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(54) **IRRADIATION PLANNING APPARATUS AND CHARGED PARTICLE IRRADIATION SYSTEM**

BESTRAHLUNGSPLANUNGSVORRICHTUNG UND SYSTEM ZUR BESTRAHLUNG MIT GELADENEN TEILCHEN

APPAREIL DE PLANIFICATION D'IRRADIATION ET SYSTÈME D'IRRADIATION DE PARTICULES CHARGÉES

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Description

TECHNICAL FIELD

[0001] The present invention relates to an irradiation planning apparatus for making, for example, an irradiation plan for a charged particle irradiation system that radiates charged particles to a target, an irradiation planning program, an irradiation plan determining method, and a charged particle irradiation system.

BACKGROUND ART

[0002] Conventionally, there have been proposed an apparatus that conducts a heavy charged particle therapy by radiating charged particles to an affected area such as cancer cells. In a heavy charged particle therapy such as a carbon filament therapy, it is desirable to realize a uniform clinical effect in the target. For achieving this, it is possible to define a clinical dose which is the product of an absorbed dose and a relative biological effectiveness (RBE), and make an irradiation plan so that the clinical dose is uniform in the target.

[0003] Fig. 4(A) is a diagram illustrating irradiation spots to which charged particles of a single ion species are to be radiated. Fig. 4(A) shows a longitudinal section of a target viewed from the lateral side of the traveling direction of the beam. In the apparatus that conducts a heavy charged particle therapy, as illustrated in the drawing, spots SP disposed on the surface perpendicular to the irradiation direction are arranged in the irradiation direction with respect to a tumor region 182 located behind a body surface 188, and thus the spots SP are arranged three-dimensionally. The apparatus that conducts a heavy charged particle therapy sequentially radiates a beam of ion species to the spots SP from the direction of the arrow illustrated in the drawing and conducts irradiation in a manner of filling the tumor region 182.

[0004] Fig. 4(B) illustrates a depth dose distribution chart by such a carbon filament therapy. In this chart, depth distributions of a clinical dose 191, an RBE 192, and an ion species irradiation dose 193 are shown. In designing a clinical dose that is uniform in the target in the carbon filament therapy, the quality (LET) distribution of carbon filament for realizing this is determined almost uniquely. Here, when the RBE 192 involves errors 192a, 192b, large distortions 191a, 191b occur in the distribution of the clinical dose 191, and the clinical dose distribution can greatly deteriorate.

[0005] RBE depends on quality of radiation (particle species or LET), dose level, cell strain, end point and so on, and RBE itself is accompanied by a large error. Therefore, it is desired to reduce the error in RBE for preventing significant deterioration in the clinical dose distribution.

[0006] There have been proposed a method and an apparatus for charged particle beam irradiation capable of radiating charged particles from a plurality of directions by having a rotary irradiation device (see Patent Document 1). With this apparatus, since charged particles can be radiated from the plurality of directions, it is possible to reduce the irradiation dose on normal sites by widely dispersing the dose to be radiated to the normal sites. Radiation of the charged particles from the plurality of directions can also reduce an error in RBE.

[0007] Increased irradiation directions, however, lead to several disadvantages. First, increased irradiation directions disadvantageously increase a burden on a staff engaged in the therapy. In addition, increased irradiation directions disadvantageously lead to a large increase in exposure volume of normal tissues. There is a disadvantage that a rotary gantry like a rotary irradiation device of Patent Document 1 is bulky. Also, there is a disadvantage that a rotary gantry for heavy charged particles has not been practically used in an actual therapy because of difficulties in its construction and operation.

[0008] Besides the above, since occurrence of a delayed effect such as cerebral necrosis from the planned therapeutic volume (PTV) after the therapy is reported for part of sites such as a cerebral tumor, it is desired to develop an irradiation method capable of effectively controlling only cancer cells without injuring normal cells contained in a tumor.

