COMPUTERS IN RADIATION ONCOLOGY: THE THIRD DECADE

Edward S. Sternick, Ph. D.

Tufts-New England Medical Center Hospital
171 Harrison Avenue
Boston, MA 02111

Summary

Computers have been used for the past 25 years in radiation oncology for such diverse activities as treatment planning, treatment machine verification, image processing, and tumor registry analysis. This paper reviews each of these areas, with examples of working systems, and outlines a computer hardware configuration most suitable for their implementation.

Introduction

The importance of the computer to radiation therapy has been evident since 1955, when K.C. Tsien first described a method for calculating isodose curves electronically rather than by hand. Although it took the development of third generation machines in the 1960's to spur the implementation of computer usage in the radiation clinic to a significant degree, the impact of this technology has now been irrefutably secured. Indeed, there are few radiation therapy centers in the Western world today that would attempt curative treatment without access to a computer for treatment planning.

There is no shortage of literature on the subject. The historical development of computer usage in radiation therapy can be traced in an extensive series of reports and symposia volumes which describe the work of a number of physicists, computer specialists, and radiotherapists who have met regularly for more than a decade at a series of international workshops and conferences.

Two book-length monographs have been devoted to radiation therapy applications exclusively, and a myriad of reports have appeared in the scientific literature over the years.

Although early programming efforts were concerned almost entirely with treatment planning, there has emerged more recently a growing awareness that major technological advances in the state-of-the-art now allow the development of a comprehensive, computer-based system or systems which can provide all of the computing facilities needed in a modern department of radiation therapy. These requirements broadly defined, include:

- Treatment planning
- Automation, verification and control of therapy equipment
- Scientific and analytic applications
- Tumor registries and medical records

A diversity of hardware components can be used to accomplish these tasks. As with most options, each has both positive and negative aspects. The final selection of a computer system must, therefore, ultimately rest on a number of considerations including computing power, software flexibility, human engineering design, and cost. The configurations presently employed or suggested for radiation therapy applications encompass:

- Batch computers
- Remote batch terminals
- Intelligent remote batch terminals
- Small dedicated computers
- Terminals to time-sharing computers
- Medium sized, multipurpose computers

The advantages associated with the use of free-standing computers, include the following: 1) Administrative and technical control remain in the radiotherapy department; 2) Turn-around time is independent of the number of users on the system and is generally very acceptable; 3) Accessory hardware can be relatively easy to interface to the computer; 4) The capability of hardwiring peripherals and accessories makes for high-speed communications; and 5) User cost is a function of materials and personnel alone and does not include runtime.

Conversely, there are a number of gains to be realized in connecting a terminal to a remotely located machine: 1) Computational power can be achieved at smaller capital cost; 2) A large computer permits the implementation of larger programs and provides more mass storage; 3) Because several higher level languages are usually available, programming may be tailored appropriately to fit a particular application; and 4) Greater reliance can be placed on the specialized services, personnel, and equipment of the central computer facilities, thus minimizing technical staffing costs.

Batch processing without terminal connection is not generally considered to be equal to the demands of modern radiation therapy.

In a busy department, the most appealing
features of all systems may be combined with the
installation of a locally based, medium-sized
multi-purpose computer. Given the increasing
demands and complexity of computer-assisted
radiation oncology, such a configuration is
perhaps the only one capable of executing all of
the applications in current use or which may come
into practice in the foreseeable future. An ideal
system, then, would seem to be one which allows
real-time and time-sharing applications to run
concurrently. For example, in the clinical
radiotherapy department, the medium-sized computer
can provide simultaneous multi-machine verifica-
tion, interactive treatment planning, and tumor
registry data retrieval.

