COMPUTED RECONSTRUCTION FOR RADIOThERAPY OPTIMIZATION

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Abstract As a result of advances in medical imaging modalities, such as CT and MRI, it is now possible to obtain a clear, detailed image of the distribution of tumor in humans. Therefore, optimization of dose distribution is now essential when external irradiation is used in radiation therapy of tumors. Computed reconstruction for radiotherapy optimization (CRRO) was studied; the principle of this method as well as its computer simulation and the results of experimental irradiation are reported in this paper. The method is advantageous since it is applicable even when the tumor surface is quite uneven or when tumors are sparsely distributed. In addition, it allows hollow-out irradiation for multiple areas with convex outer surfaces.

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INTRODUCTION

In radiation therapy, improvement of dose distribution has been attempted using various irradiation techniques such as multiportal irradiation, rotational irradiation, pendulum irradiation, irradiation using a wedge filter, dynamic irradiation and conformational irradiation.

Advances in medical imaging modalities, such as X-ray CT and MRI, have made it possible for us to obtain a detailed three-dimensional image of tumorous and normal tissue distribution. Under such circumstances, improved optimum irradiation is required for radiation therapy. A study was made of computed reconstruction for radiotherapy optimization (CRRO), a method whereby a dose distribution conforming to the actual tumor distribution is obtained. This reconstruction, based on the principle of computed tomography in reverse, uses the narrow beams from a therapy unit. This paper describes the principle of the method and the results of basic experiments.

METHODS

(1) Theory of optimization with the CRRO

The fundamental idea underlying this method is to utilize the CT image reconstruction principle to obtain an ideal dose distribution.

For each CT cross-section image, information about the body and tumor contour (and also that of the organ at risk, if necessary) is input into a computer via a digitizer or using another appropriate data conversion method. Based on the body contour and three-dimensional cancer distribution data, multi-portal irradiation with adjacent narrow beams is performed around the body at appropriate angular increments.

During this multiportal irradiation, the
Fig. 1. Relationship between the focus, collimator, multiblocks, targets, body contour and gantry. As shown on the right, holes are cut in the blocks with a numerically controlled machine in order to adjust the dose level.

dose level of each narrow beam is computer controlled according to the theory stated below, and a high dose area conforming to the target volume is reconstructed.

The algorithm for the computing procedure using the iterative method is described below (see Fig. 2 illustration).

First, the three-dimensional space occupied by a tumor lesion in a given patient is designated as $V$ (volume); and $V$ is divided into small cubes of equal size.

Assuming that the number of small cubes is $m$, the cubes are coded $1, 2, \ldots, m$. Then, a relative value equivalent to the initial value of the iterative computing procedure and the purpose value of radiation dose is given to these cubes:

$IP (1), IP (2), \ldots, IP (m)$ (IP: initial and purpose value) If the cancer lesion is to be evenly irradiated, $IP (i)$ is set at $1$ ($i=1, 2, \ldots, m$).

Statistical standardization is then performed so that the mean value of $IP (i)$ becomes 1 when $i=1, 2, \ldots, m$, and the standardized value is designated as $SIP (i)$ ($i=1, 2, \ldots, m$; $S$ means standardized).

The next step is to code each narrow beam as follows:

$j=1, 2, \ldots, n$ (if the total number of narrow beams in all directions is $n$)

The distance of the cube $i$ through which the central ray of each narrow beam $j$ passes is coded $D (j, i)$. $D (j, i)$ is multiplied by $SIP (i)$. The sum total of this product is divided by $L (j)$ (the distance of the tumor lesion $V$ passed by the beam) to yield $F (j)$.

$L (j)$ and $F (j)$ are expressed by the following equations.
For example, if the central ray of the narrow beam 1234 passes through the cubes 3, 5 and 6, the distance of each of these cubes crossed by the central ray, i.e., $D(1234, 3)$, $D(1234, 5)$ and $D(1234, 6)$ are calculated.

If the total distance of tumor lesion passed by the central ray of the narrow beam is expressed by $L(1234) = D(1234, 3) + D(1234, 5) + D(1234, 6)$, the sum total $F(1234)$ can be obtained by the following equation.

\[
F(1234) = (D(1234, 3) \cdot \text{SIP}(3)) + (D(1234, 5) \cdot \text{SIP}(5)) + (D(1234, 6) \cdot \text{SIP}(6))/L(1234)
\]

The above calculations are for the first iterative computing procedure. In the second and subsequent iterative computing procedures, $F(j)$ is obtained using SCD (to be stated later) according to the equation (3).

\[
F(j) = (\sum_i D(j, i) \cdot \text{SCD}(i))/L(j) \quad \text{if } L(j) \neq 0
\]
during the iterative procedure.