PRIOR ART DOCUMENT

PATENT DOCUMENT

[0009] Patent Document 1: Japanese Patent Laid-open Publication No. 2000-202047

SUMMARY OF THE INVENTION

PROBLEMS TO BE SOLVED BY THE INVENTION

[0010] In light of the above problems, it is an object of the present invention to provide an irradiation planning apparatus, an irradiation planning program, an irradiation plan determining method, and a charged particle irradiation system capable of realizing irradiation with desirable dose distribution with respect to a target.

SOLUTIONS TO THE PROBLEMS

[0011] The present invention provides a charged particle irradiation system according to claim 1. The present invention provides an irradiation planning apparatus for determining an irradiation parameter of a charged particle irradiation system that radiates charged particles generated by an ion source to a target by accelerating the charged particles by means of an accelerator, the irradiation planning apparatus having composite irradiation parameter determining means that determines the irradiation parameter with respect to one target by combining the charged particles of a plurality of kinds of ion species, or an irradiation planning program, and an irradiation plan determining method. Irradiation systems and methods using more than one different particle or ion species are known from US7920675, DE102009058294 and EP2400506.

EFFECTS OF THE INVENTION

[0012] In the present invention, it is possible to provide an irradiation planning apparatus, an irradiation planning program, an irradiation plan determining method, and a charged particle irradiation system capable of achieving irradiation with desirable dose distribution with respect to one target.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013]

Fig. 1 is a block diagram showing a configuration of a charged particle irradiation system.
Fig. 2 is a flowchart of a planning program executed by a CPU of a planning apparatus.
Fig. 3 is a diagram illustrating composite irradiation with a plurality of kinds of ion species, and its effect.
Fig. 4 is a diagram illustrating conventional ion species irradiation, and its effect.

EMBODIMENTS OF THE INVENTION

[0014] Hereinafter, one embodiment of the present invention will be described by referring to the attached drawings.

[0015] Fig. 1 is a block diagram showing a configuration of a charged particle irradiation system 1. The charged particle irradiation system 1 includes a plurality of ion sources 2 (2A, 2B, 2C), a multiple ion source connector 3, a linear accelerator 4, a synchrotron 5, a conveyance system 6, a fixed radiator 20, a rotary gantry 22, and a controlling apparatus 50 for controlling these. To the controlling apparatus 50, a planning apparatus 70 that transmits therapy planning data is connected.

[0016] The ion source 2 is a device that removes an electron from an atom to generate an ion, and includes a first ion source 2A for drawing an ion species of the first kind, a second ion source 2B for drawing an ion species of the second kind, and a third ion source 2C for drawing an ion species of the third kind. The first to third ion sources 2 are configured to generate different kinds of ions, e.g., oxygen ions, carbon ions, and helium ions, respectively.

[0017] The multiple ion source connector 3 is a connector that selectively connects the first ion source 2A to the third ion source 2C to the linear accelerator 4. The multiple ion source connector 3 appropriately switches the ion source 2 for supplying the linear accelerator 4 with ion species, to any one of the first ion source 2A to the third ion source 2C under the control by the controlling apparatus 50.

[0018] The linear accelerator 4 is a kind of accelerator, and accelerates the charged particles supplied from the ion source 2 to have a predetermined energy by means of an electromagnet, and supplies the charged particles to the synchrotron 5.

[0019] The synchrotron 5 is a kind of accelerator, and further accelerates the charged particles incident from the linear accelerator 4 on a circling orbit by means of an electromagnet to make the charged particles have high energy.

[0020] The conveyance system 6 conveys the charged particles drawn by an emitter 11 from the synchrotron 5 to an irradiation device 25 by means of an electromagnet.

[0021] The emitter 11 is provided at a connecting part between the synchrotron 5 and the conveyance system 6, and emits the charged particles to the conveyance system 6 from the synchrotron 5 under the control by the controlling apparatus 50.

[0022] A switch 12 is provided on the conveyance system 6, and switches the therapy rooms 9 (9A, 9B, 9C) accommodating the irradiation device 25 to which the charged particles conveyed by the conveyance system 6 are to be conveyed under the control by the controlling apparatus.

[0023] The fixed radiator 20 provided in each of the therapy rooms 9A, 9B radiates charged particles from the irradiation device 25 provided at its trailing end.