Computer Assisted Treatment Planning

The process of teletherapy treatment planning
involves a number of integrated steps which
should result in a prescription that is "optimized"
in some sense for an individual patient. The
procedures can be enumerated as follows:

1. Accurate external contour determination
2. Location and delineation of critical internal anatomical structures including the tumor volume.
3. Density determination of relevant inhomogeneities such as lung and dense bone.
4. Selection of a radiation modality and arrangement of fields, compensators, and blocks to ensure adequate tumor dosage with a minimum of radiation delivered to non-involved tissue.
5. Calculation and presentation of generated dose distributions.
6. A means of assessing the "goodness" of various plans generated. This may be accomplished visually or by mathematical and analytical techniques, or by some combination of these methods.
7. Recording of the plans for analysis and inclusion into the medical record.

When dealing with brachytherapy applications,
the most important considerations are those
relating to the display of the source distribution in
a variety of planes to allow for the assessment and possible alteration of the implant.

Localization

Although many radiation failures are due to
dissemination of tumor cells to distant sites, it has also been recognized that a number of recurrences are probably associated with local areas of radiation under-dosage. The implication is that more precise localization techniques may result in increased tumor control.

Comprehensive treatment planning demands an
outline of the patient's external contour and
delineation of selected internal anatomical structures. A variety of methods have been
proposed to acquire this information. Lead wire,
plaster gauze, mechanical tracing, photogrammetry,
ultrasonic scanning, and whole body computed
tomography (CT) all have been used in the clinical
setting.

Ultrasonic scanning, in particular, has proven itself to be a practical and useful method of acquiring certain information for accurate treatment planning. The scan can generate an external patient contour, locate deep as well as normal and abnormal surface structure, aid in the staging of malignancy, and provide a means of evaluating the response of deep tumors to therapy. In addition, distinctive echo patterns within solid tumors have been noted with sonographic techniques and may ultimately furnish a method of providing a non-invasive method for identifying abnormal tissue.

Ultrasound images are usually employed for
treatment planning either by optical projection
and tracing with a digitizer or by direct connec-
tion of the scanner to a computer.

The use of ultrasound in treatment planning,
however, is seriously restricted in certain
important areas of the body. It is of only
limited use in the chest because of the air-filled lung, and in the pelvis because of the presence of dense bone. These limitations may be resolved to some degree by employing conventional transverse tomography in conjunction with ultrasonography to produce a patient-specific cross-sectional representation of the body to serve as a map on which isodose plots can be overlayed.¹⁴

Unfortunately, due to differences between
the predicted and actual imaging properties of
conventional tomography, as well as the limited
dynamic range of x-ray film, resolution of
important anatomical structures is not always
possible with this technique. Consequently, the
edges of some anatomical structures may not be
imaged as sharp contours on the film and thus
are not easily identified (Figure 1).

![Fig. 1 Conventional transverse axial tomogram of the thorax.](image-url)
The introduction of CT into the radiotherapy department is an important advance for treatment planning, providing an accurate outline of the body contour, superior delineation of internal structures, and a quantitative matrix which can be correlated with physical density (Figure 2). However, some persons have expressed the opinion that the expense of CT scanning may not be justified for treatment planning and that more conventional techniques of acquiring anatomical information are accurate enough.

Figure 2. CT scan taken at the same anatomical level as in Fig. 1. Heterogeneity corrections are derived from the mean value of CT numbers lying within the cursor outline.

To appraise the impact of CT scanning on the prescription of a treatment plan, we examined a series of patients in which anatomical contours were obtained by two different methods: 1) Ultrasonic scanning in combination with conventional transverse axial tomography, and 2) CT scanning. Objective indexes were applied to the resultant computer generated treatment plans, and differences were scored for a number of parameters associated with the delivery of prescribed dose and assessment of dose distribution. Table I illustrates this type of comparison. Data were extracted from computer analysis of a patient being treated for esophageal carcinoma. The average difference between tumor doses calculated from anatomical information provided by CT or standard tomography ranged from 7 to 10% when corrections were made for lung heterogeneities, but it was less than 1% when all tissues were assumed to be homogeneous and of soft-tissue density. That agreement was so good in the latter case indicates that the external contours of the patient obtained by the two methods were nearly identical and that deviations in delivered dose could be correlated with lung density corrections and/or the position of internal organs.

