LA-UR-96- 3059

Title: **Prototype Demonstration of Radiation Therapy Planning Code System**

Author(s): **Robert C. Little, X TM**
Kenneth J. Adams, X TM
Guy P. Estes, X TM
H. Grady Hughes III, X TM
Laurie S. Waters, LER APT

Submitted to: **DOE Office of Scientific and Technical Information (OSTI)**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

Los Alamos
NATIONAL LABORATORY

Form No. 836 R5
ST 2629 10/91

Prototype Demonstration of Radiation Therapy Planning Code System

Robert C. Little*, Kenneth J. Adams, Guy P. Estes,
H. Grady Hughes III, and Laurie S. Waters
Los Alamos National Laboratory

John J. DeMarco, James B. Smathers, Timothy D. Solberg, and Robert E. Wallace
University of California-Los Angeles

Ronald C. Brockhoff
Kansas State University

Michelle L. Hart
Ohio State University

Abstract

This is the final report of a one-year, Laboratory-Directed Research and Development project at the Los Alamos National Laboratory (LANL). Radiation therapy planning is the process by which a radiation oncologist plans a treatment protocol for a patient preparing to undergo radiation therapy. The objective is to develop a protocol that delivers sufficient radiation dose to the entire tumor volume, while minimizing dose to healthy tissue. Radiation therapy planning, as currently practiced in the field, suffers from inaccuracies made in modeling patient anatomy and radiation transport. This project investigated the ability to automatically model patient-specific, three-dimensional (3-D) geometries in advanced Los Alamos radiation transport codes (such as MCNP), and to efficiently generate accurate radiation dose profiles in these geometries via sophisticated physics modeling. Modern scientific visualization techniques were utilized. The long-term goal is that such a system could be used by a non-expert in a distributed computing environment to help plan the treatment protocol for any candidate radiation source. The improved accuracy offered by such a system promises increased efficacy and reduced costs for this important aspect of health care.

---

*Principal investigator, e-mail: rcl@lanl.gov

1. Background and Research Objectives

The incidence of cancer in the United States is significant. It has been estimated that in 1992, the number of new cancer cases in the US was 1.1 million, with 0.5 million deaths due to cancer. The cumulative effect, or prevalence, due to the 0.5% yearly incidence rate may be ten times the yearly incidence.

Over the last thirty years, the improvement in radiation therapeutic techniques has been significant. Improved knowledge of the dose delivered to any small volume of the patient and a better understanding of biological response of normal tissues have allowed physicians to deliver higher (and thus more lethal) radiation dose to cancerous tumors while sparing normal tissues from persistent deleterious effects of irradiation. However, the aggregate effect of this work has been to improve patient absolute survival from about 40% in the 1960-63 era to about 52% in the 1981-87 era. Significant to radiation control and eradication of cancer is the ability to deliver ever higher dose to approach tumoricide while maintaining a confidence that normal tissues are able to self-repair.

The field of predictive radiation dosimetry to custom design patient treatments is well established, having evolved from semi-empirical methods first developed in the 1950s. Many of these methods persist to this day embodied in computerized systems for treatment planning. The results of National Cancer Institute (NCI) studies indicate that there is much room for improvement in the science of radiation therapy planning. The failures of conventional planning systems fall into many categories that include the scope of models of patients and radiation sources, display of anatomy and dose-distributions, among others.

The summary recommendations of the Photon Treatment Planning Collaborative Working Group, a joint panel of the National Institutes of Health (NIH) and NCI, are unambiguous: "Improvements in dose algorithms so that they can handle local doses more accurately in regions of irregular and inhomogeneous tissue structure are needed to realize the full benefit of 3-D anatomical display." A further specific conclusion was that: "Fully quantitative evaluation of the role of inhomogeneity corrections in treatment planning requires an as yet unavailable all-encompassing accurate method of dose calculation." We are endeavoring to ultimately provide just that.

Our long-term vision is an end-product that will be an integrated, easy-to-use, interactive software system that will be in routine use by technicians and radiation specialists at medical facilities throughout the United States. Computational resources will be of a seamless, distributed nature, supported by high-speed communications, so that smaller facilities without large local computational resources will still be able to participate. The product will support all types of radiation therapy facilities, including conventional (photon/electron) therapy, neutron therapy, proton therapy, and heavy-ion therapy. In addition, various modalities of treatment will be supported, such as stereotactic radiosurgery, conformal therapy, and brachytherapy.