[0024] The rotary gantry 22 provided in the therapy room 9C can change the irradiation direction of charged particles by rotation, and radiates charged particles from the irradiation device 25 at the trailing end toward the changed irradiation direction.

[0025] The irradiation device 25 controls a position in the XY direction of charged particles (planar direction perpendicular to the radiation direction of charged particles) by means of a X-direction scanning magnet and a Y-direction scanning magnet, and controls a stop position in the Z direction of charged particles (traveling direction of charged particles) by means of an energy changing part (range shifter), and measures the irradiation dose of charged particles for each irradiation spot by means of a scanning monitor. In other words, the irradiation device 25 functions as a scanning irradiation device that controls the three-dimensional position of an irradiation spot of charged particles while measuring the irradiation dose. This scanning irradiation device three-dimensionally scans a pencil beam in which charged particles are narrowed down, and conducts a therapy in a manner of filling the tumor.

[0026] The controlling apparatus 50 has a CPU (central processing unit) 51 and a memory 52. The memory 52 stores various programs and data including a control program 60, current value changing pattern data 66, irradiation parameter data 67, and maximum depth data 68. The CPU 51 operates by using the data such as the current value changing pattern data 66, and the irradiation parameter data 67 in accordance with the program such as the control program 60. By this operation, the controlling apparatus 50 functions as an ion source switching section 61, an accelerator controlling section 62, an irradiation position controlling section 63, a stop position controlling section 64, and a dose monitoring section 65. The CPU 51 also functions as a multiple ion species irradiation controller that conducts a control of making the ion source switching section 61 switch the ion species, making the accelerator controlling section 62 accelerate with an appropriate current, and making the irradiation position controlling section 63 and the stop position controlling section 64 sequentially change the irradiation spot.

[0027] The ion source switching section 61 conducts a control of switching the ion source for generating charged particles to either one of the first ion source 2A to the third ion source 2C. This makes it possible to switch the ion species between spills.

[0028] The accelerator controlling section 62 reads out an appropriate current value changing pattern from the current value changing pattern data 66 in accordance with the ion species supplied from the ion source 2, and controls the current value to be flown in the electromagnet of the accelerator 4 in accordance with this current value changing pattern.

[0029] The irradiation position controlling section 63 controls and drives the X-direction scanning magnet and the Y-direction scanning magnet of the irradiation device 25 to control the position in the plane perpendicular to the traveling direction (position in the XY direction) of charged particles to be emitted to the target.

[0030] The stop position controlling section 64 controls and drives the energy changing part of the irradiation device 25 to control the stop position of charged particles in the traveling direction of the charged particles (Z direction).

[0031] The dose monitoring section 65 acquires an irradiation dose for each irradiation spot measured by a dose monitor of the irradiation device 25.

[0032] The current value changing pattern data 66 is pattern data of current values to be flown in the electromagnets of the linear accelerator 4, the synchrotron 5, and the linear accelerator 4 for individual ion species. The memory 52 storing the current value changing pattern data 66 functions as a current pattern memory.

[0033] The irradiation parameter data 67 is data including spot number, X position, Y position, energy, irradiation amount, and ion species. The energy indicates an irradiation position in the Z direction. The irradiation amount indicates the number of charged particles to be radiated, or a dose. The ion species consists of appropriate information from which the ion species to be radiated can be identified, for example, ion species name, ion species number, or ion source ID indicating which one of the first ion source 2A to the third ion source 2C is to be used as the ion source. The irradiation parameter data 67 is received from the planning apparatus 70 and stored in the memory 52.

[0034] The maximum depth data 68 stores maximum depths of individual ion species that can be radiated by the charged particle irradiation system 1. These maximum depths are smaller in heavier ion species, and larger in lighter ion species. Therefore, the settings may be provided not for light ion species, but only for part of heavy ion species that can be used.

[0035] Besides the above, the controlling apparatus 50 also executes a control of emitting charged particles from the emitter 11 and a control of switching the destination of irradiation of charged particles by the switch 12.