Table I: Average Dose Deviations Between Treatment Plans Calculated From CT Scans and Conventional Tomograms

<table>
<thead>
<tr>
<th></th>
<th>Lung Correction</th>
<th>No Lung Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60 Co 6MV</td>
<td>60 Co 6MV</td>
</tr>
<tr>
<td>Tumor dose</td>
<td>10.4%</td>
<td>7.1%</td>
</tr>
<tr>
<td>Spinal cord dose</td>
<td>27.1%</td>
<td>23.7%</td>
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Assessment of data representing the dose to the spinal cord corroborates the impression that boundary information may be the most important component in the calculation of treatment plans. Differences in spinal cord dose averaged more than 20% whether or not corrections for lung heterogeneities were made. Small shifts in the position of the lung within the body cross section can lead to very different interpretations of the dose received.

Before the development of the whole-body CT scanner, conventional transverse axial tomography was suggested as an attractive and relatively inexpensive method of obtaining patient-specific cross sections. The poor quality of film images, however, makes standard tomograms difficult to interpret and can lead to decisions concerning anatomical relationships that are not valid for the individual patient. This results in a faulty isodose distribution as well as possible errors in the central axis dose calculation. On the other hand, transverse sections obtained by CT techniques have a spatial resolution of a few millimeters and the interpretation of edge information presents little difficulty. Additionally, CT scanning provides a two-dimensional numerical array in the tomographic plane which can be empirically related to density and allows for patient-specific heterogeneity corrections. Such information cannot be derived from the conventional tomogram.

There are also identifiable but not insoluble problems associated with the use of CT in treatment planning. Among these are accessibility of the equipment, differences in couch design between the scanner and the treatment machine, inability to orientate the patient identically within the scanning circle and under the treatment machine, possible shifts in organ position during respiration, the requirement for bolus in some scanners causing distortion of the contour, possible distortion of CT images in the display monitor, and difficulties in correlating the CT image to the anatomical transverse plane of the patient.

Several methods have been used to transfer the CT image to a form useful for treatment planning. These include: digitization of a Polaroid print or other recording medium, densimetric scanning of a film transparency, transfer of the CT images from the scanner to the computer by disc or magnetic tape, and direct interfacing of the CT scanner to the treatment planning computer.
Calculation and Display

Following the acquisition of patient specific anatomical information, alternative treatment plans are generated and displayed. A representative treatment planning system is illustrated in Figure 3. Graphics capabilities are provided on a display/minicomputer consisting of two parallel processors sharing 8192 16-bit words and a refreshable cathode ray tube (CRT). The terminal is linked to a large remotely located computer.

A file of body contours can be established on line with an x-y digitizer (Figure 4). When entering contour information into the computer, the user traces points along successive body structures. These tracings are simultaneously displayed on the CRT screen. Because the tablet of the digitizer is fabricated from frosted glass, it is possible to project through the rear an enlarged image of a Polaroid print containing an ultrasonogram or a CT scan.

Treatment plans are established with the aid of a light gun and key board, and a summary of treatment parameters suitable for inclusion into the patient's record is made on a plotter (Figure 5).

Optimization

Computer-assisted treatment planning should include a means of assessing the "goodness" of various plans generated. Optimization of the physical distribution of radiation doses has developed along three major pathways: 1) The production of a number of alternative plans developed graphically in an interactive mode using human judgement in the selection of the "best" plan; 2) The use of linear and non-linear programming solutions to reduce the requirement of human intervention and 3) The definition of a set of score functions based on clinically defined criteria to evaluate the relative merits of alternative dose distributions.

