

Perspectives on the evolution and future of X-ray computed tomography

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Stationary X-ray computed tomography (CT) replaces mechanical gantry rotation with electronically addressable, distributed X-ray sources, offering a post-rotation paradigm that overcomes fundamental temporal and mechanical limitations of conventional CT. By eliminating rotation, stationary CT enables ultra-fast multi-angle acquisition but also introduces coupled challenges, including cross-scatter contamination, limited photon flux, and sparse angular sampling. This Perspective focuses on stationary CT as a system-level imaging framework and emphasizes that its practical realization depends on the coordinated development of stationary hardware, spectral imaging, and physics-informed reconstruction. Spectral detectors provide information-rich measurements under sparse-view conditions, while advanced reconstruction methods integrate physical modeling and prior constraints to recover images from incomplete and noisy data. Rather than independent advances, these elements must be jointly designed to balance spatial resolution, temporal resolution, dose efficiency, and quantitative accuracy. Together, these considerations outline a co-design pathway toward clinically viable stationary CT systems.

INTRODUCTION: TOWARD A POST-ROTATION CT PARADIGM

X-ray computed tomography (CT) provides noninvasive, high-resolution visualization of internal structures by measuring differential X-ray attenuation from multi-angle projections. Since the 1970s, rotating gantry systems with energy-integrating detectors (EIDs) have defined conventional structural imaging.

Spectral X-ray computed tomography (CT) extends conventional structural imaging by resolving energy-dependent X-ray-matter interactions, enabling quantitative material characterization beyond attenuation contrast. However, rotating architectures remain limited in temporal performance due to mechanical inertia, load, and heat constraints, restricting scan speed and motion robustness. Recent advances in distributed X-ray source technologies have enabled stationary CT systems, which in this work are defined as systems that generate projection views without mechanical gantry rotation using multiple fixed-position, electronically addressable X-ray sources, thereby enabling ultra-fast, multi-angle imaging and distinguishing them from conventional rotating CT systems.¹

This Perspective focuses on stationary CT as a post-rotation imaging paradigm. We revisit the limitations of rotating gantry CT and examine how advances in spectral imaging, particularly photon-counting detectors, provide a foundation for stationary and sparsely sampled acquisition. We argue that realizing stationary CT requires the co-design of X-ray sources, detectors, and reconstruction, which together determine system performance. Building on this perspective, we analyze key physical and computational challenges and outline future directions toward dynamic, multiscale, and quantitatively precise CT imaging.

ROTATING GANTRY CT: ACHIEVEMENTS AND FUNDAMENTAL LIMITS

The early development of X-ray CT laid the foundation for modern medical imaging. The first clinical CT scanner introduced by Hounsfield in 1971 used a single source-detector pair, resulting in limited coverage and long scan times. Later advances in X-ray tubes, detectors, and gantry design led to rotating multi-slice spiral CT systems with greatly improved volumetric coverage.

In conventional rotating CT, image reconstruction has been dominated by analytical methods such as filtered backprojection (FBP) because of their computational efficiency and well-defined image quality under fully sampled conditions. However, under high noise or limited angular sampling, the inher-

ent high-frequency amplification of FBP increases noise and streak artifacts, degrading fine structural detail. More fundamentally, sequential acquisition with a single source-detector pair constrains temporal resolution, limiting scan speed and the imaging of rapid physiological motion.

In parallel with temporal constraints, rotating CT systems have relied almost exclusively on energy-integrating detectors (EIDs), which fundamentally limit spectral information. By integrating the total deposited energy, EIDs discard photon energy-specific information, restricting contrast resolution and material discrimination. Consequently, conventional rotating CT is largely confined to structural imaging with limited quantitative capability.

To mitigate these limitations, Siemens introduced dual-source CT (DSCT) in 2005, integrating two orthogonally mounted tube-detector pairs on a single rotating gantry.² This design substantially improves temporal resolution through faster angular sampling and, when operated at two tube voltages, enables coarse spectral differentiation for applications such as plaque characterization and virtual non-contrast imaging.

