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SPECTRAL AND DUAL-ENERGY CT IN EMERGENCY IMAGING

IMAGE QUALITY, DOSE REDUCTION AND ARTIFACT MITIGATION

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Spectral and Dual-Energy CT in Emergency Imaging: A Technical Review of Image Quality, Dose Reduction, and Artifact Mitigation

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Abstract

Dual-energy and spectral computed tomography (DECT/spectral CT) acquire attenuation data at two or more energy spectra, enabling virtual monoenergetic images (VMI), iodine maps, and virtual non-contrast (VNC) images. This narrative review examines their technical performance in emergency imaging, focusing on image quality, radiation dose, and artifact mitigation, after summarizing the physical principles and hardware implementations (source-based, detector-based, and photon-counting). We distinguish three types of benefit that are often conflated: improved image appearance or lesion conspicuity, supported mainly by phantom, technical, and reader studies; changes in radiation exposure, which in the studies reviewed arise mainly from omitting the unenhanced acquisition rather than from a lower acquisition dose (reductions of roughly 20–47% in selected abdominal protocols); and reduced iodinated contrast volume, a protocol parameter distinct from radiation exposure and from clinical safety outcomes. For pulmonary embolism, meta-analyses indicate diagnostic performance comparable to, but not demonstrably better than, single-energy CT. High-energy VMI and metal artifact reduction algorithms reduce, but do not eliminate, metal and beam-hardening artifacts. None of the sources reviewed reports improved patient outcomes, and VNC remains an approximation that requires local validation. Larger multicentre diagnostic and outcome studies are needed.

Keywords: Dual-energy CT, Spectral CT, Emergency imaging, Image quality, Radiation dose, Artifact reduction

1. Introduction

Computed tomography is the backbone of emergency imaging because of its speed, availability and broad diagnostic scope. Conventional CT, however, measures a single composite attenuation value per voxel from a polychromatic X-ray beam. Different materials (for example, iodine, calcium, hemorrhage and uric acid) can therefore produce similar Hounsfield unit (HU) values, which limits characterization in time-critical settings.

DECT exploits the energy dependence of X-ray attenuation. The idea dates back to early work on material decomposition in the 1970s and 1980s (Kalender et al., 1986), but robust clinical systems appeared only after the introduction of dual-source scanning in the mid-2000s (Johnson et al., 2007). Since then, rapid kilovoltage switching, dual-layer detectors and, more recently, photon-counting detectors have broadened access to spectral data (McCollough et al., 2015; Willemink et al., 2018).

The emergency setting imposes distinct requirements: short acquisition and reconstruction times, tolerance to patient motion and variable body habitus, minimal added workflow burden, and diagnostic confidence under time pressure. This review evaluates how spectral CT meets these requirements, with emphasis on technical performance rather than clinical outcomes alone. Dedicated overviews of DECT physics and applications for emergency radiologists are available (Odedra et al., 2022; Mohammed et al., 2018).

1.1 Literature selection and scope

This is a narrative review. Sources were identified through targeted searches of publisher and bibliographic sources (journals indexed in PubMed/PMC and publisher websites) between October and November 2026. Search topics were: dual-energy and spectral CT in emergency radiology; dual-layer and photon-counting CT; virtual monoenergetic and virtual non-contrast imaging; radiation dose and contrast-volume reduction; metal and beam-hardening artifact reduction; and DECT in pulmonary embolism, gastrointestinal bleeding, bowel ischemia, trauma, and neuroimaging. The publications included in this review date from 1986 to 2025. This publication span is distinct from the dates on which the searches were conducted. The review does not provide a comprehensive assessment of literature published in 2026.

Peer-reviewed, English-language articles were included if they addressed spectral CT technique, image quality, dose, artifacts, or emergency applications. Systematic reviews and meta-analyses were prioritized, followed by narrative reviews and primary technical or diagnostic studies. Conference abstracts, non-peer-reviewed material, and articles unrelated to technical performance or emergency use were excluded. Selection was based on the authors' judgement; no formal systematic search, risk-of-bias assessment or quality appraisal was performed, and the search should not be regarded as exhaustive.

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Table 1 shows the types of evidence on which this review draws. Throughout the text, the type of study supporting each claim is stated, because phantom and image-quality findings cannot be equated with diagnostic accuracy or patient outcomes.

