A Computer System for Optimization of Treatment Planning in Radiotherapy

— The Visual Optimization by Man-Machine Interaction —

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放射線治療計画適正化のためのコンピューターシステムの研究

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超小型電算機を主体とした線量分布計算機 THERAC-IIを用い，6MVリニアックX線々量分布曲線を正確且つ迅速に表示するプログラムを開発した．

先ずハードウエア，操作法，プログラムの概要について述べた．入射面が曲面の場合には，5㎜メッシュに配列されている全計算点の夫々について組織通過距離から深部率を求め，距離の逆自乗則による補正を加えるようにした．この方法で体表の曲りに応じた等線量分布曲線を得ることが出来るようになつた．更に胸部照射における肺補正法として等線量曲線1/2移動法を採用し肺，腫瘍及び肺通過後の軟組織において補正された等線量分布曲線が得られるようにした．その他回転照射，振

子照射，多門照射における合成線量計算自動化プログラムも開発した．

このプログラムによる計算の精度を検討するため種々のファントームを用い，電離槽及びフイルム黒化法によつて線量測定を行なつた．計算値の実測値に対する誤差は単純一門照射では極端な75° 斜入射照射の場合を含めて 3.4%以内，術後乳癌胸壁を模したファントームに対する接線照射では 2.5%以内，全回転照射では5%以内，更に比重0.25のコルクを用いた不均質胸部ファントームに対する一門照射では10%以内であつた．本プログラムは放射線治療の個別化に充分適用出来ると考えられる．

Introduction

Optimization of dose distribution in a short time has recently become possible by introduction of computers. There have been appeared two types of optimization method by computers; the one is a mathematical method by means of score functions or linear programming,[8,11,18] and the other is a visual or manual method by means of man-machine communication.[1,4,7,9,10,19,21,22,23,24] The latter has been used clinically in many radiotherapeutic clinics, and is now prevailing in the world. We have developed the additional software to THERAC-II system (THERAC stands for treatment help equipment in radiotherapy by computer) which was improved to reinforce the ability of visual optimization on the original type of THERACOM-I in National Cancer Center Hospital, Tokyo, Japan.

Main points of improvement are programs applicable in an extremely oblique field irradiation, e.g. in the case of post-operative breast cancer which is usually treated by tangential technique, in an irradiation through the curved surface which is often met with in the head and neck tumor treatment, and in the rotational or pendulum irradiation. Besides, correction for the tissue heterogeneity such as lung was also taken into account.

In this paper, isodose curves calculated according to these programs have been compared with the experimentally measured data which were obtained using various kinds of phantom irradiated with a 6 MV linear accelerator and the accuracy was discussed.

Improvement

1. Hardware

The configuration of the hardware was changed and improved from that of original type of the system[9] as shown in Fig. 1.

2. System Operation

Data which an operator has to put into the computer are:

(1) Anatomical data on the cross section of an individual patient.

(2) Parameters necessary to operate an external beam generator such as a linear accelerator.

Data which an operator can get from the computer are:

(1) Isodose curves superimposed on the patient's anatomical data.

These are displayed on the CRT screen and, if necessary, can be recorded by the XY plotter or a Polaroid camera. Comparing the various dose distribution patterns thus obtained, an operator can readily select the fittest treatment plan for the patient.

Anatomical data for the patient can be entered by the curve digitizer connected "in-line" or by a medium of tapes. The operational parameters to set up the treatment plan such as portal number, field size, start angle and stop angle in the case of arc therapy, irradiation angle of each portal, preset dose for each portal, wedge filter angle, origin of the coordinate, position of isocenter, and shielding block parameters are entered by the numerical ten keys and function keys.

3. Software

The software specification is shown in Table 1.

Improved or added ability of software is as follows.

Rotational therapy, arc therapy, multi-portal therapy up to 12 portals, any combination of moving field irradiation with fixed irradiation, and any combination of arc irradiations themselves are able to be managed.

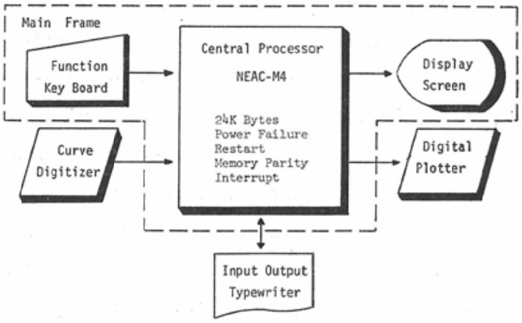


Fig. 1. Hardware configuration of THERAC-Ⅱ.

