The Evolution of CT Acquisition

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Abstract

Computed Tomography (CT) was the first digital medical imaging modality and revolutionized diagnosis with cross-sectional images in the 1970's. The evolution of CT acquisition has followed its own form of "Moore's Law", with most metrics doubling every 25 months for the past three decades, improving by more than a factor of 50,000 over that time. This has been enabled in part by faster electronics but also by clever designs that extend scan geometries, which require more sophisticated reconstruction algorithms. Recent developments indicate a continuation of this trend, creating new clinical applications. Current major issues include reduction of radiation dose and quantitation of material properties.

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Clinical Utility of Sectional Imaging

The original medical imaging modality was x-ray imaging, invented at the end of the 19^{th} Century, which was very successful in diagnosing disease, due in large part to the highly developed interpretive skills of radiologists. However, a two dimensional (2D) projection image was fundamentally limited in its ability to provide three-dimensional (3D) location and differentiate small contrast changes within the body. Computed Tomography was the first medical imaging modality to allow sectional imaging when it was introduced in the early 1970's. The great advantage of sectional imaging was the high contrast that was possible within a designated localized image section. This allows much more accurate clinical diagnosis and is now widely utilized in healthcare.

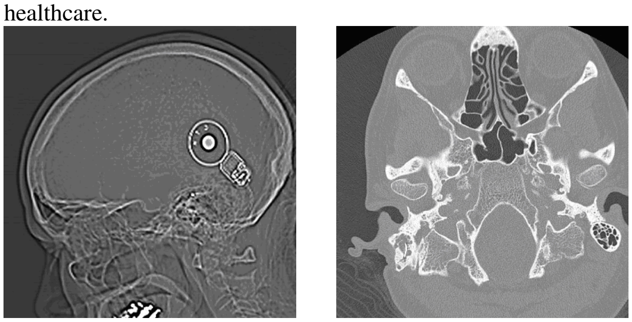

***Figure 1**. X-ray image on right lacks soft-tissue contrast and 3D detail of CT image slice on the left.*

A key factor in clinical practice is the time that it takes to scan an section of the body. This must be done in biologically relevant times (e.g., one breath hold, one heart beat) or images are distorted by motion. Driven by the clinical benefits, manufacturers have improved the performance of CT scanners at an impressive rate, equivalent to a form of "Moore's Law" with performance doubling every 25 months for over 30 years. A metric such as acquired pixels per second has increased by a factor of 10^5 in that time. This is comparable to Moore's Law for computer technology, which is considered to double every 18 months. How was such progress accomplished? Increased computer power played a role, but in fact a very multidisciplinary approach was required in the fields of electro-mechanical engineering, x-ray source technology, x-ray detectors, analog and digital electronics, and algorithm development, as well as innovative system integration designs.

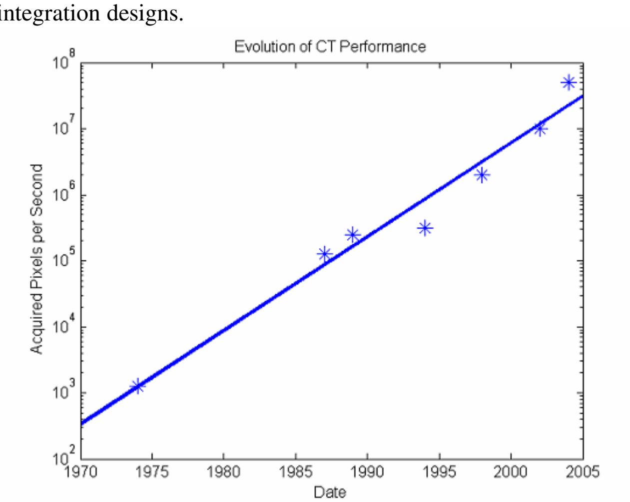

***Figure 2**. Plot of the metric for pixels acquired per second versus date reveals that performance doubles has doubled every*

Historical Steps in CT Design

To accomplish the pace of increasing performance in CT scanning, the over-riding theme in CT system design has been to parallelize operations in the scanning process. This can be seen in the early "generations" of CT scanner design [1]:

- 1^{st} Generation (1970): Single beam/single detector, translate/rotate by steps, 24 hrs/slice
- 2^{nd} Generation (1972): Partial fan beam, multiple detectors, translate/rotate by steps, 300 sec.
- 3^{rd} Generation (1976): Rotating fan beam and detector bank, 5 sec.
- 4^{th} Generation (1978): Stationary detector bank, rotating fan beam (or electron beam source), 5 seconds.

The next innovation involved the use of slip ring technology to supply electrical power and information transfer to the rotating gantry, allowing continuous 360º rotations without pausing to rewind cables. In the late 1980's the concept of helical/spiral scans was introduced, translating the patient bed continuously through the scan head, eliminating the start/stop motion of patient stepping. All the while, digital electronics processed with faster sampling rates and more computer power for faster reconstructions. By the late 1990's, the rate limiting factors were inertial forces in the rotating gantry and the amount of x-ray flux that a tube could deliver without melting. To overcome these obstacles, the concept of multi-row detector scanners were introduced, using multiple rows to utilize more of the cone beam output of x-rays and performing parallel measurements in the scan. The latest wrinkle is a recently announced system that consists of dual set of x-ray source/multirow detector bank, which are mounted orthogonal to each other in the gantry, essentially doubling the scan speed. Each of these innovation steps had significant implications for the components of the system, including reconstruction algorithms.