Table 1. Types of evidence cited in this review

Evidence type	Sources	Used mainly in
Phantom and technical studies	Kalender et al., 1986; Johnson et al., 2007; Ehn et al., 2018	Sections 2, 3, 5.1
Patient image-quality, feasibility and VNC-versus-true-unenhanced studies	Pache et al., 2010; Pomerantz et al., 2013; Bamberg et al., 2011; Lee et al., 2012; Graser et al., 2009 (non-emergency); Im et al., 2013; Si-Mohamed et al., 2019 (phantom and clinical)	Sections 4, 5.2, 6, 7
Diagnostic performance and reader studies	Gupta et al., 2010; Nicolaou et al., 2010; Reddy et al., 2015; Sun et al., 2015; Mohammadinejad et al., 2021; Oberparleiter et al., 2025a, 2025b	Section 7
Systematic reviews and meta-analyses	Abdellatif et al., 2021; Monti et al., 2021	Section 7.2
Narrative reviews and primers	Albrecht et al., 2019; Forghani et al., 2017; Gibney et al., 2020; Henzler et al., 2012; Johnson, 2012; Lell and Kachelrieß, 2020; McCollough et al., 2015; Mohammed et al., 2018; Murray et al., 2019; Odedra et al., 2022; Patino et al., 2016; Rajiah et al., 2020; Rassouli et al., 2017; Wang et al., 2022; Willemink et al., 2018; Willemink and Noël, 2019; Wortman et al., 2018	All sections
Studies with patient-outcome endpoints	None among the sources cited	–

2. Physical Principles

2.1 Energy dependence of attenuation

In the diagnostic energy range, X-ray attenuation is dominated by the photoelectric effect and Compton scattering. The photoelectric component varies approximately with the inverse cube of photon energy and with the cube of atomic number, whereas the Compton component depends mainly on electron density and varies only slowly with energy. Materials with high atomic number, such as iodine (K-edge at 33.2 keV) and calcium, therefore show a steep rise in attenuation at low energies, while soft tissue changes comparatively little. Measuring attenuation at two energies allows these materials to be distinguished (McCollough et al., 2015; Johnson, 2012).

2.2 Material decomposition

Material decomposition models each voxel's attenuation as a combination of two (or more) basis materials, commonly water and iodine. It can be performed in the image domain (as in many dual-source systems) or in the projection (raw-data) domain (as in rapid kV-switching and dual-layer systems). Projection-domain decomposition is generally less affected by beam hardening and is better suited to spatially and temporally matched data (Patino et al., 2016; Forghani et al., 2017).

2.3 Principal spectral outputs and terminology

- **Virtual monoenergetic images (VMI):** synthesized images that approximate attenuation at a single photon energy, typically 40–140 keV.
- **Iodine maps / iodine density images:** quantification of iodine distribution, used as a proxy for perfusion.
- **Virtual non-contrast (VNC) images:** images with iodine computationally removed.
- **Effective atomic number (Zeff) and electron density maps:** used for characterization of calcifications, stones and crystals.
- **Calcium suppression / bone removal:** useful for bone marrow assessment and CT angiography.

Three image types are easily confused and are kept distinct throughout this review. *True (acquired) unenhanced images* are obtained in a separate acquisition before contrast injection and add radiation exposure. *VNC images* are computed from a contrast-enhanced dual-energy acquisition by subtracting iodine; they estimate the unenhanced image, but their attenuation values and detail can differ from true unenhanced images. *VMI* are synthesized from the same data to simulate a single photon energy: low-

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keV VMI increase iodine signal and high-keV VMI reduce metal and beam-hardening artifacts, but VMI are not a substitute for an unenhanced scan. In the literature, only VNC is proposed as a potential substitute for an acquired unenhanced phase.