Table 1. Software specification of THERAC-Ⅱ

Item	Ability
1. Fixed Field 2. Moving Field 3. Combination 4. Filters	Up to 12 Portals. Both SSD and STD Method Full Rotation Therapy, Arc Thereapy (5 Degree Approximation) Fixed Fields, Moving Fields and Moving Fields Themselves Wedge Filters, Block Filters
1. Skin Surface 2. Penumbra Region 3. Tissue Heterogeneity	Skin Curvature, Oblique Incidence are Involved (Absorption in Tissue and Inverse Square Law) Build up Part is Involved Calculated to the Lower Part. Field Size and Tissue Depth are Involved Lung and Tumor in Lung. Any Shape, Size and Location are Involved
Points of Dose Calculation	1681 Points. 5mm Mesh Intervals 1mm Intervals by Bilinear Interpolation
Max. Scope of Dose Calculation	20cm × 20cm
Speed	15 Seconds/Portal 10N + 5 Seconds/N Portal
Accuracy	Below ± 2% on the Beam Axis

The program is also capable of correction for inhomogeneous tissues such as lung of any shape from any direction of irradiation for both isocentric irradiation and SSD irradiation, and geometrical consideration corresponding to shape of skin surface is included as well. SSD irradiation means such a method that dose calculation is carried out basing on the distance between source and skin surface.

The program is further capable of handling technique of off-axis irradiation or eccentric irradiation in addition to the technique of filters and block filters. Shallow region near skin surface where absorbed dose is built up to maximum dose, and penumbra region as far as very low dose level can also be taken into calculation.

Method of Dose Calculation

Fundamental method of calculation is based on the previous works.[9][10][19][24]

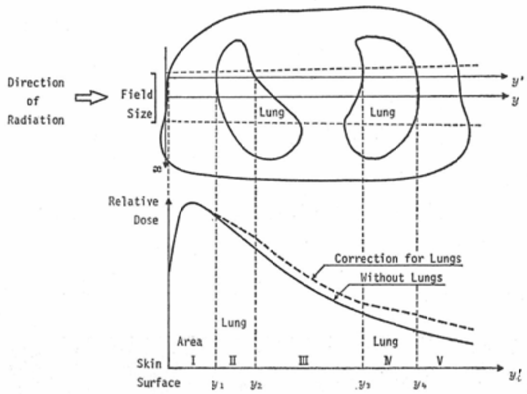
1. Compensation of Tissue Heterogeneity

Although many methods[2][3][6][12][13][14][16][20] have been proposed for the correction of tissue inhomogeneity such as lung and bone, we laid stress on the following points: Clinical and versatile utility for any shape of lung and the case of moving field irradiation, short calculation time, and easy handling of the machine. So, the following principles were adopted.

(1) Density within a lung can be considered to be uniform and difference of lung density among patients can be neglected.

(2) Scattering effect on the dose in the vicinity of lung boundary is negligible.

(3) Absorption of dose by bone is assumed to be equal to that of soft tissues because of high energy of beams used.



Area	Virtual Thickness y_l''
I	$y_l''=y_l'$
II	$y_l''=y_1+\frac{Nl}{Nw}(y_l'-y_1)$
III	$y_l''=y_1+\frac{Nl}{Nw}(y_2-y_1)+y_l'-y_2$
IV	$y_l''=y_1+\frac{Nl}{Nw}(y_2-y_1)+(y_3-y_2)+\frac{Nl}{Nw}(y_l'-y_3)$
V	$y_l''=y_1+\frac{Nl}{Nw}(y_2-y_1)+(y_3-y_2)+\frac{Nl}{Nw}(y_4-y_3)+y_l'-y_4$

Fig. 2. Method of heterogeneity calculation. Ratio $\frac{Nl}{Nw}$ is determined by the optimum lungs density and/or by empirical coefficients.

(4) Assuming those items (1)-(3), the necessary correction for tissue inhomogeneity remains only that for lung, the length of which along the beam passway can be represented by only one parameter, that is, equivalent length of soft tissues.

Fig. 2 shows the method of heterogeneity crrection' the process of which is as follows. When a beam passes through lung, the length which the beam passes lung is found and converted to the equivalent one to the soft tissue. Then summing up these equivalent lengthes, we can determine the values which can be used in the equations for dose calculation mentioned in the works.[9)10)19)24)]

Materials and Method

For the purpose of confirming the accuracy of dose calculation by THERAC-II, the measurement were carried out utilizing several kinds of phantom in some representative cases.