Despite the work that has been pursued during the past decade, clinical use of the latter two methods has been limited. Most emphasis has been in the development of equipment and software directed toward the first approach, which involves human interaction with all its attendant limitations. The lack of widespread application of a truly automatic approach is due primarily to disagreement among physicians as to clinically useful criteria on which to base the computerized decision making.
Automated Verification of Therapy Equipment

The goal of therapeutic radiology is to apply a lethal tumor dose while simultaneously delivering a minimal amount of radiation to non-involved tissues. Evidence from a number of clinical studies suggests that it is desirable to deliver the dosage to the target volume with an uncertainty of ±5% or less. Attainment of this objective is only possible when radiation fields are in careful alignment with respect to the patient. Errors in positioning or erroneous adjustment of other set-up parameters can affect the dose distribution and degrade the quality of treatment, with possible serious consequences.

Although accounts of the incidence and magnitude of set-up errors have not been extensively reported to date, several operational systems have been described which are being used to monitor selected parameters of various high energy teletherapy units. A typical arrangement is shown in Figure 6. 17 The verification system consists of a linear accelerator, a minicomputer, and various operator communications devices and interfacing hardware which link these components. Analog electrical readouts are provided for the eight mechanical parameters: gantry angle, collimator angle, upper and lower collimator jaw settings, vertical couch position, longitudinal couch position, transverse couch position, and angular couch position. In addition, a potentiometer is supplied for monitoring the dose per degree adjustment at the control console during arc therapy.

Figure 6. Verification System

It is also possible to monitor the dose, backup timer setting, and the angular stopping position for arc rotation. Finally, a simple on/off line senses the presence of the tray used to hold beam-shaping blocks.

Primary communication between the computer and therapy technician is by means of a Video Terminal (VT) located at the accelerator control console. The VT is used to enter information about the patient such as name, identification number, and portal designation prior to set-up, and it carries the computer validation reply.

Software organization is outlined in Figure 7. A Data Entry routine is used to initialize a patient's record on the system prior to treatment. This routine allows the user to establish specifications for a treatment plan employing multiple portals. The term "portal" designates a unique adjustment of the linear accelerator and the patient, usually repeated many times during a course of therapy (e.g. a treatment plan employing parallel opposed fields is characterized by two portals). A "treatment plan" consists of a complete course of radiation therapy for a particular patient.

The Verification routine is run from the VT at the control console of the linear accelerator. All other routines can be run from a terminal which is located in the computer room and is neither under routine technician control nor responsibility. This greatly eases the burden of extra work on busy personnel responsible for patient care, who need only enter some minimal patient identification and then respond to questions which require a "yes/no" answer.

Once the patient and the linear accelerator are adjusted, the computer checks the set-up, indicating any significant errors at the VT. If the set-up is accurate to a predetermined level of tolerance, the technician is allowed to proceed with treatment. Tolerances are specified internally as program constraints and can be changed as necessary.

At all times, the technician has complete control over the therapy machine and may choose to deliver a particular treatment. If an override is performed, the fact is recorded.

During a course of therapy it is often necessary or desirable to alter some of the accelerator set-up parameters. A Revision routine contains a number of features which allow changes in portal specifications. This routine is designed to be run at the control teletype in the computer room to minimize interference with normal operations at the linear accelerator.

At any time a comprehensive summary of the stored data may be obtained providing general patient information, the specifications of each portal, the treatment plan, data from individual treatments, and the accumulated doses at selected points.

Using this type of system, studies may be conducted to assess the magnitude, frequency, and types of errors committed, the effect of patient load and complexity of set-up, and other
factors which may be important to the quality of treatment delivery.

Figure 7. Verification Flow Diagram

Scientific and Analytic Applications

One of the major recent developments in radiological science has been the employment of increasingly complex imaging systems to better accomplish accurate tumor localization and staging. A well-equipped medical center uses sophisticated imaging equipment such as CT scanners, ultrasonic scanners, gamma cameras, and rectilinear scanners on a routine basis.