The objectives of this one-year LDRD project are necessarily much more modest: demonstrate and validate prototype capabilities necessary for the components of a radiation therapy planning system.

2. Importance to LANL's Science and Technology Base and National R&D Needs

The relationship of this project to national R&D needs was described in Part 1. Importance for LANL's science and technology base is also clear. This project supports several Laboratory competencies including theory, modeling, and high-performance computing; bioscience and biotechnology; and nuclear science, plasmas, and beams. In addition, it is built upon technologies developed in support of the nuclear weapons program: radiation transport modeling, nuclear data evaluation, experimental nuclear physics, high-performance computing, and scientific visualization. Successful execution of this project will strengthen those capabilities, thereby strengthening the nuclear weapons science and technology competency and providing a compelling example of "dual-benefit." Nuclear weapons personnel will be involved in this project in a manner that will help realize the DOE/Defense Programs goal of science-based stockpile stewardship.

3. Scientific Approach and Results to Date

Our results can be summarized in the following seven categories:

A. Patient-Specific Data in MCNP

Colleagues from the Department of Radiation Oncology at UCLA are developing a preprocessor to MCNP called MCNPRT (MCNP Radiation Therapy) **[1]**. The preprocessor automatically converts raw computed tomography (CT) data from the UCLA Picture Archiving and Communication System (PACS) into a manageable number of MCNP universes. CT data (essentially electron densities) are binned into six major material groups: air, lung, fat, water, muscle, and bone. The six primary groups are further subdivided with respect to density for a total of 17 universe designations. Conventional 512x512 CT matrices are generally scaled to a reduced matrix size ranging from 64x64 to 256x256. MCNPRT also supports all geometric parameters for simulating the bremsstrahlung and electron contamination spectrum from the Phillips SL-25 linear accelerator. This information is utilized to model multiple planar and non-coplanar incident beams and their associated collimators.

B. Electron Physics and Benchmarking in MCNP

Many medical applications requiring predictions of radiation dose to patients depend upon accurate modeling of electron transport. The most recently released version of MCNP, MCNP4A [2], has not been well received in the medical community for conventional radiotherapy treatment planning research due to inadequacies in its electron transport physics models. Several improvements to MCNP electron physics have been made as a result of this project. Specifically, we have explored and improved energy loss straggling, multiple scattering angular distributions, mean ionization potentials, interface crossing approximations, and energy grid sampling. Details are described in Ref. [3] and other informal memoranda; we focus here on the presentation of electron benchmark results.

The first set of results are for electron albedos. The top portion of Fig. 1 shows the percentage of backscattered electrons as a function of incident electron energy (from 10 keV to several hundred keV) for thick targets of aluminum and gold. Calculated results are compared with experiments of Neubert and Darlington. Most interesting is the improved agreement between the latest version of MCNP (labeled MCNP4xp in the figure) and experiment. We believe that the improved agreement is due to the enhanced energy loss straggling model implemented in MCNP4xp. These albedo results are likely to be important for several medical applications; for example, for stereotactic radiosurgery where small pencil beams are used to concentrate dose on specific areas and dose spread could be deleterious, and for brachytherapy where beta or gamma emitters could be placed near bones and the dose significantly perturbed by albedos.

Another benchmark of MCNP's performance is the calculation of the dose in a water phantom delivered by a stereotactic 6-MeV bremsstrahlung photon beam. Experimental ion chamber data and calculated results (both provided by J. DeMarco, UCLA) are shown in the bottom half of Fig. 1. The agreement is very good. We are currently modeling another critical benchmark with regard to MCNP for medical applications: 20-MeV electron deposition in water. This benchmark will be completed and reported at an upcoming Electron Transport Workshop.

In addition, we have benchmarked the multigroup Boltzmann-Fokker-Planck electron-photon transport capability in MCNP [4].