Phantoms used in the measurement are as follows.

1. A cubic water phantom of 30 cm × 30 cm × 40 cm volume. Walls of the vessel are made of acrylics, and are 1 cm thick.
2. A thoracic phantom of water. Wall of the vessel is made of vinyl-chloride, and is 3 cm thick.
3. A head phantom of Mix-D.
4. A thoracic phantom of Mix-D.
5. An inhomogeneous thoracic phantom which has a pair of lung phantoms and a tumor phantom within one of them (See Photo. 1). The lung phantoms are made of cork of density 0.25 g/cm^3. The tumor phantom is water contained in a cylindrical vinyl-chloride vessel of 3 cm diameter.

Dosimeters used in the dose measurement are as follows.

1. A depth dose measurement system with ion chamber and scanner (Toshiba Ltd.).
2. Film dosimetry system by Fujilith Ortho PT-100 and dose distribution analyzing unit (Toshiba Ltd.).
3. A Siemens' Dosimeter and its Midget thimble chamber for measurement in the inhomogeneous thoracic phantoms and Mix-D phantoms.
4. A dose rate meter installed in a 6 MV linear accelerator in order to keep X-ray output constant.

All experiments were carried out using high energy X-ray beams generated from the 6 MV linear accelerator, NELAC-1006D. Unless otherwise stated, experimental factors such as phantoms used,

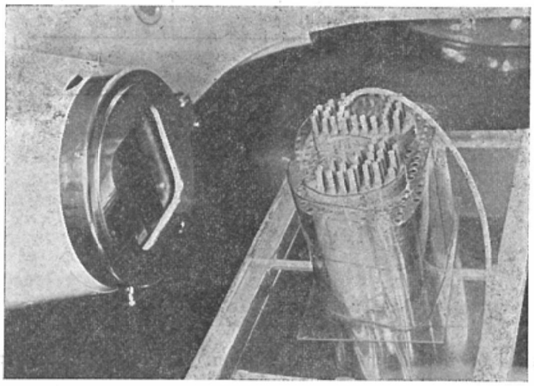


Photo. 1 Dose measurement in lung phantom.

dosimetry, measured points, source skin distance, field size, direction of irradiation, incident angle etc. were indicated in the legends of figures presenting the results. Since the deviation of the calculated doses from the measured ones was expressed by various ways according to circumstances, the method of presenting result was described in each paragraph of the results.

Experimental situations were selected from the theoretical and clinical points of view; that is, cases difficult to calculate the correct dose in addition to simulation of clinical cases frequently met with were selected. Thus, irradiation to the oblique surface, curved surface, uneven surface, rotationary irradiation and irradiation to the inhomogeneous tissues were attempted.

The Results

1. Irradiation to Oblique Surfaces

In this case, in order to express the difference between the calculated and measured doses, we adopted the following way. Ninety percent dose points were adopted as the reference point on both the calculated and measured depth dose curves. Superimposing both 90% dose points, the measured points of interest were plotted on the calculated isodose chart by applying the depth from the reference point of the measured point of the same percent dose as the calculated. Since dose is expressed as the percentage, the difference is also expressed as percentage to the maximum dose. Thus, the deviation of the measured points from the calculated chart indicates the difference. Points measured were selected on the beam axis and on the parallel lines 1 cm and 2 cm apart from the beam axis to both sides.

Cases of incidence angle 0°, 30°, 45°, 60° and 75° were calculated and measured. Fig. 3(a) to Fig. 3(e) shows the comparison between calculated isodose curves and measured isodose points. Fig. 4(a) to Fig. 4(e) are distribution of deviations of measured doses from calculated doses.

Summarizing all the results above mentioned, the arithmetic means and the standard deviations were as follows:

Incidence angle 0°:	− 0.3% ± 0.83%
Incidence angle 30°:	−0.5% ± 0.72%
Incidence angle 45°:	0.0% ± 0.62%
Incidence angle 60°:	− 0.6% ± 1.17%
Incidence angle 75°:	+ 0.5% ± 0.85%

Although the maximum deviation was 3.4% average deviation was 0.18%. The agreement between the measured and calculated doses was very good generally as seen in figures 3(a)—(e).

2. Irradiation to the Curved Surface: Simulation of Tangential Irradiation in the Case of Post Operative Irradiation to the Mammary Carcinoma

The experimental design is illustrated in Fig. 5. Irradiation was performed keeping the output of X-ray beams at the constant rate of 100 rads per minute by dose rate monitor installed in a 6 MV linear accelerator. Calculated and measured dosees were expressed in rad. Points of measurement were selected on

(1) 8 depth dose curves along 8 lines on and off axis.