The above procedure is repeated for each
j ( j =1, 2, . . . , n), and the dose at the
central point of each cube under irradiation
from total narrow beams at the intensity of
F (j) ( j =1, 2, . . . , n) is calculated.
(As shown here, this method does not
require calculation of the does level for all
matrix points of the dose distribution; rather
it only requires calculation of the dose level
at the central point of limited small cubes.
Hence, iteration time can be saved.)

The relative dose level for each value of i
(i =1, 2, . . . , m) is designated as ID (i);
where ID means irradiated dose. This value
is then statistically standardized as stated
above and expressed as SID (1), SID (2),
. . . . , SID (m).

The SID values are then compared with
the above-mentioned SIP values. If, for
example, SIP (1) is larger than SID (1), SIP
(1) is increased slightly and the resulting
value is designated as CD (1), where CD
means corrected dose. If, for example, SIP
(2) is smaller than SID (2), SIP(2) is slightly
reduced and the resulting value is designated
as CD (2). The same procedure is repeated
for each of i (i =1,2, . . . , m).

The iterative procedure is carried out
under the condition of CD (i)≥0 to avoid
negative irradiation. (Strictly speaking, it is
acceptable that CD (i) is slightly negative
given that F (j) is equal to or larger than 0;
however, this condition is difficult to fulfill.)

Then CD (1), CD (2), . . . . , CD (m) are
standardized to yield SCD (1), SCD (2),
. . . . , SCD (m); using these values as new
initial values, the above procedure is
repeated.

To summarize, F is calculated from SCD,
and ID is obtained; ID is then standardized
to yield SID, and the previous SCD is
cumulatively adjusted based on a compar-
ison between SIP and SID. The adjusted
SCD is standardized to yield new SCD, F is
then derived from this new SCD, and ID is
obtained. ID is then standardized to yield
SID, and previous SCD is cumulatively
adjusted based on a comparison between
SID and SIP, and so on (iterative method).

The sum total of the absolute values of
differences between the previous SID (1),
SID (2), . . . . , SID (m) and the current SID
(1), SID (2), . . . . , SID (m) is expressed by Σ

\[ \text{ABS (previous SID (i)—current SID (i))}. \]

When this value reaches a certain minimal
value, the calculation is complete and con-
vergence has occurred.

The dose distribution irradiated at F (j),
j =1, 2, . . . . , n, which is obtained at the
condition of last SCD (1), SCD (2), . . . . ,
SCD (m), is a relative optimum dose distri-
bution. Now, the dose is calculated for all
points of each matrix in the dose distribu-
tion, and this relative dose distribution is
estimated. The practical dose level for each
narrow beam j =1, 2, . . . . , n can be easily
calculated by specifying the desired dose
level to the reference points (i.e., the center
or some marginal points at the tumor) based
on the relative ratio of ID value to each F
(j), j =1, 2, . . . . , n at these points.

In the case of hollow-out irradiation, the
space to be hollowed out is designated as
VO, and the F (j) at which the central ray of
the narrow beam passes through VO is fixed
as F (j)=0 in the software iterative proce-
dure: the dose distribution can thus be easily
obtained.

Even when there is a scattered distribution
of many V or VO, the procedures above are
applicable in exactly the same way.

(2) Experimental method

For the sake of simplicity, a model of the
human body was prepared with a combina-
tion of circles and ovals. Using this model,
computer simulation and experimental irra-
diation were implemented; the intensity of
irradiation for each narrow beam was
computed using the theory described above.
For this experiment, an NEC PC 9801E
personal computer fitted with a floating-
point processing unit was used; the pro-
gramming language was Japanese PC-
FORTRAN.

A computer simulation was performed in
order to test the dose distribution obtained
when irradiation was carried out at the intensity levels computed by the iterative method detailed above.

In subsequent experimental irradiation, a cobalt-60 unit (Theratron-60) was combined with an experimental unit which allowed adjustment of the increments in narrow beam irradiation angles and one-after-one irradiation of each narrow beam (Fig. 3). When the bundle of narrow beams is aimed in one direction with this equipment, the width of the irradiation field can be set to a maximum of 35 cm (5 mm (width)×70 (steps)). Fig. 4 shows the mechanism of this apparatus.