3. Technical Implementations

Technology	Principle	Strengths	Limitations
Dual-source DECT	Two tubes and detectors at different kV (e.g., 80/140 kV with tin filtration)	Independent tube current optimization; large spectral separation	Smaller field of view for second detector; cross-scatter; temporal offset between datasets
Rapid kV-switching	Single tube alternating between low and high kV within a rotation	Near-simultaneous projection data; projection-domain decomposition; full field of view	Limited ability to modulate tube current per kV; spectral separation moderate; photon starvation in large patients
Dual-layer detector	Single polychromatic beam; top layer absorbs lower energies, bottom layer higher energies	Spectral data available for every acquisition; perfectly registered; no field-of-view penalty	Lower spectral separation than source-based approaches; limited by detector spectral overlap (Rassouli et al., 2017)
Split-filter / sequential	Beam split into two spectra by filter, or two sequential scans	Simple hardware; useful in static regions	Misregistration with motion; limited spectral separation
Photon-counting CT	Direct conversion detectors count and bin photons by energy	Superior spatial resolution, intrinsic multi-energy data, reduced electronic noise, better iodine signal	Higher cost; limited availability; evolving clinical workflows (Willemink et al., 2018)

For emergency practice, the key distinguishing factor is whether spectral data are available retrospectively without a prior decision to scan in dual-energy mode. Dual-layer and photon-counting systems offer this advantage, which fits the unpredictable nature of emergency work (Rassouli et al., 2017; Rajiah et al., 2020).

4. Image Quality

4.1 Contrast and contrast-to-noise ratio

Low-keV VMI (approximately 40–70 keV) increase iodine attenuation by moving toward its K-edge, improving vessel and parenchymal enhancement and often the contrast-to-noise ratio (CNR) of contrast-enhanced studies (Albrecht et al., 2019). This is particularly valuable in suboptimally opacified vessels, as can occur in acute pulmonary embolism, aortic dissection, or poorly timed trauma protocols. These are gains in image appearance and conspicuity; they should not be equated with demonstrated improvements in diagnostic accuracy or patient outcomes (see Section 7).

4.2 Noise and the noise–contrast trade-off

Lower energy VMI are associated with increased image noise and noise texture changes, because low-energy photons are more strongly attenuated, especially in larger patients. The result is a trade-off: contrast rises, but so does noise, and beyond a certain keV the CNR may no longer improve. Noise-optimized VMI reconstructions that combine the high-contrast information from low energies with the low-noise characteristics of higher energies have been introduced to mitigate this (Albrecht et al., 2019). Iterative and deep-learning-based reconstruction further reduce noise in spectral datasets (Willemink and Noël, 2019).

4.3 Optimal energy selection by task

There is no universal best keV. Typical choices reported in the literature include:

- 40–55 keV for vascular and parenchymal iodine conspicuity, particularly in low-contrast-volume examinations.
- 65–75 keV for general-purpose reading, approximating the appearance of a conventional 120 kVp image; in unenhanced head CT, virtual monoenergetic reconstructions at roughly 65–75 keV have been reported to improve gray-white matter differentiation and image quality compared with polychromatic CT (patient image-quality study; Pomerantz et al., 2013).
- High keV (100–140+) for metal and beam-hardening artifact reduction (Bamberg et al., 2011).

4.4 Quantitative image quality

Spectral CT adds quantitative biomarkers: iodine concentration (mg/mL), Zeff, and HU curves across energies. These may support characterization (for instance of hyperattenuating lesions) and may reduce inter-reader variability, although reproducibility depends on vendor, calibration, phantom size and acquisition parameters. Cross-vendor comparability remains a limitation.

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5. Radiation Dose, Iodinated Contrast Volume, and Image Quality

Three different claims are often grouped under “dose reduction” and are separated here: (i) the dose of the DECT acquisition itself, (ii) the reduction in cumulative radiation exposure achieved by omitting an unenhanced acquisition, and (iii) the reduction in iodinated contrast volume. Image quality is a separate outcome (Section 4). Table 2 summarizes the evidence for each.

5.1 Dose of the dual-energy acquisition

DECT acquisitions are generally reported to be dose-comparable to single-energy CT, but the platform, protocol, comparator and dose metric differ between reports, so the comparison depends on local protocols (Rassouli et al., 2017; McCollough et al., 2015; Henzler et al., 2012). Detector-based systems derive spectral data from the same exposure, whereas dose in dual-source and rapid kV-switching systems depends on the kV pair, filtration and tube-current settings and should be verified locally. In a phantom study of one dual-layer system, spectral quantification remained accurate across exposure levels without compromising image quality; this was not a patient dose comparison (Ehn et al., 2018). Notably, in a meta-analysis of DECT for pulmonary embolism, radiation dose and contrast dose did not decrease with year of publication (Monti et al., 2021), indicating that theoretical savings are not automatically realized in practice.