(2) 20 decrement curves along 20 lines which are normal to beam axis.

Calculated depth isodose curves are expressed as lines.

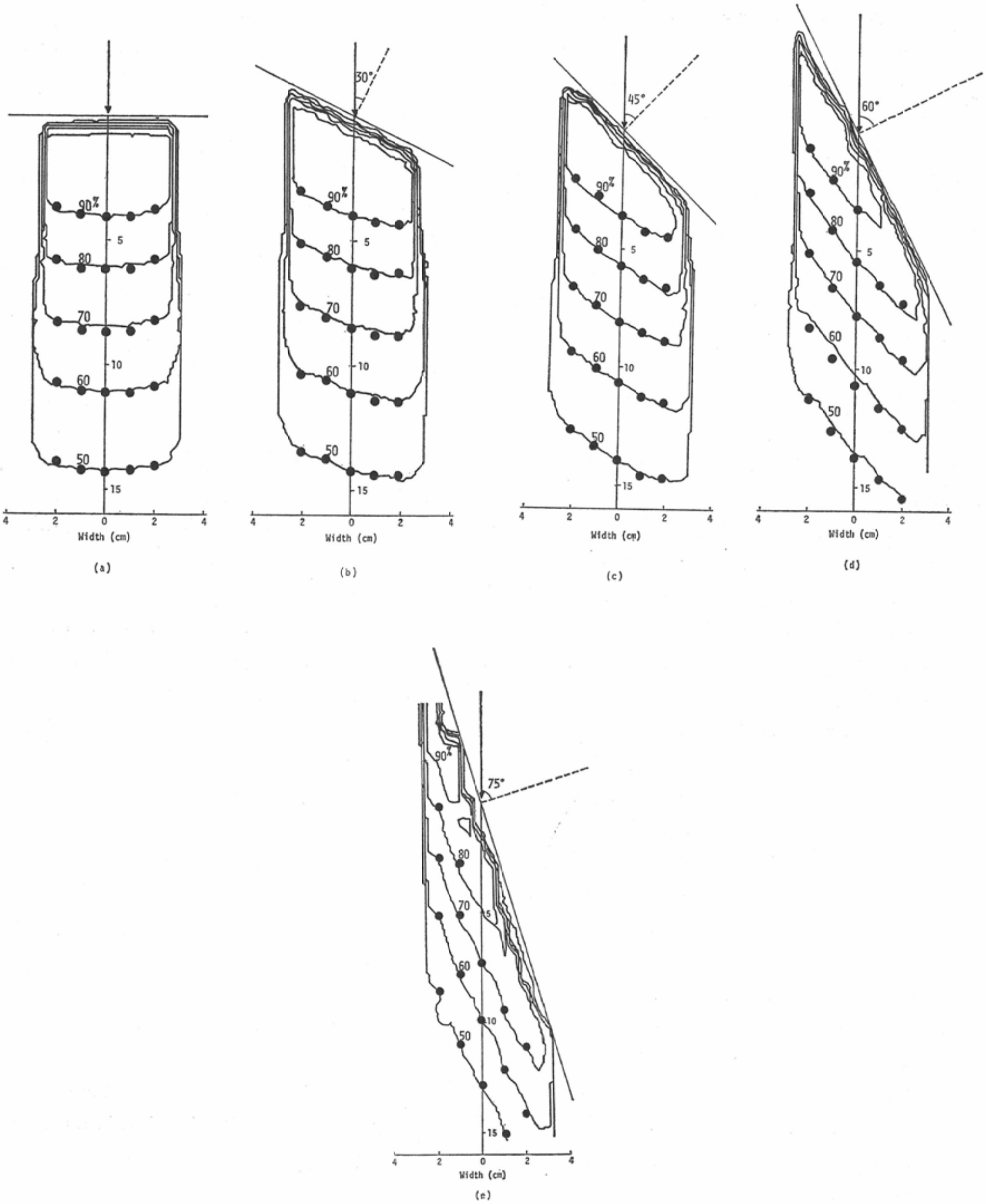


Fig. 3. Irradiation to oblique surface. SSD: 98.5cm, F.S.: 6×6cm, Incidence angle: (a) 0°, (b) 30°, (c) 45°, (d) 60°, (e) 75°, Phantom: Cubic water phantom, Dosimetry: Ion chamber and scanner, Solid line: Isodose curves by THERAC-II calculation output, Closed circle: Measured dose.