Despite these advantages, dual-source dual-energy CT still relies on energy-integrating detectors, where each measurement represents a weighted integral over a broad and partially overlapping X-ray spectrum. As a result, spectral information is encoded through a limited number of discrete measurements rather than explicit photon energy resolution, leading to inherently coarse spectral sampling. These limitations highlight a central challenge for post-rotation CT architectures: increasing spectral and quantitative information under limited angular sampling and strict temporal constraints. This challenge is particularly acute for stationary CT systems, where image quality critically depends on extracting maximal information from sparsely sampled projections, motivating the development of energy-resolving detectors for true spectral CT imaging (Figure 1).

SPECTRAL IMAGING: AN INFORMATION FOUNDATION FOR STATIONARY CT

Spectral imaging has emerged as a critical capability for next-generation CT systems, particularly for architectures that depart from dense angular sampling and conventional acquisition paradigms. The emergence of photon-counting detectors (PCDs) has significantly advanced spectral CT imaging. By leveraging direct-conversion semiconductor materials (e.g., CdTe, CdZnTe), PCDs convert incident X-ray photons directly into electrical signals, enabling simultaneous photon counting, energy discrimination, and multi-energy data acquisition.³ Through optimal combination of energy-threshold data, clinical PCD-CT systems can achieve excellent image quality while preserving rich spectral information. These intrinsic capabilities provide a critical information foundation for spectral imaging. Clinical translation has already begun, exemplified by the Siemens NAEOTOM Alpha system introduced in 2021, which enables multi-energy coronary CT angiography and improved assessment of coronary disease and myocardial perfusion.⁴

Despite these strengths, spectral decomposition with PCD data inherently relies on measurements with reduced photon statistics in individual energy thresholds. While this is effectively managed in conventional rotating CT through threshold combination and optimized weighting, the challenge becomes more pronounced in emerging stationary CT architectures. Unlike rotating systems, stationary CT operates under sparse-view, multi-source acquisition conditions, where spectral decomposition must be performed with angular undersampling, increasing noise amplification and reconstruction instability.

Against this backdrop, advanced reconstruction methodologies play an increasingly important role. Rather than merely iteratively minimizing discrepancies between measured and predicted projections, iterative recon-

