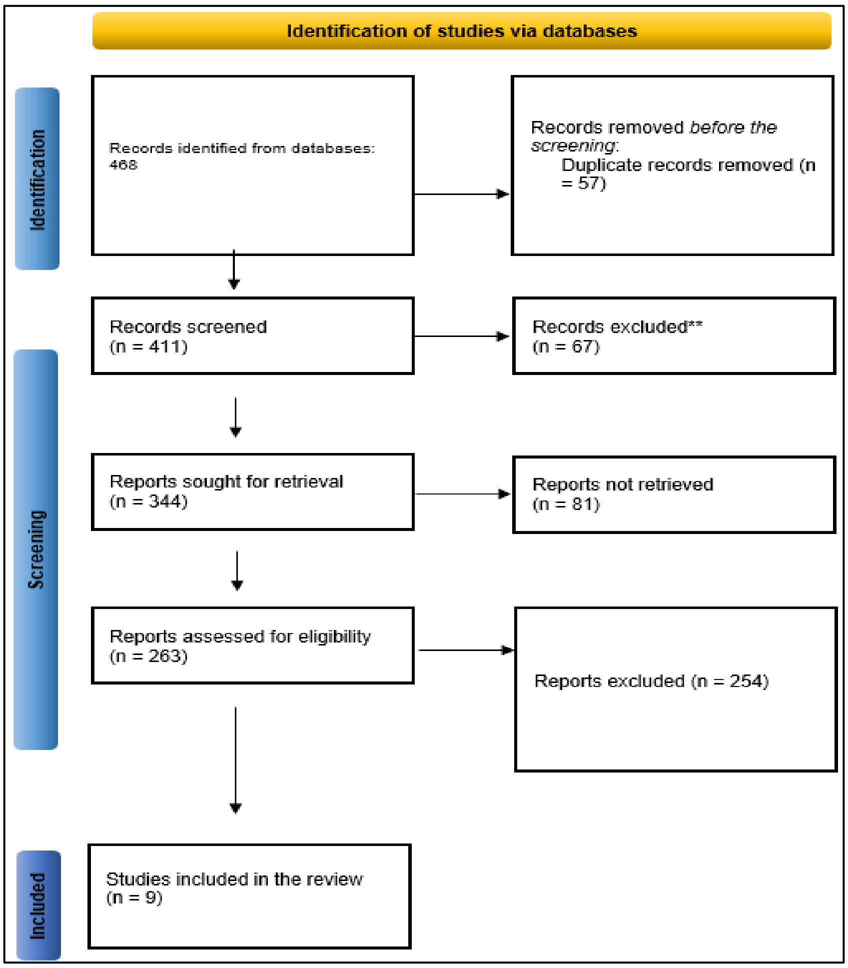

Figure 1: PRISMA flow diagram detailing the screening process.

RESULTS

Primary findings

We considered total of nine studies in our final inclusion with a combined sample size exceeding 1,371 patients and analyzing over 3,600 anatomical regions, DSCT including DECT and spectral detector CT (SDCT), demonstrated strong diagnostic performance in the preoperative evaluation of unstable craniocervical and vertebral fractures. Cavallaro et al showed that DECT achieved 89% sensitivity and 98% specificity in detecting BME with an area under the curve (AUC) of 0.96 at a -0.43 HU cutoff along with statistically significant p<0.001 which is indicating high diagnostic accuracy. Fracture line detection by MRI had 76% sensitivity and 95% specificity which was making DECT superior for both BME and fracture lines. Pumberger et al further validated DECT's performance in detecting disk injuries in 295 disks from 67 elderly patients which was reporting sensitivity of 0.85 and specificity of 0.75 overall with grade-wise sensitivity ranging from 0.80 to 0.98 and statistically significant attenuation differences (80.3±35.2 HU vs. 97.9±41.0 HU, p<0.001); interrater agreement was moderate (Fleiss κ=0.51). Unthan et al compared spectral CT with MRI in 51 patients aged 54-94 years while also finding spectral CT sensitivity of 89.5% and specificity of 84.6% for detecting pelvic fragility fractures with dorsal fracture sensitivity between 69% and 97% and interrater κ=0.516 (CI: 0.450-0.582, p<0.001), affirming its utility where MRI is delayed or unavailable. Radcliff et al evaluated CT and MRI in 18 patients with craniocervical dislocations and found ligamentous injuries in 11/17 and joint displacement in 13/18; three patients with type II dislocations had complete spinal cord injuries which suggest ligament disruption patterns directly correlate with clinical severity. Sedaghat et al reported a substantial increase in hematoma detection sensitivity from 33-50% (CCT) to 77-83% using C+ED SDCT with specificity rising from 75-80% to 85-90% and accuracy improving from 55-66% to 84% (p=0.04); κ improved from 0.44 (CCT) to 0.82 (C+ED), confirming diagnostic benefit. Bäcker et al synthesized 13 studies covering 515 patients and 3335 vertebrae while reporting pooled DECT sensitivity of 86.2%, specificity of 91.2%, and accuracy of 89.3% which is outperforming conventional CT (sensitivity 81.3%, specificity 80.7%, accuracy 80.9%) with statistical significance for specificity (p<0.001) and accuracy (p=0.023), establishing DECT's superior diagnostic yield.