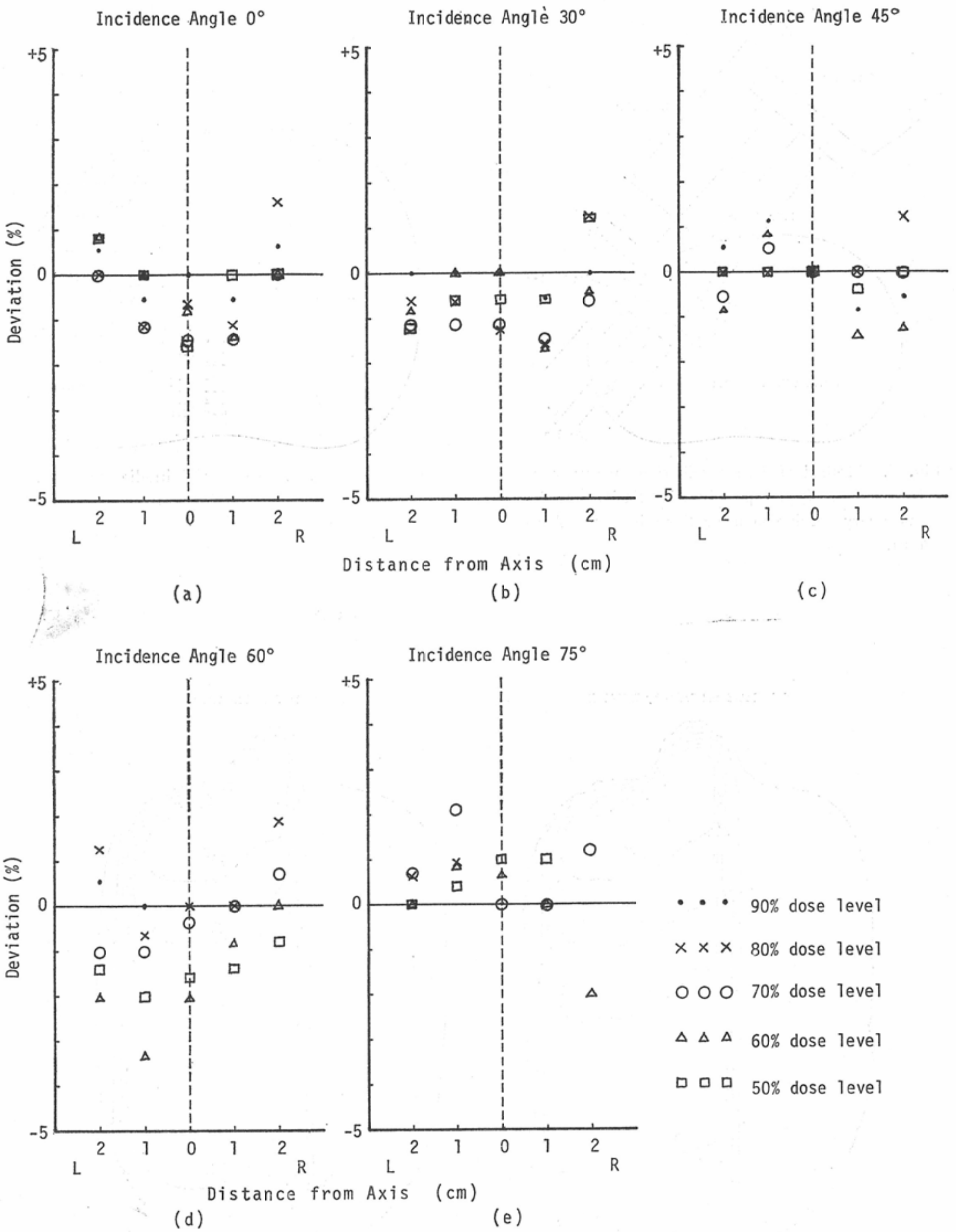


Fig. 4. Distribution of deviations of measured doses from calculated doses.

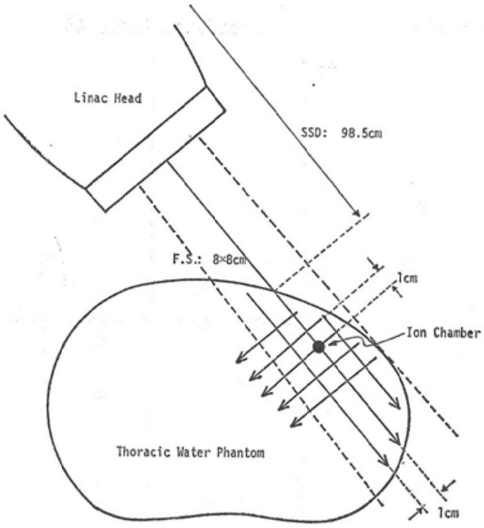


Fig. 5. Method of dose distribution measurement in the case of postoperative irradiation to the mammary carcinoma using thoracic water phantom.