5.2 Reduction of cumulative exposure by omitting the unenhanced acquisition

Where a protocol normally includes an unenhanced phase, VNC images reconstructed from the contrast-enhanced scan can in principle replace it. This reduces cumulative radiation exposure by omitting a scan phase; it does not change the dose of the dual-energy acquisition itself. The evidence is as follows:

- **Acute abdomen (patient study; Im et al., 2013):** in 202 patients who had both acquired unenhanced and dual-energy portal-phase images, VNC attenuation values and image quality were comparable with acquired unenhanced images and hemorrhage was detected similarly, whereas small stones were detected better on acquired unenhanced images. Omitting the acquired unenhanced phase reduced mean radiation dose by 33% in a virtual triple-phase protocol and by 47% in a virtual dual-phase protocol.
- **Gastrointestinal bleeding (retrospective reader study; Oberparleiter et al., 2025b):** in 52 patients with active bleeding and 52 controls, a DECT protocol with VNC images and iodine maps was non-inferior to conventional triphasic CT for sensitivity, specificity, reading time and diagnostic confidence, with a 20% lower total dose-length product when the acquired unenhanced phase was omitted. An earlier report noted that the utility of VNC in this setting was not well established because previous studies had used acquired unenhanced images rather than VNC (Mohammadinejad et al., 2021).
- **Non-emergency comparator (renal masses; Graser et al., 2009):** omitting the acquired unenhanced scan reduced estimated dose by approximately 35%. This study was not performed in an emergency population.

These findings come from single studies of selected abdominal indications and different scanners and protocols, and they should not be extrapolated to other indications. For suspected aortic intramural hematoma, Si-Mohamed et al. (2019) compared VNC with acquired unenhanced images on dual-layer DECT in a phantom and in 21 patients with confirmed hematoma. The authors estimated a 40% reduction in mean effective dose if the unenhanced acquisition were omitted. This estimate is protocol-specific and comes from a retrospective cohort with confirmed disease. VNC remains an approximation: some calcifications, small stones and small high-density structures may be partly suppressed, so its use should be validated locally for each indication. Where the baseline protocol is already single-phase, there is no scan phase to omit and no such saving.

5.3 Iodinated contrast volume

Low-keV VMI may maintain vascular enhancement with a lower administered iodine dose in selected protocols (Albrecht et al., 2019). Administered iodine dose and radiation exposure are separate parameters. The evidence summarized here does not establish that the lower iodine dose reduces contrast-related adverse events or improves renal outcomes in emergency patients. The evidence cited here is at review level; individual primary studies of contrast reduction in emergency populations are not summarized in this review. Retrospective spectral reconstruction may also rescue suboptimally enhanced examinations and avoid repeat scanning, but this has been described mainly in reviews and not quantified in controlled studies.

5.4 Dose considerations in different patient sizes

In large patients the low-energy dataset may suffer photon starvation, increasing noise and reducing spectral accuracy; protocols should account for body habitus, and some systems require a minimum dose for reliable spectral decomposition. The higher iodine

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signal at lower tube voltage can allow lower dose in smaller patients, but this is a general CT principle and not exclusive to spectral CT.

Table 2. Summary of evidence for dose, contrast volume, and image-quality claims

Claim	Evidence (platform, comparator, metric where reported)	Evidence level	Main caveat
DECT acquisition dose is comparable to single-energy CT	Henzler et al., 2012; McCollough et al., 2015 (reviews); Ehn et al., 2018 (dual-layer phantom; quantification accurate across exposure levels)	Reviews; phantom	Metric, platform and comparator vary; no patient-level dose comparison
Omitting the unenhanced scan lowers cumulative exposure	Im et al., 2013 (acute abdomen, n = 202; VNC vs acquired unenhanced; mean dose −33% and −47% in virtual triple and dual protocols); Oberparleiter et al., 2025b (GI bleeding; VNC plus iodine map vs triphasic CT; DLP −20%); Graser et al., 2009 (renal masses, non-emergency; about −35%); Si-Mohamed et al., 2019 (aortic intramural hematoma, dual-layer DECT; estimated mean effective dose −40%)	Patient studies, retrospective reader studies and a phantom/clinical comparison	Indication- and platform-specific. Small stones may be missed on VNC. The aortic cohort included confirmed cases only.
Low-keV VMI allows lower contrast volume	Albrecht et al., 2019	Review	Lower administered iodine is a protocol result. Emergency safety and renal outcomes are not established by the evidence summarized here.
Low-keV VMI improves contrast and conspicuity	Albrecht et al., 2019 (review); Pomerantz et al., 2013 (unenhanced head CT, 65–75 keV vs polychromatic)	Review; patient image-quality study	Image appearance is not diagnostic accuracy; noise rises at low keV