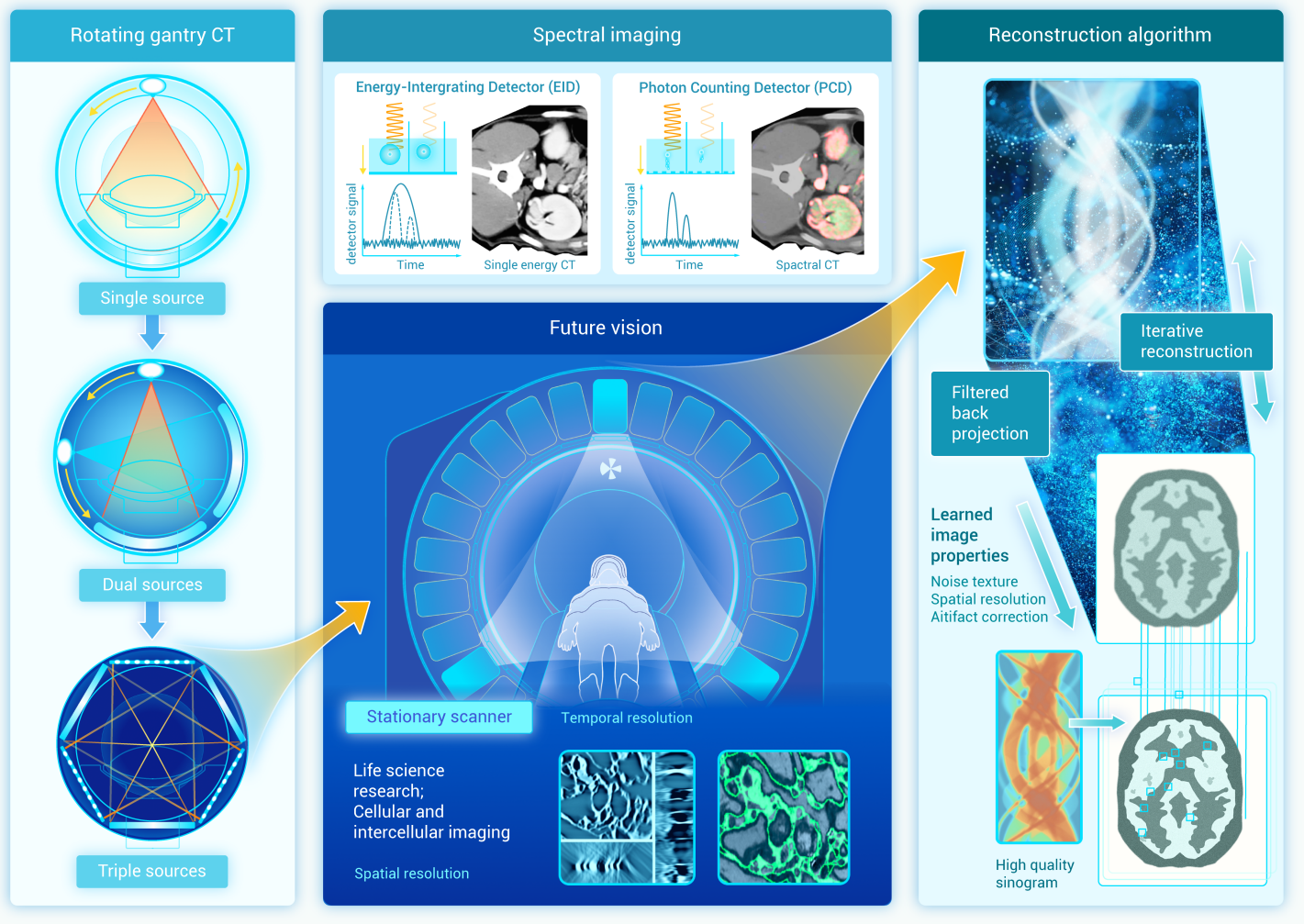


Figure 1. Evolution of CT technology Evolution of CT technology across system architecture, detectors, and reconstruction, highlighting the transition from conventional rotating systems toward emerging stationary CT paradigms.

struction (IR) frameworks derive their primary strength from incorporating diverse constraints and prior knowledge into the reconstruction process. In particular, their ability to integrate sparse-view sampling, multi-source geometry, and constraint-based spectral modeling within a unified framework makes IR especially well suited for stationary CT configurations. Nevertheless, repeated forward–backward projection operations introduce substantial computational overhead, leading to prolonged reconstruction times that remain a major obstacle in time-critical clinical workflows. Moreover, the nonlinear, constraint-driven nature of IR results in contrast-dependent spatial resolution, under which conventional image quality metrics such as modulation transfer function (MTF) and noise power spectrum (NPS) are not always well defined.

Consequently, spectral detectors and reconstruction algorithms should be viewed as tightly coupled components within a unified system design. Reconstruction frameworks that explicitly model detector response and photon-counting statistics offer a promising pathway to fully exploit spectral information under sparse and stationary acquisition conditions. In this sense, spectral detection does not represent an isolated technological advance, but rather a foundational element that enables the transition from rotation-based CT toward stationary, electronically steered imaging architectures.

STATIONARY CT: ARCHITECTURE, CHALLENGES, AND CO-DESIGN PRINCIPLES

The temporal limitations of rotating gantries have spurred stationary CT systems, which eliminate mechanical motion entirely. Compared with state-of-the-art rotating systems, including dual-source CT, stationary CT employs distributed, electronically addressable X-ray sources to enable quasi-simulta-

neous multi-angle acquisition. This improves temporal fidelity under motion, reduces motion blur. In addition, by eliminating mechanical rotation, slip rings, and complex gantry structures, stationary CT simplifies system design, reduces size and mechanical complexity, and enhances robustness.⁵ The use of distributed cold-cathode sources further alleviates high focal spot heat loading, enabling more efficient thermal management and compact system configurations.