B. Electron Physics and Benchmarking in MCNP

Many medical applications requiring predictions of radiation dose to patients depend upon accurate modeling of electron transport. The most recently released version of MCNP, MCNP4A [2], has not been well received in the medical community for conventional radiotherapy treatment planning research due to inadequacies in its electron transport physics models. Several improvements to MCNP electron physics have been made as a result of this project. Specifically, we have explored and improved energy loss straggling, multiple scattering angular distributions, mean ionization potentials, interface crossing approximations, and energy grid sampling. Details are described in Ref. [3] and other informal memoranda; we focus here on the presentation of electron benchmark results.

The first set of results are for electron albedos. The top portion of Fig. 1 shows the percentage of backscattered electrons as a function of incident electron energy (from 10 keV to several hundred keV) for thick targets of aluminum and gold. Calculated results are compared with experiments of Neubert and Darlington. Most interesting is the improved agreement between the latest version of MCNP (labeled MCNP4xp in the figure) and experiment. We believe that the improved agreement is due to the enhanced energy loss straggling model implemented in MCNP4xp. These albedo results are likely to be important for several medical applications; for example, for stereotactic radiosurgery where small pencil beams are used to concentrate dose on specific areas and dose spread could be deleterious, and for brachytherapy where beta or gamma emitters could be placed near bones and the dose significantly perturbed by albedos.

Another benchmark of MCNP's performance is the calculation of the dose in a water phantom delivered by a stereotactic 6-MeV bremsstrahlung photon beam. Experimental ion chamber data and calculated results (both provided by J. DeMarco, UCLA) are shown in the bottom half of Fig. 1. The agreement is very good. We are currently modeling another critical benchmark with regard to MCNP for medical applications: 20-MeV electron deposition in water. This benchmark will be completed and reported at an upcoming Electron Transport Workshop.

In addition, we have benchmarked the multigroup Boltzmann-Fokker-Planck electron-photon transport capability in MCNP [4].

C. MCNP Efficiency for Dose Calculations

Although the ultimate goal of 1-hour turn-around time for Monte-Carlo-based radiotherapy planning is still in the future, we have been able to increase the efficiency of MCNP for these calculations. Early results indicated that MCNP performed relatively poorly (from a timing perspective) as the number of tally regions increased. This is an important concern, because the need is to calculate dose in every voxel of the patient geometry. We have modified the code to more efficiently utilize the lattice nature of the geometry when making tallies; preliminary results indicate as much as a factor of 500 increase in efficiency for the tally routines. UCLA has optimized the photon tracking routines and introduced a dedicated mesh geometry package that, together, have decreased overall run times by factors of three to four [1]. They have also explored the parallel workstation implementation of MCNP on large workstation clusters such as the 80-node RS/6000 cluster at the Maui High Performance Computing Center.

D. MCNP Dose Calculations with Patient-Specific Geometries

Dose distributions have been calculated with MCNP for actual patient geometry. In Ref. [1], a preliminary dose distribution through the center slice of a 17-slice CT study is presented. The simulation phantom contained approximately 69,000 lattice elements with a voxel dimension of 5x5x4 mm^3. For a 25-MeV photon beam and a 20-mm stereotactic collimator, approximately 50 million histories were necessary to reduce the standard error to less than 5% for the majority of the tally elements. We have made similar calculations at Los Alamos with MCNP based on CT scan data as will be described in the following section.

E. Visualization of 3-D Results

Modern visualization techniques applied to 3-D geometries and calculated results are essential to convey information and understanding of complex simulations such as found in medical applications. Two visualization sets are important to radiation therapy: patient geometry and dose or energy deposition profiles. Standard MCNP geometry plotting capabilities allow 2-D slices of the geometry to be conveniently displayed. Three slices though our test geometry are exhibited in the left-hand-side of Fig. 2. We are researching more complex three-dimensional renderings.

The visualization of energy deposition results was accomplished by taking the ASCII output from MCNP and porting it to a large variety of visualization tools. For radiation therapy treatment planning purposes, the physician will be most interested in isodose contours. Isodose contour values might be 90%, 50%, and 10%. The higher contours would be used to ensure that the entire tumor volume is receiving the desired dose. The lower contours might be used to check whether a particular field choice is overdosing sensitive healthy tissue. The right-hand-side of Fig. 2 shows how the commercial package, SPYGLASS, was used to overlay MCNP-calculated contours on a representation of the CT scan. In these calculations four planar beams were incident on the patient, from the top, bottom, left, and right. We have successfully linked MCNP results from this calculation to other commercial visualization packages.