6. Artifact Mitigation

6.1 Metal artifacts

Metallic implants and fixation hardware are frequent in emergency patients (trauma, post-operative complications). Beam hardening and photon starvation create streaks and dark bands that obscure adjacent structures. High-keV VMI reduce these artifacts by decreasing the contrast between metal and soft tissue attenuation and reducing beam hardening. In patients with metallic implants, monoenergetic extrapolation (Bamberg et al., 2011) and VMI from a rapid kV-switching system, with and without dedicated metal artifact reduction (MAR) software (Lee et al., 2012), have been reported to improve visualization of adjacent tissue. These are technical and image-quality studies; they do not demonstrate improved diagnostic accuracy or outcomes. Artifacts are reduced, not eliminated: photon starvation persists near dense implants (for example, large arthroplasty components), and soft-tissue contrast falls at very high keV.

6.2 Beam hardening

Beam hardening, which causes cupping and dark bands near dense bone (for example, the posterior fossa) or highly concentrated intravenous contrast, is expected to be reduced in higher-energy monoenergetic reconstructions, helping assessment of the posterior fossa and reducing streaks from dense contrast in the superior vena cava and subclavian vein. This expectation follows from the physics of the technique; this review did not identify primary studies that systematically validated it in emergency populations.

6.3 Iodine-related pitfalls

- **Contrast staining versus hemorrhage:** after intra-arterial therapy or angiography, iodine staining may mimic hemorrhage; in a diagnostic study, DECT with iodine and VNC images differentiated the two (Gupta et al., 2010).
- **Pseudo-enhancement and VNC errors:** VNC may be unreliable with very dense iodine, in the presence of calcium, or with motion; iodine maps can show false defects from beam hardening or noise.

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6.4 Spectral-specific artifacts

Spectral CT introduces its own pitfalls: misregistration in sequential or dual-source approaches, limited field of view of the second detector in some dual-source systems, cross-scatter, and decomposition errors in the presence of materials not modelled by the chosen basis pair (for example, high concentrations of gadolinium, barium or metal). Conventional-like 120 kVp images should always be reviewed alongside spectral reconstructions.

6.5 Motion artifacts

Systems that acquire both energies nearly simultaneously (rapid kV-switching, dual-layer, photon-counting) are less affected by temporal mismatch, which is an advantage in uncooperative or unstable emergency patients. Dual-source systems have a short temporal offset between the two tubes' data, but with high temporal resolution this is rarely a major limitation.

Table 3. Artifact mitigation: reconstruction used, effect reported, and remaining limitations

Artifact	Reconstruction	Effect reported (study type)	Remaining limitations
Metal streaks and beam hardening near implants	High-keV VMI (monoenergetic extrapolation), with or without MAR software	Improved visualization of adjacent tissue (Bamberg et al., 2011; Lee et al., 2012; technical and image-quality studies)	Photon starvation persists near dense implants; soft-tissue contrast falls at very high keV; artifacts reduced, not eliminated
Posterior-fossa and dense-contrast beam hardening	Higher-keV VMI	Expected from physics; limited primary data in the sources reviewed	Not systematically validated here
Iodine staining mimicking hemorrhage	Iodine map plus VNC	Differentiation after intra-arterial therapy (Gupta et al., 2010; diagnostic study)	VNC may fail with dense iodine, calcium or motion
Noise at low keV	Noise-optimized VMI; iterative or deep-learning reconstruction	Reduced noise (Albrecht et al., 2019; Willemink and Noël, 2019; reviews)	Contrast–noise trade-off persists
Spectral-specific errors (misregistration, field-of-view limits, cross-scatter, decomposition errors)	Review of 120 kVp-equivalent images alongside spectral series	Descriptive (reviews)	Platform-dependent

7. Clinical Applications in Emergency Imaging

For each application, the image type evaluated, the comparator, and the level of evidence are stated where known. Unless otherwise stated, the evidence reflects image quality, lesion conspicuity or reader performance, not patient outcomes.

