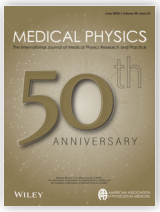
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Early CT physics research at Massachusetts General Hospital

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Abstract

Although CT imaging was introduced at Massachusetts General Hospital (MGH) quite early, with its first CT scanner installed in 1973, CT research at MGH started years earlier. The goal of this paper is to describe some of this innovative work and related accomplishments.

1 INTRODUCTION

On August 2, 1973, Massachusetts General Hospital (MGH) became the second institution in the US to install an x-ray CT scanner.[1] However, that was not the beginning of CT research at MGH; that had begun years before. Here, we describe this early CT physics work.

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The Physics Research Laboratory at MGH was founded by Gordon Brownell, who pioneered positron imaging using coincidence detection in the 1950s to achieve much higher efficiency than could be obtained with collimators.[2] By 1970, the Physics Research Laboratory was focused on all aspects of positron imaging (instrumentation, tracers, applications) and also on computer processing in nuclear medicine. The group had developed the positron camera, PC-I, which had two 2-D arrays of NaI crystals, each in coincidence with 25 crystals on the opposite face,[3] and the camera arrays could translate parallel to the detector faces to increase spatial sampling. When the counts in the lines of response were projected back onto focal planes, the system produced tomograms with 2D blurring functions.

2 DEVELOPMENT OF FILTERED BACKPROJECTION RECONSTRUCTION

In 1970, the work at EMI that would revolutionize radiological imaging was still largely unknown but there was research activity in many centers on tomographic imaging in nuclear medicine. Like in x-ray tomography at the time, available methods could produce an image in which objects on the focal plane would be in focus but objects outside that slice would be blurred and superimposed. That was the case with the tomographic images produced by PC-I, as described above.

Early in 1970, David Chesler at MGH realized that projections from equally spaced angles all the way around the object could be used to produce accurate reconstructions of any plane through the object, that, for positron emitters, transmission measurements could be used to correct for absorption of the annihilation photons

in the object, and he developed the filtered backprojection algorithm for reconstruction (Figure 1). He initially validated the reconstruction method using simulated data. The first test with experimental data was in mid-1970.[2] He acquired emission and transmission projections of a circularly symmetric annular phantom using a simple table-top set-up that measured a single projection with only one coincidence detector pair, and produced three tomographic images, an emission image, an attenuation corrected emission image, and an image of the distribution of attenuation coefficients (at 511 keV) from the transmission measurements (Figure 2). He then applied the technique to emission data collected with a gamma camera and with the then-recently completed PC-I (Figure 3). This innovation was first described at the Society of Nuclear Medicine meeting in 1971 and the Symposium on Radionuclide Tomography the following year.[4, 5]

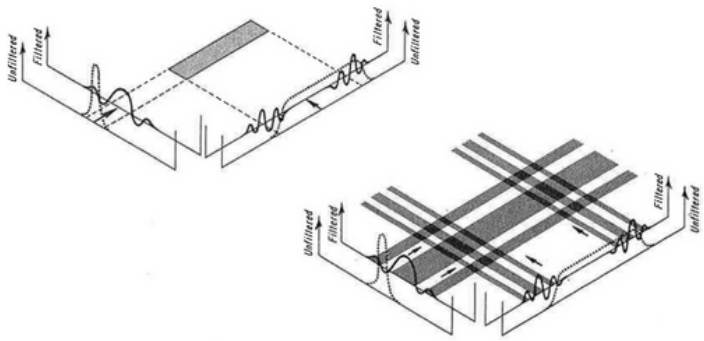


FIGURE 1 Open in figure viewer | PowerPoint

Graphical description of filtered backprojection. Reprinted from ref. 5.

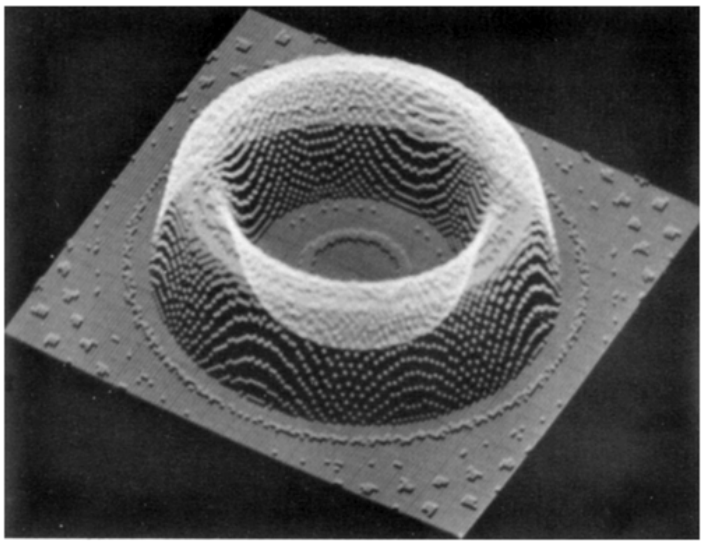


FIGURE 2 Open in figure viewer | PowerPoint

Absorption corrected image of ^{68}Ga in a cylindrical annulus. Apparent height is proportional to reconstructed value. Note ~0 values outside the phantom. Reprinted from ref. 5.