Muchow et al in a meta-analysis of 464 patients across five studies, confirmed MRI's gold-standard role with sensitivity 97.2%, specificity 98.5%, and NPV 100% while identifying MRI-only abnormalities in 97/464 patients (20.9%), with PPV of 94.2% (CI: 75.0-98.9), highlighting its unique ability to detect occult injuries. Roy et al demonstrated that MRI identified transverse ligament injury in 6/8 patients compared to inconsistent craniometric CT findings where ADI was elevated in 4/8, AOI >1.4 mm in 4/8, and BDI >8.5 mm in 2, reinforcing MRI's superiority in evaluating CVJ instability.

Our findings from Fujii et al in 122 patients with WHO grade III gliomas showed that achieving ≥53% T2-weighted extent of resection (T2-EOR) was associated with improved overall survival in anaplastic astrocytoma (AA) and anaplastic oligoastrocytoma (AOA) but not anaplastic oligodendroglioma (AO), suggesting fMRI-guided volumetric thresholds are relevant for surgical planning in high-risk lesions, although IDH and 1p/19q subtypes were not analyzed.

Taken together, the evidence makes the DSCT modalities such as DECT and SDCT credible and high specific options to replace MRI in acute trauma diagnostics, where MRI access is restricted or unfeasible and where functional MRI plays a crucial role in providing oncologic neurosurgical planning with survival-related prognostic insights.

Table 1: Study characteristics.

Author(s)	Year	Study design	Population characteristics	Sample size	Duration/ follow-up	Intervention	Methodology
Cavallaro et al[11]	2022	Retrospective comparative study	Acute vertebral fracture patients	88 patients	12-week DECT readout interval	Dual-energy CT and 3T MRI	5 radiologists assessed BME and fracture lines
Pumberger et al[12]	2019	Prospective diagnostic accuracy study	Patients >50 years with vertebral fractures	67 patients; 295 disks	MRI-DECT interval: 4.4±9.0 days	DECT for disk injury detection	DECT vs. MRI using Sander classification; 3 readers
Unthan et al[13]	2024	Prospective diagnostic accuracy study	ED patients ≥54 years with suspected pelvic FFP	51 patients	MRI after 2±3 days	Spectral CT followed by pelvic MRI	Imaging vs. MRI using OFP classification; 4 raters
Radcliff et al[14]	2012	Retrospective cohort analysis	Acute traumatic craniocervical dislocation patients	18 patients	Not specified	CT and MRI evaluation of CCJ	CT/MRI to assess joint spacing and ligament injury
Sedaghat et al[15]	2021	Diagnostic accuracy study	Post-trauma cervical spine patients	38 patients	Not reported	SDCT with electron density images	MRI as reference; CCT vs. C+ED
Bäcker et al[16]	2021	Systematic review and meta-analysis	Spine fracture/ vertebral trauma patients	515 patients; 3335 vertebrae	Not reported	Dual-energy CT	13 studies; MRI as reference
Fujii et al[17]	2017	Retrospective volumetric analysis	Patients with WHO grade III gliomas	122 patients	March 2000-Dec 2011	Intraoperative MRI-guided resection	T2-EOR calculated volumetrically
Muchow et al[18]	2008	Meta-analysis	Blunt trauma patients	464 patients	MRI within 72 hrs	MRI for C-spine clearance	Log odds meta-analysis
Roy et al[19]	2015	Retrospective case review + literature review	Cervical spine trauma needing fusion	8 patients	Not reported	MRI following CT in CVJ trauma	CT vs. MRI findings; craniometrics