Despite the complexity and high cost of this equipment, most of the present systems lack the sophisticated image processing capabilities that would enhance their utility in the diagnosis and extent of malignant disease.

In order to be of value to a physician, the system must be interactive and easy to operate, i.e., the user should be able to sit at a terminal with an image viewing capability, give commands to the system, and immediately evaluate the effect of the instructions. By this method, the clinician should be able to optimize the image, in a diagnostic sense, for a particular patient.

To accomplish this task the computer facility must exhibit two essential characteristics. First, the processing system must be fast and interactive. Image processing problems in general require a number of different approaches that must be taken to arrive at an optimum solution, and it is not always obvious at the outset which of these approaches will be most effective. Thus, a number of attempts may be launched and an optimum conclusion arrived at through an interactive technique that will be useful for the particular problem being studied. A number of processing steps might be attempted before the optimum sequence of steps is determined and a reasonable turn-around time is necessary in order to keep the total problem solving time short. Since many possible enhancement techniques are non-linear, their effects are not easily predicted, and a user may have to try a number of variants before arriving at a solution. This would be intolerable unless turn-around time were reasonably short.

Secondly, the design of the system should allow for as much flexibility as possible consistent with economic and speed constraints. Since the techniques of image enhancement are still in an evolutionary stage, it is important to design a system that can grow with developments in the field.

Fundamental requirements for an image processor are the ability to store large two-dimensional arrays efficiently and the ability to perform complex numerical calculations quickly. A number of different types of operations may have to be performed on the generated images:
- Point operations in which the image is processed point by point in a straightforward manner. Examples include histogram shaping, selective display of gray-level ranges (segmentation), logic operations between two pictures, and display of the least-significant bits of a picture element.

- Neighborhood operations in which each processed point is a function of the unprocessed point and its immediate neighborhood of points. Examples include the gradient, the Laplacian Operator, Averaging, dimension changing and simple convolutions.

- Fast transform operations

Tumor Registries and Records

In designing a tumor registry, several requirements must be considered:

- The service area should be so defined that it correlates with the divisions used by the Bureau of Census to allow for the reporting of incidence rates.

- The majority of cases that arise in the area should be diagnosed and treated within that area.

- The population should be large enough to permit statistically valid epidemiological studies, but not so large as to become overly cumbersome.

A regional registry, which meets these requirements was established in 1973 for New Hampshire and Vermont. These states encompass a rectangular area slightly greater than 18,000 square miles for which statistics are readily available from the Bureau of Census.

Because of natural and political boundaries, cancer patients generally seek treatment within the area, and the population base of 1.3 million people is sufficient for statistical studies, but of manageable size. As of September, 1976, approximately 14,700 cases had been abstracted, processed, and entered into a computerized registry.

In order to allow a user to store and access many pieces of information on multiple items in the database both quickly and easily, a comprehensive software system was developed. The computer programs afford the user a great deal of statistical power on a large body of data and allows him to set-up new registries or subsets of this data to obtain specialized information.

There is considerable flexibility built into the system in that it allows on-line accessing of many different "registries" containing different types of data. Very simply, a registry is a block of data on a number of items in which the same information is kept on each of these items. The items may be cancer cases, protocol patients, occupational histories, or anything else on which the user might want to keep data.

Data are stored as integers in "fields" where each question is assigned one "field" in each record. There are two types of "fields": 1) numeric, in which the field value is a pure number with no other meaning, and 2) interpretable, in which the field value represents a specific answer to a multiple choice question. Interpretable fields may be either simple or multi-valued. Single-valued fields have a single answer, whereas multi-valued fields allow the user to choose one or more of the answers.

The software was designed so that multiple users may run it simultaneously, referencing the same or different registries and performing a wide range of operations. The only limitation placed on this multiple use is that, when a user wishes to modify the information in a particular registry, no one else may be concurrently using the information in that registry.