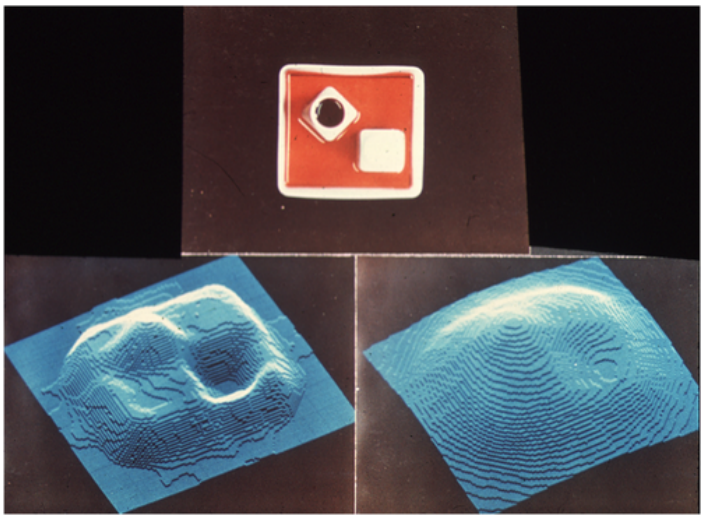


FIGURE 3 Open in figure viewer | PowerPoint

(top) Photograph of a phantom. The square inner region

was filled with dilute ^{99m}Tc while the white square created a cold region and the round region in the other square contained a higher concentration of ^{99m}Tc. (lower left) Reconstruction using filtered backprojection. (lower right) Reconstruction with simple backprojection. Apparent height is proportional to reconstructed value. Reprinted from ref. [5].

At the time of this work, Chesler was unaware of the work at EMI, or the work of Cormack, or the reconstruction research in radioastronomy (e.g., by Bracewell). He had learned of the work by DeRosier and Klug[6] from another former MIT student, Thomas Huang, before Chesler started working on radionuclide imaging. The 1968 paper described reconstruction from electron micrographs starting with the projection slice theorem (which was known to crystallographers) and used interpolation in frequency space. Huang also told Chesler about reconstruction work by Oleh Tretiak, another MIT alum who, at the time, was on the MIT faculty and had conceived of reconstructing 3D images from x-ray projections, also by interpolation in frequency space, and tested his method using digitized ex-vivo radiographs of a bone rotated on a turntable.[7] Chesler recognized he could use backprojection rather than interpolation in frequency space if the projections were first filtered by a ramp filter (Figure 1).

These were the first-ever accurate (i.e., not blurred) tomograms of radionuclide emissions. Chesler's reconstruction of attenuation coefficients from the transmission measurements places him among the first to produce transmission CT images (although after Cormack, Hounsfield, and Tretiak), and possibly the first using backprojection. The images were limited by the

quantum noise in the projections. The data was adequate for absorption correction of the emission measurements but would have required very long acquisition times to produce high quality attenuation images. As it turned out, perhaps for this reason or the poor contrast of attenuation coefficients at 511 keV, reconstruction of the attenuation data by itself was seldom performed by the MGH group.

His derivation called for use of a ramp filter in frequency space. The images had ringing artifacts at rapid transitions in intensity, as did the early images from the EMI head scanner (even though the latter were reconstructed with an algebraic algorithm). Chesler recognized that these were due to the sharp cutoff of the frequency response of the algorithm, and that they could be reduced with a more gradual roll-off of the filter. The group showed that a Hanning window achieved good results at the expense of spatial resolution if the same cutoff frequency was used, but that the spatial resolution and noise would be comparable if the sampling rate and frequency cutoff were doubled.[8] This could be done with the translational movement of the positron camera. However, Chesler also realized that if the center of rotation was aligned off-center by 1/4 sample, rays from 180° opposed projections would interlace and provide the needed sampling increase, a technique that would later be applied to x-ray CT by the MGH group and others and termed quarter-offset. The research also found that computing the filtered projection with finer sampling than the measured rays, which can readily be done, led to more accurate images with a small penalty in computation time.[8]