Table 2: Outcomes and findings.

Primary outcome (s)	Secondary outcome (s)	Quantitative data	Key findings	Limitations/ biases
BME sensitivity (DECT): 89%, Specificity: 98%	MRI fracture line sensitivity: 76%, specificity: 95%	Cutoff -0.43 HU; AUC 0.96; p<0.001	DECT outperforms MRI for BME and fracture lines	Retrospective; reader variability
DECT Sensitivity: 0.85, Specificity: 0.75	Grade-wise sensitivity: 0.80-0.98; fleiss κ: 0.51	Attenuation: 0.3±35.2 vs. 97.9±41.0 HU; p<0.001	DECT collagen maps identify disk injuries accurately	Reader variability; incomplete MRI/DECT data
Spectral CT Sensitivity: 89.5%, Specificity: 84.6%	Dorsal fracture sensitivity: 69-97%; κ=0.516	L5: 68±30 HU; κ CI: 0.450–0.582	Spectral CT effective but slightly less sensitive than MRI	Small sample; mild interrater variability
13/18 had displacement; 11/17 had cruciate injury	Occipitoatlantal capsule rupture linked with type II	Cruciate injury: 11/17; SCIs: 3/18	Capsule rupture linked to instability, SC injury	Small sample; unclear MRI timing
Sensitivity ↑ from 33-50% to 77-83%	Specificity ↑ from 75-80% to 85-90%	Accuracy ↑ from 55-66% to 84%; κ=0.82 vs 0.44; p=0.04	C+ED SDCT improves hematoma detection	Small sample; CCT inter-reader variability
Sensitivity: 86.2%, Specificity: 91.2%, Accuracy: 89.3%	CT alone: Sens 81.3%, Spec 80.7%, accuracy 80.9%	p<0.001 (specificity), p=0.023 (accuracy)	DE-CT accurate for marrow/disc edema	Interobserver variability; heterogeneity
T2-EOR ≥53% linked to better survival	Not significant in AO subtype	T2-EOR ≥53% improved OS in AA/AOA	EOR=key prognostic factor in AA/AOA	No IDH1/2 or 1p/19q subgroup analysis
NPV 100%, Sensitivity: 97.2%, Specificity: 98.5%	97/464 had MRI-only detected injuries	PPV 94.2% (CI: 75.0-98.9)	MRI reliably excludes C-spine injury	False positives indeterminate
MRI detected ligament injury missed by CT	Craniometrics inconsistent; judgment critical	ADI ↑ in 4/8; AOI >1.4 in 4/8; BDI >8.5 in 2	MRI superior for CVJ ligament instability	Small sample; subjective MRI interpretation

DISCUSSION

The relative diagnostic effectiveness of DECT and MRI is on a developmental course, especially within the understanding of the craniocervical trauma where quick identification of soft tissue injury and bone injury are paramount to their surgical planning. A series of recent reports have noted the growing usefulness of DECT as a competent or preferred substitute in cases where MRI is not indicated (because of, e.g., implanted material or device or as an alternative in cases where MRI is not available.