Statistical reports may be easily extracted from the data base; the user can generate several different types of cancer incidence tables and contingency tables, analyze survival rate statistics, and provide specialized information for hospital service reports such as regional referral patterns.

Computer Configuration

Ideally suited to support the computer oriented tasks described in the previous sections is a single "medium-sized" hardware configuration. Such a comprehensive system design is diagrammed in Figure 8. The hardware is capable of sustaining simultaneous interactive and real-time applications for multiple users and supporting a number of high-level programming languages such as FORTRAN, BASIC, and MUMPS for ease of software development and debugging.

There are certain hardware features in the system that are particularly desirable for the specific applications enumerated here:

Central processor

The use of a high speed cache memory to augment the efficiency of the main memory improves the utility of the central processing unit and floating point unit. This allows formidable numerical tasks such as image processing or treatment planning, to be performed concurrently with several smaller tasks such as data input and/or treatment machine verification. Inclusion of both a line clock and a real-time clock permit real-time tasks to be processed simultaneously with time-sharing tasks.
Disc Controller and Discs

The selection of a disc subsystem must include consideration of the factors of speed, size, reliability, and accessibility. A multiple drive cartridge system allows sufficient on-line storage to meet daily requirements at a cost of a single large system while providing greater protection against catastrophic system shut-down. In addition, the cartridge medium is widely used by different manufacturers, thus facilitating transfer of data and programs between cooperating radiation therapy centers.

Tape Controller and Drives

Magnetic tape records of seldom used data and/or large files (e.g. the tumor registry) are the most efficient means of long term storage. In addition, tape provides for back-up of important programs and data. A dual drive system is required to edit and copy tapes, particularly when dealing with large registry files.

Control Terminal

In any multi-user or time-sharing computer system a control terminal is reserved for privileged access. This terminal is employed to set user priorities or to initiate and record confidential information such as user validations or billing data.

Line Printer

The maintenance of registry systems involves large quantities of printed output to verify data, and provide general information, statistical analyses, and tabulations. A medium speed line printer provides this capability.

Plotter

Essential to any graphical display system is an accurate hard-copy device. An electrostatic plotter provides clean copies of treatment plans which can be inserted directly into the medical record. In addition, hard copy graphics are used for the presentation of results generated by image processing techniques and for charts and graphs created for the tumor registry.

Mark Sense Reader

The assimilation of registry data into the computer system requires a bulk entry device. Experience with mark sense forms has proven the method to be acceptable and efficient in terms of data throughput.

Multi-terminal Interface

The most efficient means of connecting several terminals to a single computer is through a multiple terminal interface.

Figure 8. Medium-Sized Computer Configuration
The terminals (or terminal-like devices) can then be located in areas of the radiotherapy department where they are most needed. This may include the receptionist's desk, an examining room, or a private office. By using a standard universal interface, different types of terminals may be easily connected to the computer.

Graphical Subsystem

The graphics subsystem consists of a central graphics processor and interface driving a single graphics terminal used for treatment planning and image processing. Included also is a film digitizer to allow the direct input of x-ray films into the computer for analysis and enhancement.

Conclusion

There are few other medical specialties in which the computer has made its presence felt so strongly as it has in radiology. Although all of the functions and activities described in this paper are not practiced by all radiotherapy departments at the present time, they are increasingly being implemented by the larger centers. The first decade of the computer in radiotherapy was a time of developing a philosophy, of laying the groundwork for future growth. In the second, the expansion of quantitative capabilities demanded greater accuracy and definition in treatment techniques. As we move through the third decade we are seeing the consolidation of past developments and a new emphasis on employing sophisticated imaging systems more directly into patient treatment. The aim has always been the same—to improve cancer survival rates. This hypothesis has never been rigorously tested. Perhaps we have the experience and techniques to do so now.

References


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Edward S. Sternick, Ph. D.
Tufts-New England Medical Center Hospital
Department of Therapeutic Radiology
Medical Physics Division
171 Harrison Avenue
Boston, MA 02111