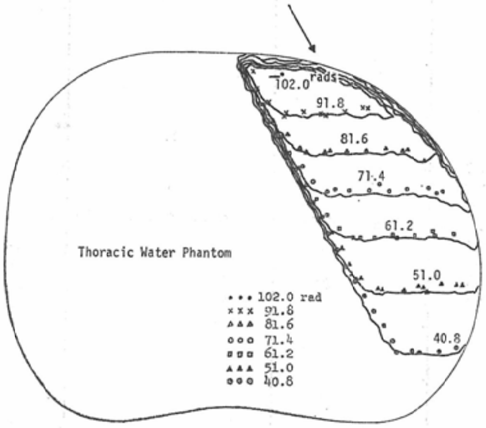


Fig. 6. Tangential irradiation

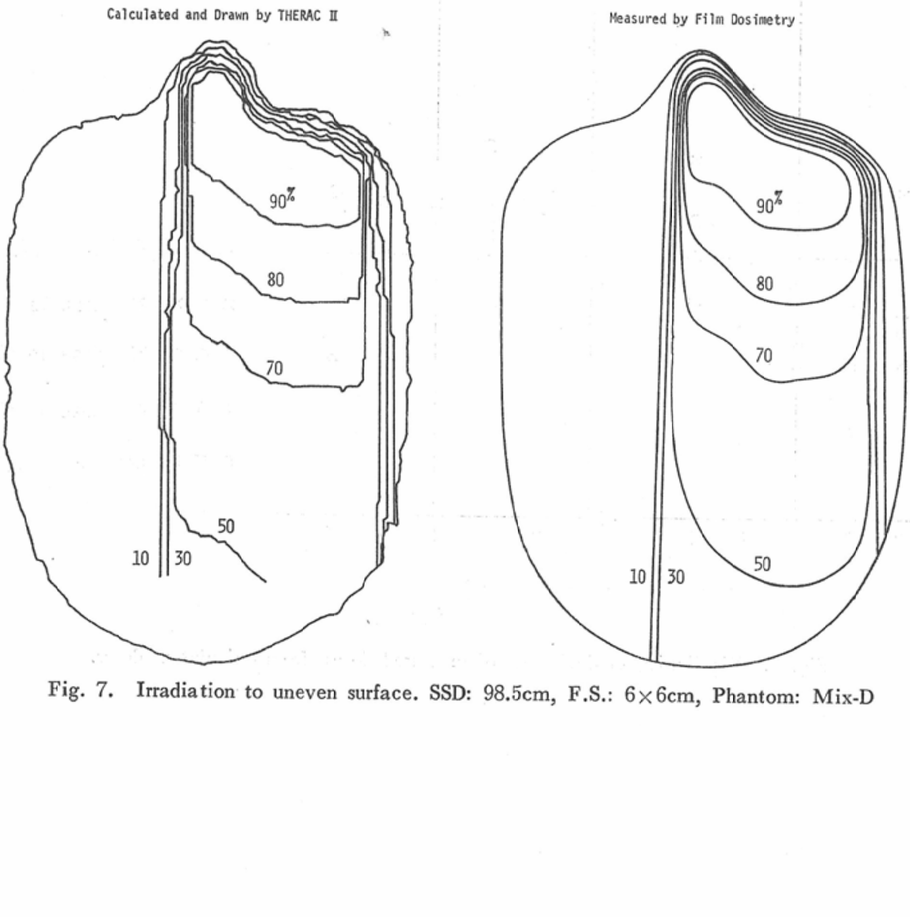


Fig. 7. Irradiation to uneven surface. SSD: 98.5cm, F.S.: 6×6cm, Phantom: Mix-D

The result is illustrated in Fig. 6 on which the same symbol of points and isodose curves indicates the same dose in rad. The maximum deviations were 1.5% for the 91.8 rads, 1.4% for the 81.6 rads, 3.5% for the 71.4 rads, 2.8% for the 61.2 rads, 3.1% for the 51.0 rads and 2.5% for the 40.8 rads, maximum deviation among all points being 3.5%. Rather larger deviation exists on the left hand side, namely, shorter source skin distance part.