F. Application of MCNP to Computed Tomography

There are a number of medical applications for transport codes in addition to those involving dose calculations. We have focused on one of those, namely using MCNP to simulate medical CT scans. Our studies **[5,6]** have shown the potential applicability of this technique to medical diagnostic scan interpretation, radiation treatment planning, and CT machine design. An example of the results of this method is shown in Fig. 3. The original CT scan of a chest from a UCLA patient is shown in the top left. A condensed 64x64 voxel representation of the CT scan (top right) was used as input to MCNP (bottom left). The resulting MCNP simulated CT scan is shown in the lower right. The results are very encouraging.

G. Other Activities

We have promulgated the successes described above in several ways. First, we have published our methods and results in the references mentioned so far and in Ref. **[7]**. We have presented our results at a variety of professional meetings; many of our electron enhancements were described at a recent specialists' workshop on electron transport methods in Seattle. Finally, we have pursued a variety of collaborations with university, industrial, and government agencies.

4. Conclusion

The Los Alamos Monte Carlo radiation transport code MCNP has been successfully demonstrated as a viable tool for radiation dose calculations necessary for therapy planning. We have positioned the Laboratory for continued programs in this area.

References

1. DeMarco, J. J., T. D. Solberg, R. E. Wallace, and J. B. Smathers, "Performance Analysis of the Monte Carlo Code MCNP4A for Photon-Based Radiotherapy Applications," Proc. Int'l. Conf. on Mathematics and Computations, Reactor Physics, and Environmental Analyses, Vol. 2, pp. 838-846 (1995).

2. Briesmeister, J. F., Editor, "MCNP^{TM} - A General Monte Carlo N-Particle Transport Code," LA-12625-M (Nov., 1993).

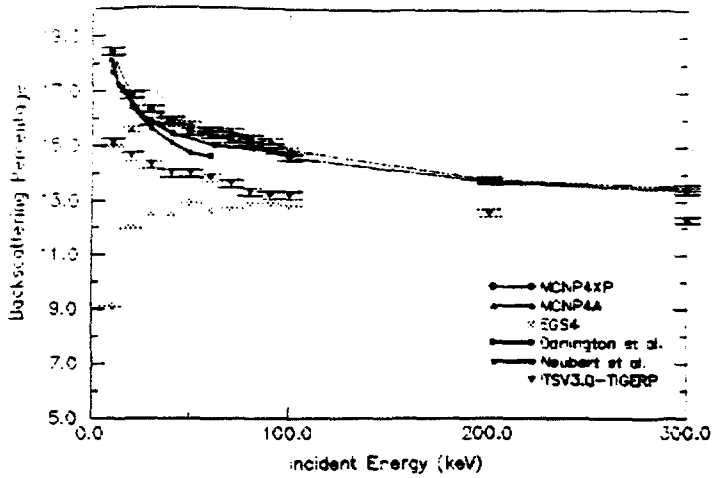
3. Hughes, H. G., "Status of Electron Transport in MCNPTM," Trans. Am. Nucl. Soc., **73**, 333 (1995).

4. Adams, Kenneth J. and M. Hart, "Multigroup Boltzmann Fokker Planck Electron-Photon Transport Capability in MCNP^{TM}," Trans. Am. Nucl. Soc., **73**, 334 (1995).