[0036] The switching of the irradiation spot and the switching of the ion species by the controlling apparatus 50 may be conducted in an appropriate order. For example, after completion of irradiation to all the irradiation spots with one ion species, the ion species may be switched to the next ion species, or after irradiating a predetermined range of irradiation spots with all ion species, the irradiation spots may be switched to the next predetermined range of irradiation spots. The predetermined range of irradiation spots can be appropriately set in such a manner that it is the whole of the irradiation spots in the plane perpendicular to the irradiation direction at one depth position of the irradiation direction, or it is one irradiation spot. Since it is necessary to change the current value to be flown in the synchrotron 5 or the like in accordance with the current value changing pattern data 66 when the ion species is changed, it is desired to irradiate all the irradiation spots sequentially with each ion species.

[0037] This charged particle irradiation system 1 allows generation of the charged particles of the plurality of kinds of different ion species by the ion source 2, and allows irradiation of one target with accelerated charged particles of various ion species while switching the plurality of kinds of ion species.

[0038] The planning apparatus 70 is a computer having a CPU 71, a memory 72, an input part 74, and a display part 75, and functions as an irradiation planning apparatus or a therapy planning apparatus.

[0039] The memory 72 stores various programs including a planning program 73 as an irradiation planning program, and various data.

[0040] The CPU 71 operates using data in the memory 72 in accordance with a program such as the planning program 73. By this operation, the planning apparatus 70 generates the irradiation parameter data 67, and transmits the irradiation parameter data 67 to the controlling apparatus 50.

[0041] The input part 74 is configured by input devices such as a keyboard and a mouse, and receives an input operation, for example, by a person who is planning the therapy.

[0042] The display part 75 is configured by a display device such as a display for displaying characters and images, and displays various images including CT captured image, MRI image and PET image, and various regions (GTV, CTV, PTV) and so on.

[0043] By means of the charged particle irradiation system 1 configured as described above, it is possible to execute an intensity modulated composite ion therapy (IMCIT) that radiates charged particles while modulating the beam intensity by using a plurality of kinds of ion species based on the irradiation parameter data 67.

[0044] Next, an operation for creating the irradiation parameter data 67 using a plurality of kinds of ion species by the planning apparatus 70 will be described.

[0045] The intensity modulated composite ion therapy of the present invention sequentially determines "which ion species m", "to which spot i", and "how many $w_{i,m}$" is to be radiated, by inverse planning. The spot i indicates the spot number of the irradiation parameter data 67.

[0046] First, the planning apparatus 70 selects the number of ion species M to be radiated, and the ion species, and creates a dose kernel for irradiation of each spot for each ion species. The dose kernel $d_{i,m}(r)$ indicates a dose applied to a position r in a patient body by a pencil beam of ion species m radiated to the spot i. The dose kernel $d_{i,m}(r)$ reflects physical characteristics of each ion species. The physical characteristics used herein include extension of beam due to scattering, and an amount of generated fragments, and LET (Linear Energy Transfer).

[0047] In a therapy planning of the intensity modulated composite ion therapy, it is possible to determine the irradiation parameters ($w_{i,m}$) for the purpose by formulating the evaluation index f of the repetitive operation by a least square method or the like depending on the purpose.

<1> First evaluation index f

[0048] As the first example, an evaluation index f can be calculated by Mathematical formula 1 and Mathematical formula 2 below.

[Mathematical formula 1]

$$f(\mathbf{w}_m)=\sum_{j\in T}\left(Q_T^{o}\,H'\left[\sum_{m=1}^{M}D_j(\mathbf{w}_m)-D_T^{\max}\right]^2+Q_T^{u}\,H'\left[D_T^{\min}-\sum_{m=1}^{M}D_j(\mathbf{w}_m)\right]^2\right)+\sum_{j\in O}Q_O^{o}\,H'\left[\sum_{m=1}^{M}D_j(\mathbf{w}_m)-D_O^{\max}\right]^2$$

[Mathematical formula 2]

$$D_j(\mathbf{w}_m)=\sum_{i=1}^{N}d_{i,m}(\mathbf{r}_j)w_{i,m}\equiv\sum_{i=1}^{N}d_{i,m}w_{i,m}$$

[0049] The evaluation index f represented by [Mathematical formula 1] consists of three terms. The first term and the second term are operations for a target. The target used herein refers to an irradiation region that is determined based on a tumor-invasion region specified by a physician or the like while an irradiation error or the like is taken into account. The third term is an operation for OAR (Organ At Risk).