However, the architectural shift alters the data-acquisition physics of CT imaging and introduces a set of tightly coupled physical and computational challenges. Simultaneous emissions from distributed source arrays (e.g., cold-cathode sources⁶) introduce severe cross-scatter and provide limited photon flux. In addition, the limited number of distributed sources results in inherently sparse or non-uniform angular sampling. From a mathematical perspective, these factors degrade the conditioning of the forward operator: sparse sampling reduces data completeness and enlarges the null space, while low photon flux increases noise sensitivity. Meanwhile, cross-scatter introduces structured model mismatch that violates the ideal linear attenuation assumption and leads to bias in the reconstructed images. Their combined effect further exacerbates the ill-posedness of the inverse problem, making the reconstruction more sensitive to noise and modeling errors, and ultimately degrading stability and quantitative accuracy.

Data-driven reconstruction methods, including deep learning–based approaches, show strong potential for recovering images from sparse and noisy data.⁷ However, purely data-driven methods may introduce hallucinated structures unsupported by measurements, raising concerns about clinical reliability. Moreover, limited interpretability and uncertainty quantification hinder confidence assessment, especially under nonstandard acquisition

conditions. These limitations highlight the need to incorporate explicit physical constraints, such as system geometry, noise statistics, and data consistency, into reconstruction frameworks.⁸

These limitations suggest that image reconstruction is no longer an independent post-processing step but a central component that co-defines system performance together with hardware and acquisition.⁹ This interdependence reflects a shift toward coordinated system–algorithm co-design and, at the same time, defines the current research landscape in stationary and multi-source CT, which is primarily focused on addressing these coupled challenges through scatter-aware modeling and correction for multi-source interference, reconstruction methods tailored to sparse and ill-conditioned acquisition (including physics-informed and learning-based approaches), and hardware innovations aimed at improving photon flux and acquisition efficiency.

Ultimately, for stationary CT systems, image quality, temporal fidelity, and dose efficiency are jointly determined by coordinated design across hardware, acquisition, and computation. In this regime, co-design is not optional but essential for translating the theoretical advantages of stationary CT into clinically viable imaging performance.

FUTURE PERSPECTIVES: TOWARD PRACTICAL AND INTELLIGENT STATIONARY CT

The future development of stationary CT is expected to follow a unified trajectory driven by three coupled advances: stationary hardware innovation, spectral imaging and physics-informed reconstruction. Collectively, these advances enable CT to move beyond mechanically constrained structural imaging toward multiscale, dynamic, and quantitative characterization, while jointly enhancing temporal and spatial resolution—the two fundamental dimensions of CT imaging.

Stationary CT enhances temporal resolution through electronically steered multi-angle acquisition, which improves angular synchrony and shortens the exposure time per projection. Importantly, this improvement does not rely on fully simultaneous acquisition—constrained by cross-scatter, spectral contamination, and patient safety—but instead is achieved through rapid electronic source switching. This acquisition paradigm places stringent demands on both X-ray sources and detectors. Micro-focus sources enable high spatial resolution, while distributed compact sources aim to deliver sufficient photon flux in short acquisition times, though this is limited by thermal constraints. On the detector side, high frame rates, together with high spectral resolution and detection efficiency, are essential to maintain adequate signal-to-noise ratio under rapid imaging conditions, thereby enabling high-quality spectral imaging.

These hardware and acquisition advances, in turn, necessitate corresponding developments in reconstruction methodologies. Reconstruction serves as the computational bridge that converts measurements enabled by advanced hardware and acquisition strategies into clinically meaningful images, making it central to stationary CT. Because stationary CT involves sparse sampling and complex geometries, reconstruction must be closely integrated with system design and explicitly model acquisition physics and noise. This motivates hybrid, physics-informed reconstruction strategies suited to stationary and sparsely sampled architectures.¹⁰ Together, coordi-

nated progress in reconstruction and hardware underpins high temporal and spatial resolution in stationary CT systems.

From a translational perspective, the successful clinical deployment of stationary CT will also depend on practical considerations such as system complexity, detector cost, radiation collimation, and the long-term reliability of distributed components. While not fundamental physical limitations, these factors may affect clinical adoption and workflow integration. Overall, stationary CT has the potential to redefine CT imaging beyond a mechanically limited structural modality, highlighting the broader clinical and scientific significance of overcoming spatiotemporal constraints. More importantly, it represents a realistic pathway toward electronically steered, dynamic, and quantitatively enhanced imaging.

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.