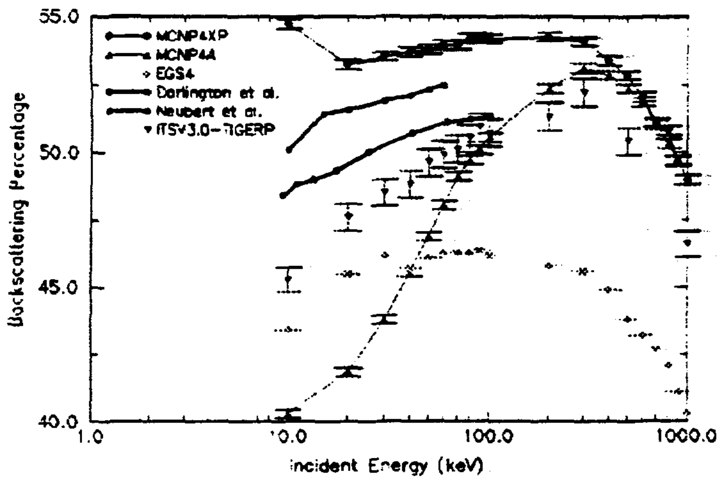
5. Hills, C. R., R. C. Brockhoff, and G. P. Estes, "CT Scan Simulation with the MCNP Monte Carlo Code," Medical Physics, Vol. 22, No. 9, p. 1534 (Sept. 1995).

6. Estes, G. P., R. C. Brockhoff, C. R. Hills, J. J. DeMarco, and T. D. Solberg, "Application of MCNP^{TM} to Computed Tomography in Medicine," Proc. 1996 ANS Topical Meeting on Radiation Protection and Shielding, **2**, 633 (1996).

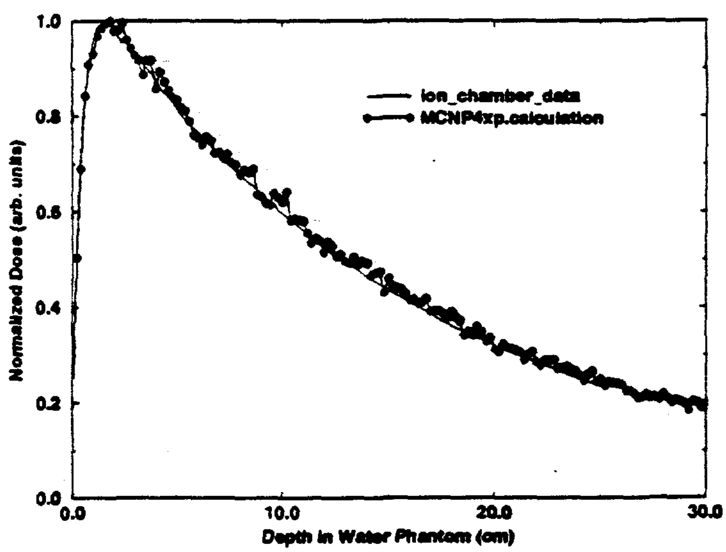
7. Adams, K. J., G. P. Estes, H. G. Hughes, L. S. Waters, R. C. Little, J. DeMarco, J. Smathers, T. Solberg, and R. Wallace, "The Use of MCNP^{TM} in Conventional Radiotherapy Planning," Medical Physics, Vol. 22, No. 9, p. 1546 (Sept. 1995).



Electron albedoes or back-scatter from a thick slab of aluminum for mono-energetic electron sources with normal incidence.

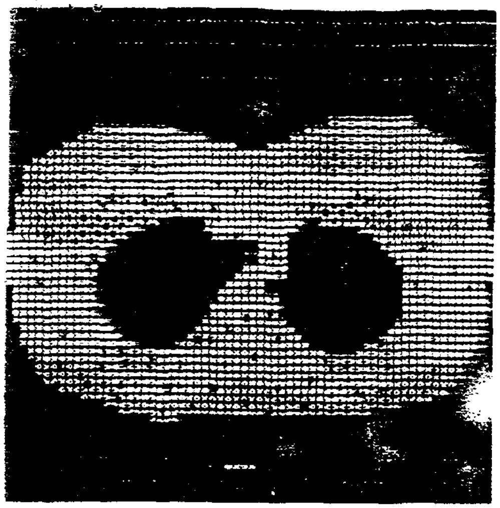


Electron albedoes or back-scatter from a thick slab of gold for mono-energetic electron sources with normal incidence.