Cavallaro et al demonstrated strong support to the idea of DECT, stating that it has demonstrated a comparative extent with a 3T MRI in the detection of BME, as well as such indicators as sensitivity of 89% and specificity of 98%, as well as an excellent level of diagnostic confidence (2.30 vs. 2.32, p=0.72). It is worth noting that a greater degree of confidence was apparent when DECT was used in detecting fracture lines in comparison to that of MRI (p<0.001), making it perhaps more practical value in acute injuries where the clarity of structures is paramount.[11] in the same way, Pumberger et al found DECT effective in assessing disc injuries with performance improving across injury grades. Sensitivity reached 98% in severe cases which stresses its diagnostic reliability where MRI access is limited or delayed.[12] Unthan et al extended this evidence to fragility fractures of the pelvis while reporting DECT sensitivity of 89.5% and specificity of 84.6% with moderate inter-rater reliability metrics comparable to MRI in detecting dorsal fractures.[13] We reported that MRI advantage remains evident in certain domains. Radcliff et al demonstrated MRI's ability to identify capsular disruption and ligamentous injury patterns that correlate with neurological outcomes in craniocervical dislocations critical details often missed on CT.[14] Sedaghat et al in their research, also noted that dual-layer spectral CT with electron density imaging markedly improved hematoma detection but still fell short of MRI's tissue contrast and spatial resolution.[15]

A meta-analysis by Bäcker et al found that DECT consistently outperformed conventional CT in specificity and accuracy for detecting spinal edema although MRI remained the gold standard.[16] Furthermore, functional MRI maintains a crucial role in intraoperative planning. Fujii et al showed that extent of T2-signal resection was prognostic in high-grade gliomas which was demonstrating MRI's broader utility beyond diagnosis.[17]

Research by Muchow et al and Roy et al confirm that MRI reveals clinically significant injuries missed by CT in ligamentous disruptions critical to surgical decisions.[18,19]

Recent breakthroughs in medical imaging have revolutionized diagnostics and treatment planning such as DSCT is seen to enhance tissue differentiation by simultaneously capturing high- and low-energy X-ray spectra while improving fracture detection in complex craniocervical injuries. Most current studies show DSCT reduces metal artifacts and increases diagnostic accuracy for unstable fractures compared to conventional CT.[20] fMRI has advanced with ultra-high-field 7T scanners while offering superior spatial resolution for assessing neural pathways near fracture sites.[21] This aids neurosurgeons in minimizing postoperative deficits. AI-powered fMRI analysis now predicts recovery outcomes by mapping functional connectivity disruptions.[22] In neurosurgical navigation, augmented reality (AR) overlays 3D reconstructions from DSCT/fMRI onto the surgical field while also improving precision in craniocervical stabilization.[23] In the same time, quantitative susceptibility mapping (QSM) which is a novel MRI technique which detects microbleeds near fractures, reducing intraoperative complications.[24] Portable MRI systems like Hyperfine's low-field devices, enable intraoperative imaging, critical for unstable fractures.[25] Combined with robot-assisted surgery, these tools reduce operative time and improve screw placement accuracy.[26] Certain other comparative evidences and literature also highlight DSCT's superiority in bony detail (sensitivity: 98% vs. fMRI's 85%).[27] While fMRI excels in neural risk assessment but integrating both modalities optimizes preoperative planning.[28] Cost and accessibility remain challenges so, future directions include hybrid DSCT-fMRI protocols and AI-driven predictive modeling.[29,30]

CONCLUSION

This review demonstrates how DSCT and fMRI have been optimised in terms of assessing unstable craniocervical fractures. DSCT is quick and precise in detecting fractures and bone marrow edema and thus becoming the ideal protocol in emergency trauma. Conversely, fMRI has no match in the measurement of ligaments and spinal cord particularly at a time when it is imperative to eliminate a possibility of a neurologic injury. Both are good: DSCT provides clear images of the bones in a short time and fMRI also provides clear soft tissue imaging that aids in surgery. Practically, the priority of DSCT is valid in case the patient is unstable, whereas fMRI is supposed to be added when neurological symptoms are present or the outcomes of DSCT are ambiguous. Nevertheless, present studies fall short as the imaging procedure lacks consistency and research is mainly retrospective in nature. In the future, one should expect stable benchmarks and investigate AI-based fusion of images to increase accuracy. An intelligent, context/aware imaging plan might result in safer, safer and more successful care.

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