Based on the computer output, the intensity of each narrow beam was adjusted corresponding to the duration of irradiation. Irradiation was performed at an SAD (source axial distance) of 80 cm with the
adjusted narrow beams at various rotatory angles; an irradiated dose distribution was obtained using the film method.

**RESULTS**

1) *Computer simulation and experimental irradiation*

Figures 6 and 7 show the results of both simulated and experimental irradiation using a model of a human head bearing many metastatic cancer lesions (Fig. 5).

Figure 6 shows the results of a computer simulation designed to test a Cobalt-60 dose distribution obtained by the iterative method. The results shown in this figure are

![Fig. 6. Simulation of this method on a computer: irradiation is concentrated on the metastatic lesions.](image)

Fig. 5. A model of a human body consisting of circles (assuming metastatic lesions) and ovals (assuming the body contour around the head). This model was used for the experiment.

![Fig. 7. A film of irradiation of the human body model (Fig. 5) with the unit shown in Fig. 3.](image)
for irradiation to 5 tumor lesions from 36 directions. An excellent high-dose area was formed in each of the 5 lesions.

Figure 7 shows the results of experimental irradiation in which 5 mm-wide beams from a Cobalt-60 unit (Theratron-60) were irradiated at the intensity levels designated by the computer; the unit was rotated through 360 degrees at 10-degree intervals with an SAD of 80 cm. The dose distribution obtained by the film method in this experiment was approximately the same as that obtained by computer simulation. On the film, the ratio of the dose in the target area to that in the normal tissue was approximately 2:1.
As stated in the section on theory, this method allows software-controlled hollow-out irradiation in any number of outward convex areas, if the software is designed to restrict the passage of narrow beams through a specific region of the human body.

Figures 9 and 10 show the results of simulated and experimental irradiation to a human body cross section (including both eyes) with three tumor lesions (Fig. 8). Figure 9 shows the results of a computer simulation which suggests that a high-dose area can be formed in each lesion with hollow-out areas. Figure 10 shows the results of experimental irradiation with Cobalt-60 narrow beams using the instrument above. In this experiment, the dose distribution obtained was approximately consistent with that of the computer simulation, and irradiation to both eyes was blocked.

Then, using the same experimental apparatus and Cobalt-60 unit, an experiment to determine the optimum number of irradiation directions and the optimum width of narrow beams was carried out. The head phantom described above (assuming a case of brain metastasis of cancer) was first irradiated with 5 mm-wide beams at an SAD of 80 cm, and the optimum number of irradiation directions was examined. Five mm-wide beams were used since this width was believed to be approximately equal to the minimum width technically possible for the irradiation field.

Irradiation was first done in one direction (0 degrees); then in 2 directions (at an interval of 180 degrees), 4 directions (at intervals of 90 degrees), 8 directions (at intervals of 45 degrees), 12 directions (at intervals of 30 degrees), 24 directions (at intervals of 15 degrees), 36 directions (at intervals of 10 degrees) and 72 directions (at intervals of 5 degrees). In this way, it was possible to determine how the dose distribution changed with the number of directions.

When irradiation was done in 24 or 36 directions, an excellent dose distribution conforming to the shape of the target was obtained.

Assuming the minimum beam width to be 5 mm, we studied the degree of deterioration in the dose distribution caused by increasing the width to 10 mm, 15 mm and 20 mm.

When irradiation was done in 36 directions, the dose distribution deteriorated as the beam width was increased from 5 mm to 20 mm: This result endorses the necessity of assuming a beam width of 5 to 10 mm.

In the present study, evaluation was only made in axial sections, but the results of our computer simulations indicated that the above theory is also valid in matching the dose distribution to the contour of cancer.

Fig. 11. Design of multi-block irradiation using a circular arrangement: the cartridge holding the block is connected to the gantry by a roll-bearing so that the cartridge remains stationary even when the system rotates. Multicartridge holder is also considerable.
lesions in sagittal and coronal planes. This will be described in another report.