Reconstruction Algorithms

The acquisition step involves the measurement of the x-ray beam flux transmitted through an object, which under certain conditions can be shown to be equivalent to the superposition of all the attenuations in the beam path. This can be viewed as a linear algebra problem, with a number of unknowns (pixels in the image, typically 512x512~250,000) and a number of equations (each measurement, typically $\sim 10^6$). While such matrices are too large to be inverted directly, iterative schemes are available to solve for an image, albeit requiring large computational resources. Alternative approaches employing analytic solutions are based on Radon's theorem, which was first discovered in 1917. This states that an image of any region of a plane can be recovered if there are sufficient measurements taken by rays passing at all orientations with each point in the plane. An intuitive feel for this theorem can be obtained by considering the projection of an object at one orientation. The Fourier transform of the projection represents a line in the frequency domain representation of the object. By making measurements of at all orientations, the frequency domain representation of the object can be obtained, the so-called "Central Slice Theorem". For discrete samples, transforming from the frequency domain back to the image domain is nontrivial. The algorithm that overcomes this, and made clinical reconstructions feasible, is called "filtered back projection", which applies a ramp filter in the frequency domain before projection in the image domain and allows rapid image computation [2]. Intuitively, this is equivalent to signal averaging with specific kernel in order to separate contributions in the measurements for specific image points. This has been the exclusive method of reconstruction for the past 30 years, until recently when multirow detectors began to violate the assumption planar data, requiring new algorithms for cone beam geometries. This is currently an active area of research.

System Components

A CT acquisition system consists of many components, spanning a range of technical disciplines, and each undergoing significant improvements in performance for acquisition. These will be briefly described:

- X-ray sources: A beam of electrons is accelerated into a target, which then emits x-rays upon atomic collisions. The energy transfer is inefficient, with most of the energy converted into heat. Anodes are rotated to spread the heat over larger areas and thermal radiation allows cooling. Recent designs use electron optics to steer the beam into different locations for spatial sampling and incorporate direct liquid immersion to transfer heat.
- Gantry: The rotation of the housing for electronics, x-ray tube, and detectors causes an environment with forces up to 30 G's (3 rps with a 0.5 m radius), while maintaining position accuracies of 50 μm.
- Detectors: Originally pressurized gas sensors were used as energy converters, but recent designs rely on solid state scintillators, such as ceramic rare earth phosphors. These are now fabricated in integrated modules, housing hundreds of detectors and their support electronics.
- Signal electronics: The dynamic range of measured signals can approach 10^6, with readout rates in the megahertz range. Auto-ranging analog amplifiers and fast A/D converters contribute negligible noise to the data stream.
- Reconstruction Compute Engines: ASIC chips perform reconstructions using kernel or Fourier domain filtering, reaching 20 images per second (10 MP/s) rates.

Future Technical Directions

The pattern of parallelization is approaching some fundamental limitations due to mechanical forces. One likely alternative for acquisition will utilize the development of flat panel detectors for x-ray projection imaging. These are large devices (~ 40 cm wide) with relatively small (~100 μm) pixels that could acquire the whole volume of a patient in a single rotation. Thus the rotation rate could be much slower and still satisfy sampling requirements. A key obstacle is the presence of scattered radiation caused by the large volume exposed at once. New reconstruction algorithms will be required to handle the issues of non-planarity.

Another important issue with x-ray CT is the concern with radiation dose. Although CT imaging is used on only a small fraction of patients seen in radiology, it accounts for almost 2/3 of the man-made dose in the whole population. Schemes are being deployed to minimize this exposure by adaptively modulating x-ray tube current to use an amount "as low as reasonably achievable". CT images have a unique, global pattern distinct from normal x-rays.

Future Clinical Applications

The rapid acquisition times and new features have enabled many new clinical applications. Cardiac imaging is benefiting from scan times as short as 18 msec, which can freeze heart motion in any portion of the cardiac cycle. "Fluoroscopic CT" may make possible interventional surgery with direct image guidance. As low-dose protocols are defined, population screening for disease such as "virtual colonoscopy" or at-risk tobacco users may be feasible. As a research tool, micro CT devices are being used for animal studies of genetics and pharmacology development.

Forecasting Progress

A decade ago, CT was considered a mature technology with very little prospects for improvements and was not seen as a promising area for technology research. Nevertheless, rapid advancements followed and "Moore's Law" has held well into its fourth decade. How long can this continue? Much like computers and magnetic storage, the demise of CT acquisition advancement has been long predicted but at the present shows no signs of occuring.

References

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[2] Hsieh, J. (2003). Computed Tomography. Bellingham WA, SPIE.

Author Biography

Bruce Whiting is a Research Assistant Professor at the Washington University School of Medicine, with 21 years of experience in medical imaging. He joined the Health Imaging Division of the Eastman Kodak Company in 1984, contributing to the development of digital x-ray systems based on storage phosphors and holding several research management positions. While in Rochester, he held several offices in the IS&T Chapter, including president. Since moving to the Electronic Radiology Lab at the Mallinckrodt Institute of Radiology in 1997, his research interests include modeling the physics of CT acquisition and development of CT reconstruction algorithms.