3. Irradiation to Uneven Surface: Simulation of Irradiation to the Maxillary Antrum

In this case, measured and calculated depth dose curves were indicated separately. As shown in Fig. 7 the difference was 2% for the 90% dose point, 2% for the 80% dose point, 2% for the 70% dose point and 1% for the 50% dose point. Consequently, the maximum deviation so far was 2%. It is remarkable that the isodose curve from THERAC-II has rather sharp curvature at the turning point from penumbla region to middle part of the field.

4. Rotational Irradiation

Doses were measured by a ion chamber at fixed 5 points in the Mix-D phantom. Fig. 8(a) shows isodose curves which were drawn by film dosimetry. Doses at the corresponding 5 points in the dose

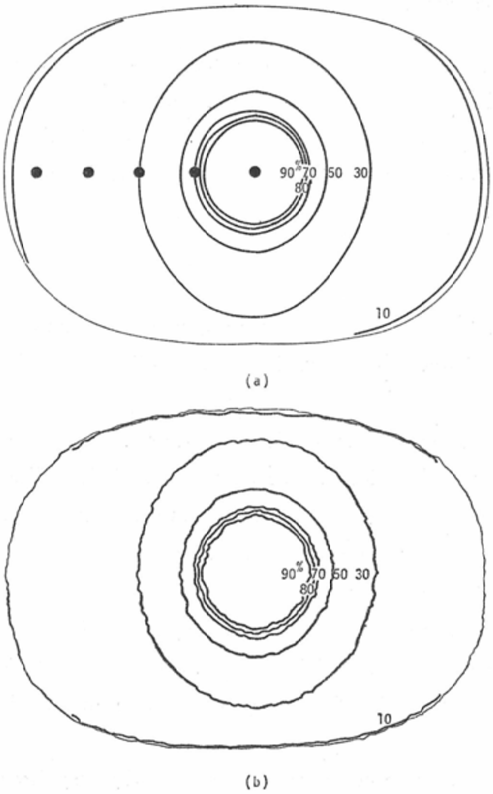


Fig. 8. Rotational irradiation
STD: 100cm, F.S.: 6×9cm
Full rotation
Phantam: Mix-D
Dosimetry: Ion chamber and film

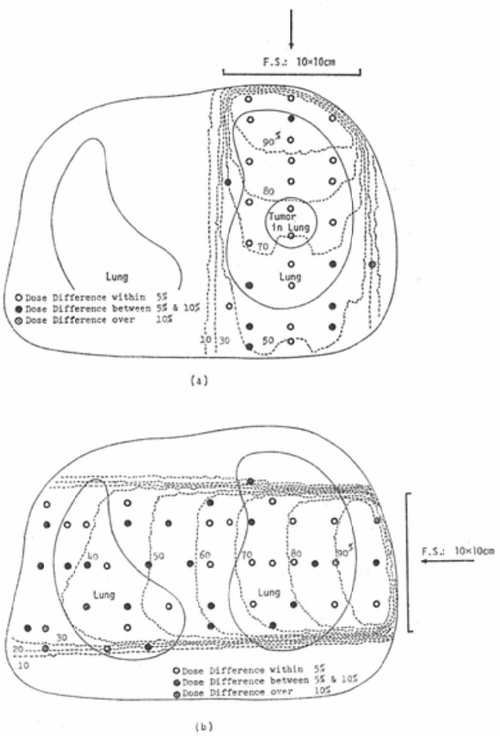


Fig. 9. Irradiation to heterogeneous tissue
SSD: 100cm, F.S.: 10×10cm
Phantom: Inhomogenous thoracic phantom
Dosimeter: Siemens' dosimeter, Midget thimble chamber

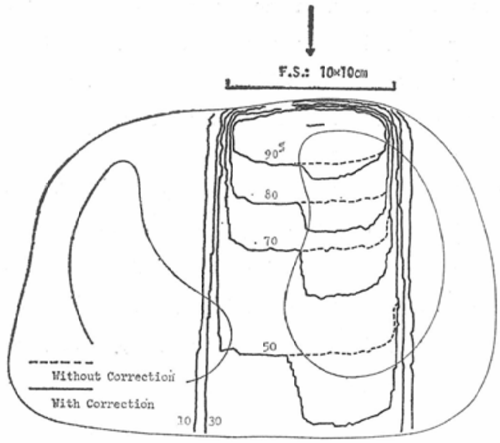


Fig. 10. The comparison of isodose curves by THERAC-II plotter output between two cases:
SSD: 100cm, F.S.: 10×10cm,
Solid line: Calculation with correction of lungs effect,
Dotted line: Calculation without correction.

matrix from THERAC-II calculation were shown in Fig. 8(b). While the measured doses at 5 fixed points were 100%, 62%, 31%, 19% and 12%, calculated doses at the corresponding points were 100%, 66%, 31%, 20% and 14%, respectively. Thus, the deviation was 6.4% for 62% dose, 0% for 31% dose, 5% for 19% dose and 14% for 12% dose, respectively. The average deviation was 5% and the maximum deviation was 14%.