2) Design of a radiotherapy unit for practical use

We assessed various designs for realization of the above irradiation and found one radiotherapy unit to be appropriate. This unit comprises a mechanism which adjacent narrow beams are entirely covered with one-direction irradiation, as shown in Figure 1. Many compensators prepared from a material such as low melting point lead or iron, are used to produce such irradiation (multi-block method). Each block is prepared by a numerically controlled machine run by computer output, and a hole is cut in the area where the narrow beams pass. Each hole is only cut to a certain depth: the computer output data determines the extent of the uncut portion to precisely control the dose intensity of the narrow beam. When these blocks are set in an appropriate support, serial irradiation is started. Preparation of a large number of such blocks is not difficult because precise numerically controlled machines are available nowadays.

For the best realization of this multi-block method, a circular or chain-belt arrangement of the blocks seems to be applicable. It is not necessary to irradiate all blocks in a single day: for example, 36-direction irradiation can be divided into four days with irradiation in 9 evenly arranged directions carried out each day. Fig. 11 shows an example of irradiation by circular arrangement.

DISCUSSION

Various attempts have been made to improve the spatial dose distribution in radiotherapy. These attempts include multiportal irradiation, rotational irradiation, pendulum irradiation, tangential irradiation, irradiation using a wedge filter, dynamic irradiation (1 and 2) and conformational irradiation (3-8).

The conformational method permits hollow-out irradiation where irradiation is concentrated on the cancer and the critical organs can be avoided. The irradiation unit is rotated with the collimator controlled by a cam (or a computer) so that the beam conforms to the tumor contour. However, when the tumor is concave or there are many scattered tumors (as in cases of multiple metastases), the conformational method is not applicable.

The concepts described in this paper were also referred to in the report of Brahme (9 and 10) in connection with an irradiation unit using ultrahigh-energy electron or photon beams. With our CRRO method, however, even a relatively low-energy unit is applicable. Unlike the conformational method, our CRRO method permits the formation of a high-dose area conforming to the shape of the tumor(s) even when lesion is concave or there are many scattered cancer lesions. Furthermore, with the CRRO method, direct irradiation to any number of critical organs can be blocked so long as their outer surface is convex (i.e., these organs are exposed only to scattered beams).

Like other such irradiation methods, the CRRO method requires accurate positioning and immobilization of the patient. In addition, the irradiation position must be precisely reproduced daily for radiotherapy lasting several days (11): a laser beam positioning unit will be necessary. To maintain the accuracy of radiotherapy with the CRRO method, the actual irradiation beams must be monitored with a silicon diode detector or other instruments.

The above arguments and experiments were for multiportal irradiation in as many as 36 directions. However, even when the CRRO method is applied to ordinary multiportal irradiation in fewer directions (e.g., 4, 6 or 8 directions), an even dose distribution within the irradiation target and protection of critical organs from exposure will be possible. This is achieved by simply preparing the compensators for the directions of irradiation after the iterative
procedure and calculation of the dose weight for each direction according to the theory described above.

Although a Cobalt-60 unit was used in the present experiment, it is essentially not suited for our purpose because the large penumbra it produces. In fact, accurate densitometry of Figs. 7 and 10 might have yielded disappointing results. A linear accelerator is considered to be more appropriate for the application of this method to radiotherapy, considering the power and sharpness of their dose distribution.

In recent years, computer-linked automatic radiotherapy systems have been increasingly used (10-12); if the CRRO method is incorporated into such systems, their effectiveness will further increase.

Once such therapy is achieved using linear accelerators, almost the same quality of dose distribution can be obtained with proton beam radiotherapy, pai-meson therapy, and heavy particle beam therapy. This will result in significant improvements in the cost-benefit relationship and the therapeutic results of cancer therapy.

CONCLUSION

1) The principle of computed reconstruction for radiotherapy optimization as well as the results of a computer simulation and an experimental irradiation with this method were reported.
2) The results of the study suggest that irradiation concentrated on cancer lesions is possible with the method, and that it allows hollow-out irradiation for any number of areas with convex outer surfaces.
3) One viable technique for realization of the method is the multi-block method using a numerically controlled machine.

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REFERENCES

要旨：CT, MRI 等の発達で癌の体内での分布が細部まで極めて明確にわかるようになってきた。そのため、線量分布の最適化の問題が外部照射においても、極めて重要になってきている。この目的のため、Computed Reconstruction for Radiotherapy Optimization (CRRO) 法を検討している。本論文ではこの CRRO 法に関して、その原理とコンピューター・シミュレーションおよび照射実験の結果を示す。本法では、腫瘍がいかに凹凸不正または、離散して分布していても、対応出来る利点がある、またソフトウェアの制御により、任意の外部に凸な複数の領域につき、打ち抜き照射を行なうことが出来る。