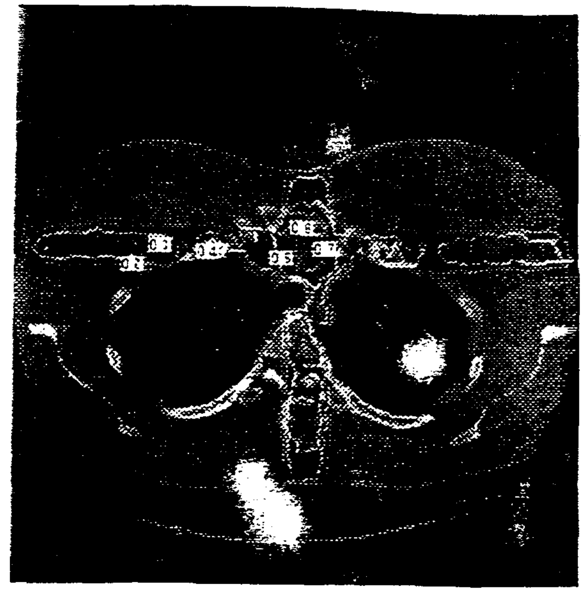


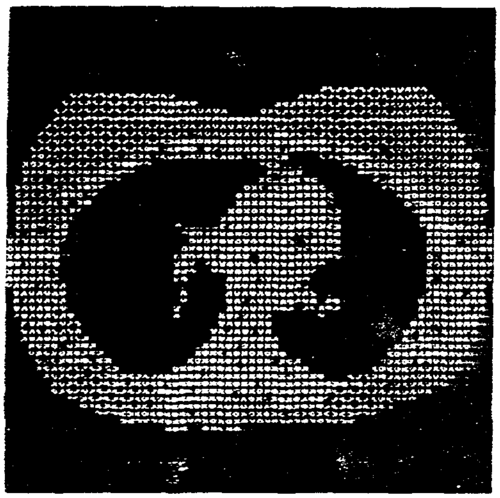
Ion Chamber measurements and MCNP calculations for dose deposited by 6MV photon treatment system

Figure 1: Benchmark Results. The top portion shows measured and calculated percentage of backscattered electrons as a function of incident electron energy for thick targets of aluminum and gold. The bottom portion shows experimental and calculated results for dose in a water phantom from a stereotactic 6 MeV bremstrahlung photon beam (results from J. DeMarco, UCLA).