3 MGH TRANSVERSE SECTION X-RAY CAMERA

In mid 1972, Gordon Brownell decided that the Physics Research Lab at MGH would embark on a major effort to build a whole-body CT scanner and communicated the decision to the relevant lab members, including David Chesler and Charles Burnham, the latter being the gifted engineer/researcher who had built other complex instruments at MGH, including two positron cameras. This decision is remarkable in several ways, including the timing. At the time there were no CT scanners installed in the US. Only two public presentations of x-ray CT images from the EMI scanner had taken place, one at the British Institute of Radiology meeting in April 1972 and one at a neuroradiology course in New York about a month later. The unveiling of the EMI scanner at RSNA was still months away, and the first installations in the US (Mayo Clinic and later MGH) were not until 1973. What motivated Brownell, a scientist who certainly knew x-ray physics but whose own research had been focused on radionuclide imaging and other medical uses of nuclear physics? It is likely that the decision was influenced by Juan Taveras, Radiologist-in-Chief at MGH, who had attended the presentation in New York and had hosted a visit to MGH by EMI (likely including Hounsfield) in May 1972.[9]

One target application for the whole-body scanner would be imaging of abdominal cancer. The group realized that the scan time would need to be greatly shortened compared to the 5-min required by the EMI head scanner. They targeted a required acquisition time of 10 seconds for a 360° scan of a single slice. To achieve this, they adopted a rotating fan-beam (later called “third generation”) design. They also realized that the images would be useful for radiation therapy treatment planning,[1] both by providing accurate definition of the anatomy of the tumor and surrounding radiosensitive tissues, and also estimates of the absorption an external beam would experience before reaching the tumor.

Consistent with the “camera” term included in the names of positron imaging instruments previously built by the group, the new machine was dubbed the “MGH Transverse Section X-ray Camera”.

Brownell reached out to American Science and Engineering (AS&E), a firm in Cambridge, MA that had previously developed scanning x-ray systems, to explore the possibility that MGH and AS&E might join forces in this effort. The next step was a meeting between Chesler of MGH and Jay Stein of AS&E. Both remember the meeting as a cordial and interesting discussion. At this meeting, Stein wondered whether the scans would require an unreasonably high radiation dose and asked Chesler whether the need to reconstruct images from projections imposed a major dose penalty. Chesler derived the relationship between photon statistics and CT image noise that evening and obtained the surprising finding that the noise variance in reconstructions was only ~1/3 higher than the variance that would be achieved if reconstruction was not required. He communicated this to Stein who was similarly surprised. This result was included in Chesler's presentation of filtered backprojection at the Symposium on Radionuclide Tomography in September of 1972[5] and later published in a peer-reviewed paper.[10]

AS&E decided not to embark on the project with MGH. One wonders what might have happened if the collaboration had ensued. As we know, about 2 years later AS&E was part of the collaboration that won a contract from the National Cancer Institute (NCI) of NIH to build a whole-body scanner, and that led to the development of the 4th generation CT architecture.[9] If the MGH-AS&E collaboration had happened in 1972, would the 4th generation design have been developed 2 years earlier?

The MGH group decided to apply for funding from NCI to conduct research and build a system. The application, entitled “Transverse Section X-ray Camera” was submitted in the first half 1973 (again, about 2 years before responses to the NCI RFP to build a whole-body CT system) and funded in Nov 1973 (CA015882), providing ~$380K over 3 years. Figure 4 shows an artist's conception of the system from an article published at the time.[1]

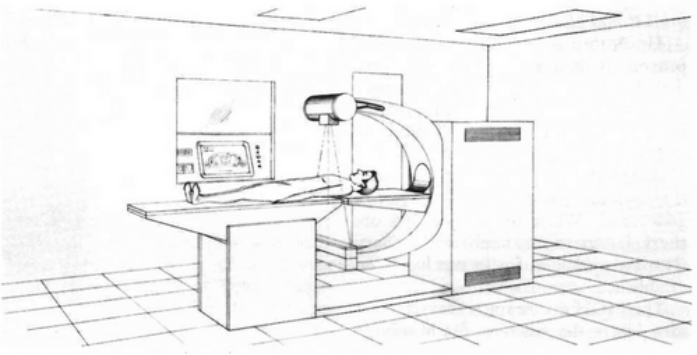


FIGURE 4 Open in figure viewer | PowerPoint

Artist's conception of the MGH transverse section x-ray camera.[1] Courtesy of Massachusetts General Hospital.

David Chesler led the project and defined the reconstruction and other needed algorithms. Among the proposed specifications were: 360° rotation of a fan beam in a 10 s. breath-hold for a single slice, ~2 mm spatial resolution, noise standard deviation of 0.5% of the attenuation coefficient of water. He understood the stringent requirements for detector (and measurement electronics) performance due to sensitivity to ring artifacts. Reconstruction was by rebinning to parallel rays with doubled sampling from quarter-offset alignment and 360° rotation. One unique aspect of the geometry was

that the fan-beam rays were not equiangularly spaced. Instead, they were equally spaced in radial distance (i.e., their perpendicular distance to the center of rotation) so that no radial interpolation was needed in the rebinning step. The computational team, led by Linda Deveau and Joan Correll, who had built nuclear medicine computer systems at MGH, selected the recently released Data General Eclipse minicomputer for the scanner.