[0050] The first term represents a penalty for the value over the maximum allowable value, and is multiplication of Q_T^O and H' [(subtraction)]^2. The (subtraction) part is a formula that subtracts a maximum dose D_T^{max} which is the maximum allowable value, from a dose applied to each position j (three-dimensional position in the patient body, preferably specified with higher resolution than the resolution for the position specified by the spot i) of the target when w_m nuclides of a plurality of kinds of ion species m are radiated. The H' [] part represents a Heaviside function, and the value is fetched when the value of the (subtraction) part is positive, and zero is assigned when it is negative. Therefore, when the dose is less than or equal to the maximum allowable value, the first term is zero which is assigned for an appropriate value, and does not increase the evaluation index f. Q_T^O is a penalty coefficient, and when it is set large, the value over the maximum allowable value calculated by H' [(subtraction)]^2 greatly influences the evaluation index f.

[0051] The second term represents a penalty for the value under the minimum allowable value, and is multiplication of Q_T^U and H' [(subtraction)]^2. The (subtraction) part is a formula that subtracts a dose applied to each position j (three-dimensional position in the patient body) of the target when w_m nuclides of a plurality of kinds of ion species m are radiated from a minimum dose D_T^{min} which is the minimum allowable value. The H' [] part does not increase the evaluation index f when the dose is more than or equal to the minimum allowable value because the second term is zero which is assigned for an appropriate value. Q_T^U is a penalty coefficient, and when it is set large, the value under the minimum allowable value calculated by H' [(subtraction)]^2 greatly influences the evaluation index f.

[0052] The third term represents a penalty for the value over the maximum allowable value of dose that can be radiated to organ at risk, and is multiplication of Q_O^O and H' [(subtraction)]^2. The (subtraction) part is a formula that subtracts a maximum dose D_O^{max} which is the maximum allowable value, from a dose applied to each position j (three-dimensional position in the patient body) of the target when w_m nuclides of a plurality of kinds of ion species m are radiated. The H' [] part does not increase evaluation index f when the dose is less than or equal to the maximum allowable value because the first term is zero which is assigned for an appropriate value. Q_T^O is a penalty coefficient, and when it is set large, the value over the maximum allowable value calculated by H' [(subtraction)]^2 greatly influences the evaluation index f.

[0053] For example, assuming the case where a peripheral region of the target is set as OAR, and coefficient of a risk degree Q_O^O of the third term is set at a large value, the number $w_{i,\,m}$ of ion species m to be radiated to each spot i is optimally determined so that the evaluation index f (w_m) is minimum in the inverse planning that inversely calculates an optimum irradiation method from the optimum dose distribution. Therefore, by setting the coefficient of risk degree Q_O^O at a large value, it is possible to determine "to which position", "with which ion species", and "how much" irradiation is to be made for minimizing the dose application to the peripheral region of the target while keeping a necessary and sufficient dose (first term, second term) for the target.

[0054] By using the first evaluation index f, it is possible to increase dose concentration to the tumor, compared with the conventional example where only one kind of ion species is used.

<2> Second evaluation index f

[0055] As a second example, an evaluation index f can be calculated by Mathematical formula 3 below.

[Mathematical formula 3]

$$f(\mathbf{w}_m) = \sum_{j \in T} \left(Q_T^o H' \left[\sum_{m=1}^{M} D_j(\mathbf{w}_m) - D_T^{max} \right]^2 + Q_T^u H' \left[D_T^{min} - \sum_{m=1}^{M} D_j(\mathbf{w}_m) \right]^2 \right) + \sum_{j \in T'} Q_{T'}^o H' \left[LET_{T'}^{min} - LET_j(\mathbf{w}_{m-1,M}) \right]^2$$

The third term of [Mathematical formula 3] represents a penalty for the case where the irradiation amount to a region T' of high-grade tumor is less than the minimum allowable value, and is multiplication of $Q_T'^O$ and H' [(subtraction)]^2. The (subtraction) part is a formula that subtracts an energy amount LET applied to each position j (three-dimensional position in the patient body) of the target when w_m nuclides of a plurality of kinds of ion species m are radiated, from a minimum energy amount $LET_{T'}^{min}$ which is the minimum allowable value. The H' [] part does not increase the evaluation index f when the dose is more than or equal to the minimum allowable value because the third term is zero which is assigned for an appropriate value. Q_T^O is a penalty coefficient, and when it is set large, the value under the minimum allowable value calculated by H' [(subtraction)]^2 greatly influences the evaluation index f.