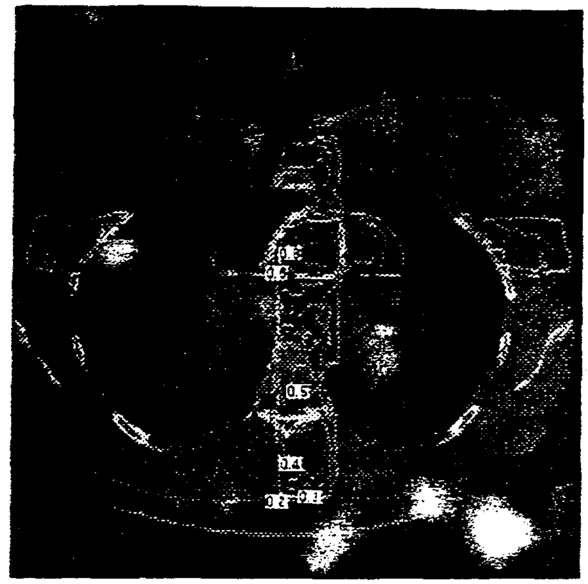


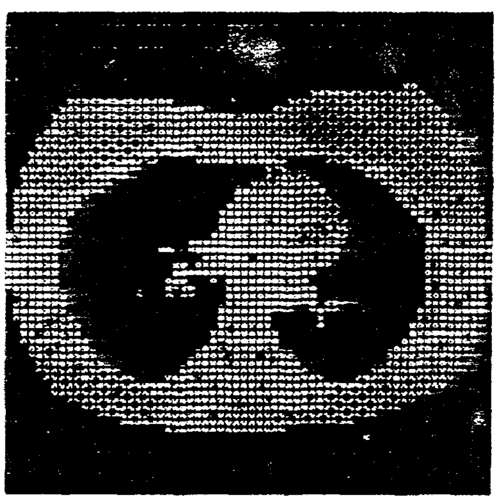
Lower Axial Cut
through
Thoracic Region





Middle Axial Cut
through
Thoracic Region





Upper Axial Cut
through
Thoracic Region

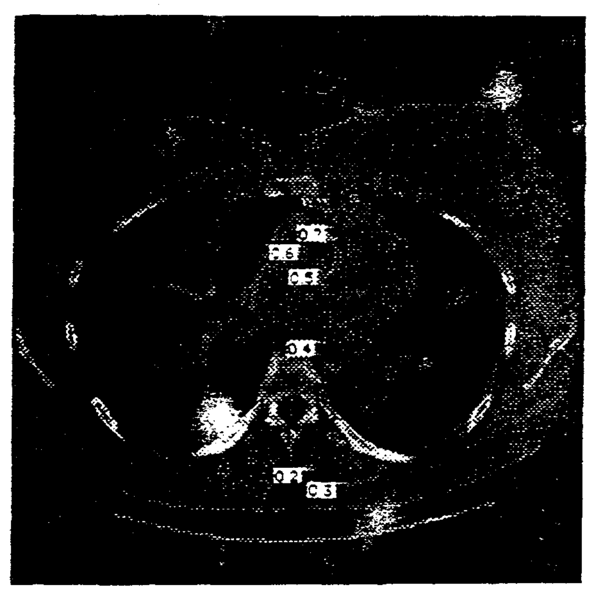
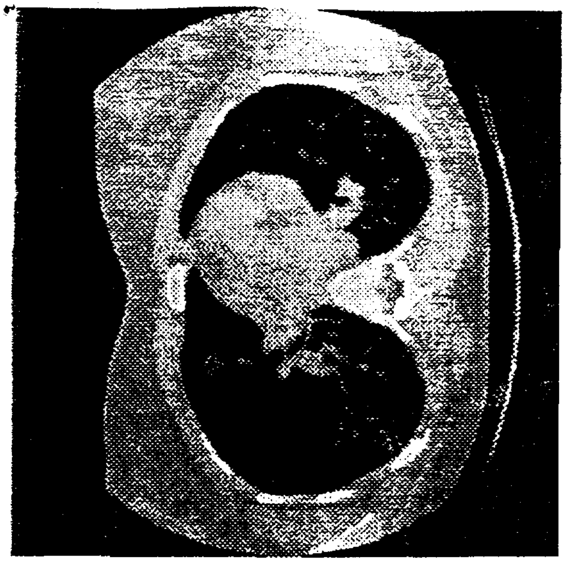
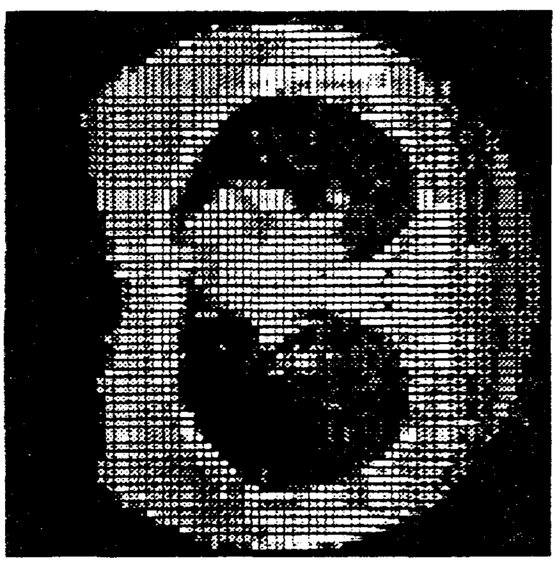


Figure 2: Visualization Results. Left is the MCNP rendering of the patient CT geometry used in the energy deposition calculation. Right are SPYGLASS-rendered displays of the isodose contours superimposed on the CT image.



UCLA CT scan with 512x512 voxels

UCLA 64x64 condensed CT scan
(from 512x512 voxels)



UCLA 64x64 MCNP geometry based on the
64x64 condensed CT

MCNP simulated CT scan

Figure 3: MCNP applied to CT. Original 512x512 CT scan is shown in upper-left. Condensed 64x64 CT scan is in upper-right; MCNP geometry based on that scan is shown in bottom-left. The resulting MCNP-simulated CT scan is shown in the bottom-right.