Detector development was led by Richard Lanza, a physicist from MIT with significant experience in detector design. After considering several options including gas-filled detectors, direct conversion semiconductors, and scintillator-photodiode designs, he selected high pressure (10 atm) xenon in ionization chamber mode since his group had previously built gas-filled multi-wire proportional counters for medical applications[11] and counting photons was out of the question at the time. The detector was in a straight (not curved) pressure vessel with a high voltage electrode on one side (in z) of the x-ray beam and a circuit board with 256 signal electrodes on the other side of the beam. The signal electrodes printed on the circuit board defined the measurement paths that were equally spaced in radial distance with quarter-offset alignment. In contrast to later designs that had electrode plates within the fan beam,[12] this detector was susceptible to crosstalk from fluorescence x-rays and required a higher voltage to achieve the needed electric field (due to the larger spacing of the electrodes).

The detector electronics design was led by Charles Burnham, who had developed the positron imaging systems at MGH. The current from each detector channel was integrated in a capacitor, but Burnham worried that the time-varying voltage could lead to nonlinearities. He came up with a creative idea that both avoided this problem and performed digitization at the same time.

The voltage on the capacitor was compared to a reference, and each time it exceeded this reference a small negative charge pulse would be fed to the capacitor and a counter would be incremented. This kept the capacitor voltage nearly constant. The exact value of the charge pulse determined the channel gain which was corrected by calibration (as was the dark current). This design also avoided accumulation of round-off error since any charge remaining on the capacitor at the end of one view was carried over to the next view.

As subsystems were completed, they were integrated into a table-top system, largely by John Dobbs, Tim Walters, and Gerald Polucci. The system had a fixed anode x-ray source with a highly regulated power supply and an oil-to-water heat exchanger. Walters also wrote much of the system software. The table-top system was completed and was used by several doctoral students.[13] Unfortunately, the envisioned full gantry-mounted system was not built.

4 RELATED CT RESEARCH

In addition to the research related to the design and construction of the fan-beam system that had the innovative aspects described above, the project created an environment that fostered creative work and contributed to the education of trainees.

Early on in the project, Chesler derived the relationship between dose, noise, and spatial resolution. He also recognized that, in contrast to 2D x-ray or nuclear images with uncorrelated noise, the noise in reconstructed images would have spatial correlations that would cause the variance of the average of the values in a region of interest (ROI) to depend on the shape of the ROI.[14] The variance of the mean of values in a round ROI would be

lower than that from a long but narrow ROI of the same area, relevant to the use of CT images for radiation therapy treatment planning.[14] This was fully explored in a paper describing the noise power spectrum in x-ray CT.[15]

Computer simulation was used not only in the system design and in the studies described above, it was also used to explore various artifacts and the impact of system imperfections. This included spatially dependent CT number errors from beam hardening, and artifacts from an insufficient number of projections, view truncation from a limited measured field-of-view, and errors from non-parallel rays after imperfect rebinning. Also studied were the spatial resolution limitations from the focal spot (including the target angle and the resulting dependence on location in the field of view), system misalignment, and object motion.[14, 16, 17] The understanding of motion artifacts in turn led to a grant application in 1976 to develop cardiac-gated CT that was unfortunately not funded.

Other research projects included CT bone densitometry[18] and dual energy CT.[13, 19] Among the accomplishments in the latter were the first experimental demonstration of quantitation of electron density and effective atomic number and exploration of the optimal kVp for dual energy imaging in which the spectral modulation is accomplished by a switching filter.[13]

5 CONCLUDING COMMENTS

We discussed some of the research at the Physics Research Laboratory of MGH in the early to mid 1970s. This was an exciting time in medical imaging, with the advent of reconstruction methods for emission and transmission computed tomography. The work at MGH was highly innovative. Some, such as the description of

noise in CT, is well-recognized while other is less so; we sought to tell some of this history as we recognize significant anniversaries of the development of CT and of Medical Physics.

One might argue that describing this history of an academic laboratory is perhaps not warranted. After all, a major fraction of the technical innovations in CT developed in the 1970s occurred in industry, not academia, by individuals who were perhaps not aware of these earlier developments. Were research efforts like these in academia needed? However, it should be appreciated that in 1972, when the project to build the MGH Transverse Section X-ray Camera began, the EMI head scanner had just been introduced and the major imaging companies were not involved in CT (at least publicly).[9] In that context, the research to build a fast whole-body CT scanner was highly innovative and worthwhile. In addition to the new knowledge generated by the project, it was foundational for the trainees who went on to successful careers in our field. The stories of such programs should not only be told, they should be a template for future endeavors.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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