5. Irradiation to Inhomogeneous Tissues.

(1) Irradiation from the anterior

Dose measurement by ion chamber was carried out at 29 fixed points in the inhomogeneous thoracic phantom, and each dose value was compared with the calculated dose on the corresponding points in the dose matrix obtained from THERAC-II.

Fig. 9(a) shows the result of comparison. Open circle shows the point which the dose deviation are within 5% and solid circle shows the point which the dose deviation are between 5 and 10%. The maximum deviation was 11.5% (⊙), being the only one points beyond 10%. As seen in the figure, most of the larger deviation are situated near the boundary region between the cork and water.

(2) Irradiation from the right side.

The fixed points for dose measurement were as many as 45 in this case (Fig. 9(b)). As shown in Fig. 9(b), the deviations within 5% were found at 21 points (open circle), between 5 and 10% at 17 points (closed circle), and beyond 10% at 3 points (open double circle), the maximum deviation being 33.7%.

It is also seen from the figure that points on the boundary region between the cork and water showed rather large deviation of dose. Being this tendency same as in the case of irradiation from the anterior, it appears to be caused by the fact that THERAC-II program neglected the scattering effect in the region where the density of tissues suddenly changed.

Fig. 10 shows the difference of depth isodose patterns between corrected and uncorrected in regards to tissue inhomogeneity, indicating the necessity of the correction.

Discussions

1. The Case of Curved Surfaces

Since irradiation to the curved surface is considered to be combination of partial irradiations to the oblique surface, several cases of oblique irradiation were examined at first to confirm the accuracy of dose calculation. The result showed that average deviation was 0.18% in the case of from 0° to 75° incidence, and the maximum deviation was 3.4%. It is reported that correction by distance from the source alone can make the calculated dose agree well with measured value to the extent of oblique incidence angle as far as 60°.[5)15)16)17)] Since in the case of even beyond 60° the result in the present experiment showed only 3.4% deviation, our method is excellent in correcting the SSD effect.

Secondly, the case of tangential irradiation to the thorax phantom was examined. The deviation was within 3% except shallow region of 1 cm depth from the surface.

Thus, it can be stated that the program developed newly has satisfactory accuracy as far as clinical application is concerned.

2. The Case of Rotational Therapy

In the present program, dose calculation anywhere in moving field is performed automatically by summing up the calculated doses of 5° intervals of multi-portal stationary irradiation. This method requires minimum handling and minimum data entry to the computer. Onai et al.[17)] reported that 5° intervals method was excellent approximation, the error caused being within 10% in whole region of tissues to the extent of lower dose level, with which our results agreed very well.

The calculation time in the case of full rotation therapy (72 portals approximation) is about 7 minutes, which is considered to be satisfactory for practical use.

3. The Correction for the Inhomogeneity Effect

Onai et al[16)] reported that 1/2 shift method did not cause errors greater than 5% as far as 10 cm thickness of lungs is concerned. We applied this 1/2 shift method to our program. Present result has shown that the difference between calculated and measured dose was within 5% in the most part of the thoracic phantom with lung phantom of 0.25 density, and was within 10% in the other smaller part of the phantom, which agreed quite well with Onai's report.

Conclusion

Programs of digital type computer system were developed for the purpose of improving accuracy and speed of visual optimization of treatment planning in radiotherapy. The program was applied to the supervoltage external X-ray beams (6 MV linear accelerator).

This paper described a method of calculation in the cases of irradiation to the inhomogeneous tissues including lung.

Calculated doses were compared with that of experimental data which were measured using ion chambers and photographic films inserted in several kinds of phantom. The results were as follows: The maximum difference between measured and calculated doses was 3.4% in the single field including extremely oblique field such as incidence angle of 75 degree, within 2.5% in the tangential field for the homogeneous thorax phantom within 5% in the rotation therapy, and within 10% in the single field for the inhomogeneous thorax phantom having cork of specific density 0.25. Generally speaking, the results obtained were excellent and proved that this machine was satisfactorily applicable to clinical use.

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