7.1 Neuroradiology

- **Intracranial hemorrhage versus contrast staining:** iodine map and VNC images differentiated residual contrast from blood after intra-arterial therapy (diagnostic study; Gupta et al., 2010).
- **Gray-white matter differentiation:** VMI of unenhanced head CT at about 65–75 keV improved image quality compared with polychromatic CT (patient image-quality study; Pomerantz et al., 2013).
- **CT angiography:** bone removal and low-keV VMI are reported to improve vessel visualization and reduce coil and clip artifact (review; Gibney et al., 2020).

7.2 Thoracic emergencies

- **Acute pulmonary embolism (meta-analyses).** A meta-analysis of seven studies (182 patients, 108 with pulmonary embolism) reported a pooled sensitivity of 88.9% (95% CI 81.4–94.1%) and specificity of 94.6% (95% CI 86.7–98.5%) for DECT; the authors noted that the studies were small and reference tests were not standardized (Abdellatif et al., 2021). A larger meta-analysis of 17 studies, restricted to lobar and segmental emboli, grouped results by image product: linear blending (conventional-like) images alone, 0.87 sensitivity and 0.93 specificity (6 study parts, 348 patients); linear blending plus iodine maps, 0.89 and 0.90 (14 study parts, 1007 patients); linear blending plus iodine maps plus VMI, 0.90 and 0.90 (2 studies, 144 patients). These estimates were compared indirectly with published single-energy CT performance (0.83 sensitivity, 0.96 specificity), and the authors concluded that DECT and single-energy CT can be used comparably (Monti et al., 2021). Iodine maps and low-keV VMI may improve conspicuity of perfusion defects and rescue poorly opacified pulmonary arteries (review; Albrecht et al., 2019), but gains in diagnostic accuracy over single-energy CT have not been demonstrated.

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- Aortic syndromes: Si-Mohamed et al. (2019) compared VNC and acquired unenhanced images using a phantom and a retrospective two-centre cohort of 21 patients with confirmed aortic intramural hematoma. Contrast-to-noise and reader confidence were similar on the dual-layer platform studied. The design did not establish the safety of routinely omitting the acquired unenhanced phase in an unselected emergency population. Low-keV VMI can aid visualization of the aortic wall, branches and dissection flap (Murray et al., 2019). VMI and VNC serve different purposes in this setting.

7.3 Abdominal emergencies

- **Acute abdomen (VNC versus acquired unenhanced):** see Section 5.2 (Im et al., 2013).
- **Gastrointestinal bleeding:** a retrospective study of 52 patients with active bleeding and 52 controls found DECT with VNC and iodine maps non-inferior to triphasic CT for sensitivity, specificity, reading time and diagnostic confidence (Oberparleiter et al., 2025b). Dual-source DECT angiography with VNC and iodine maps has also been evaluated for image quality, radiation dose and diagnostic performance (Sun et al., 2015).
- **Acute bowel ischemia:** in a retrospective reader study of 25 patients with surgically proven acute mesenteric ischemia and 25 matched controls, adding DECT-derived iodine maps and VNC images to conventional CT increased reader sensitivity and diagnostic confidence while maintaining specificity, without a significant increase in reading time (Oberparleiter et al., 2025a). The outcome measured was reader performance, not patient outcome, and the sample was small.
- **Bowel trauma and solid organ injury:** clinical evidence for bowel trauma is limited to few studies (Wang et al., 2022). For solid organ injury, low-keV VMI and iodine maps are reported to improve conspicuity of parenchymal lacerations, contusions and active hemorrhage (review; Wortman et al., 2018); this reflects conspicuity, not demonstrated gains in diagnostic accuracy.
- **Urolithiasis:** Zeff and dual-energy ratio techniques are described in reviews as able to differentiate uric-acid from calcium-containing stones, informing medical versus urological management (Murray et al., 2019).

7.4 Musculoskeletal and trauma

- **Gout:** dual-energy post-processing detected monosodium urate deposits in acute arthritis (diagnostic study; Nicolaou et al., 2010).
- **Bone marrow edema:** virtual non-calcium images were evaluated for posttraumatic bone marrow lesions (feasibility study; Pache et al., 2010) and for occult, undisplaced hip fractures (Reddy et al., 2015); a review also describes use in trauma (Wortman et al., 2018).
- **Hardware assessment:** high-keV VMI may aid evaluation of fractures near fixation devices (see Section 6.1).

8. Practical Considerations for the Emergency Department

The following considerations are based largely on expert reviews and local-validation principles rather than on controlled trials.

1. **Protocol design:** where available, use spectral-enabled protocols as default (particularly dual-layer or photon-counting), so that spectral data are available retrospectively without delaying the scan.
2. **Standardized reconstructions:** define a limited set of automatically generated series (e.g., conventional-equivalent, 50–55 keV VMI, iodine map, VNC) to avoid reading overload.
3. **Workflow and storage:** spectral data sets increase image numbers and storage; integrate with PACS and consider automatic hanging protocols.
4. **Training:** radiologists and technologists should be aware of the typical artifacts and limitations (Section 6).
5. **Quality assurance:** periodic phantom checks of iodine quantification and keV accuracy, and local validation of VNC for each indication before it replaces an acquired unenhanced phase.
6. **Patient selection:** consider body habitus limits and system field-of-view limits; ensure standard single-energy backup for atypical cases.

9. Limitations and Challenges

- Most evidence for image quality and artifact reduction comes from phantom, technical, and retrospective single-centre studies; none of the sources cited reports patient-outcome endpoints.

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- Diagnostic accuracy data are limited and, for pulmonary embolism, show performance comparable to single-energy CT rather than superiority.
- Dose-saving claims depend on omitting an unenhanced phase in selected abdominal protocols; they have not been demonstrated for all emergency indications, and VNC is not identical to acquired unenhanced imaging (for example, small stones may be missed).
- Variation between vendors in spectral approach, reconstruction algorithms and quantitative values limits generalizability and the use of universal thresholds.
- Possible increase in reporting time and information load when many series are generated.
- Higher equipment cost and uneven availability, particularly of photon-counting systems.
- Need for further standardization of terminology and protocols.
- This is a narrative review without a formal systematic search or quality appraisal; relevant studies may have been missed.

10. Future Directions

Photon-counting CT offers intrinsically multi-energy acquisition, improved spatial resolution, reduced electronic noise and potentially improved iodine sensitivity, with the possibility of multi-material decomposition and K-edge imaging with novel contrast agents (Willemink et al., 2018; Lell and Kachelrieß, 2020). **Artificial intelligence** is being explored for spectral reconstruction (for example, denoising of low-keV VMI; Willemink and Noël, 2019) and for automated detection, but evidence for emergency use remains limited. Prospective multicentre studies with diagnostic-accuracy and clinical-outcome endpoints, health-economic analysis, and cross-vendor standardization are required to define the role of spectral CT in routine emergency imaging.

11. Conclusion

Spectral and dual-energy CT offer a versatile toolset for emergency imaging, but the benefits differ in kind and in strength of evidence. Low-keV virtual monoenergetic images can improve contrast and lesion conspicuity and may allow a lower administered iodine dose in selected protocols. The evidence summarized here does not establish a clinical safety or renal benefit from lowering iodine dose. Reductions in radiation exposure reported in selected abdominal protocols (roughly 20–47%) result from omitting the unenhanced acquisition using virtual non-contrast images, not from a lower acquisition dose, and virtual non-contrast images require local validation because they are an approximation. For pulmonary embolism, meta-analyses show performance comparable to single-energy CT. High-keV reconstructions combined with dedicated algorithms reduce, but do not eliminate, metal and beam-hardening artifacts. With appropriate protocols, training, quality assurance, and further outcome-oriented research, spectral CT can be integrated into emergency practice, particularly on systems that provide retrospectively available spectral data.

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Data availability: This narrative review is based on previously published literature cited in the reference list.
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