[0056] By adding the third term of [Mathematical formula 3] as described above, it is possible to provide a limit that prevents LET of a partial region (T') in the tumor from being lower than a certain value $LET_{T'}^{min}$.

[0057] By using the second evaluation index f, it is possible to provide an effective therapy in accordance with, for example, difference in radiation sensitivity between normal cells and cancer cells contained in the tumor.

<3> Third evaluation index f

[0058] As the third example, an evaluation index f can be calculated by the following Mathematical formula 4.

[Mathematical formula 4]

$$f(\mathbf{w}_m)=\int_{\alpha_{\min}}^{\alpha_{\max}}\sum_{j\subset T}\left(Q_T^{o}\,H'\left[\sum_{m=1}^{M}D_j(\alpha,\mathbf{w}_m)-D_T^{\max}\right]^2+Q_T^{u}\,H'\left[D_T^{\min}-\sum_{m=1}^{M}D_j(\alpha,\mathbf{w}_m)\right]^2\right)\phi(\alpha)d\alpha$$

[0059] In [Mathematical formula 4], parameter α defining a biological effect is varied within the range of assumed errors $\alpha_{min} \le \alpha \le \alpha_{max}$, and a weight w_m for each ion species with which dose distribution in the target falls within the allowable values shown by the following mathematical formula [5] for every α is optimally determined for individual ion species. Here, ϕ (α) represents probability (probability density function) of assuming α.

[Mathematical formula 5]

$$D_T^{\min}\le\sum_{m=1}^{M}D_j(\alpha,\mathbf{w}_m)\le D_T^{\max}$$

[0060] By using this third evaluation index f, it is possible to provide a robust therapy that is insusceptible to relative biological effectiveness (RBE) and irradiation, and registration error.

<4> Setting of depth limit for individual ion species

[0061] A dose kernel cannot be created for a depth exceeding the maximum accelerable energy for ion species (nuclide). For this reason, maximum depths for individual ion species are registered in the maximum depth data 68, and ion species that is selectable are limited. As a result, for the depth exceeding the maximum accelerable energy for a certain ion species, an ion species that is lighter than the certain ion species is radiated. For example, in a facility having a synchrotron capable of radiating 16 cm for oxygen, 22 cm for carbon, and 66 cm for helium, the position exceeding 22 cm is automatically irradiated with helium by registering the specification in the therapy plan, and imposing the limitation.

[0062] As a result, the advantages of lower prices and smaller sizes of the heavy charged particle therapy apparatus equipped with the charged particle irradiation system 1 are obtained.

[0063] By formulating the objective functions of inverse planning in conformance with the purpose as shown in <1> to <4> with the use of the flexibility associated with the use of a plurality of kinds of ion species, it is possible to automatically determine irradiation parameters that are consistent with the purpose.

[0064] Fig. 2 is a flowchart of a process executed by the CPU 71 of the planning apparatus 70 to generate the irradiation parameter data 67 in accordance with the planning program 73. The CPU 71 executing this process functions as composite irradiation parameter determining means.

[0065] First, the CPU 71 receives input of data about target/organ at risk based on data obtained by separate CT imaging from the input part 74 (step S1). This data input is made by a physician, for example by surrounding respective regions of GTV and CTV in a CT captured image displayed in the display part 75. GTV is a macroscopic tumor volume that can be observed in an image or by palpation, whereas CTV is a clinical target volume including GTV and a microscopic progression range. At this time, the planning apparatus 70 also permits input of an allowable evaluation value C for which the evaluation index f is a sufficiently small value.

[0066] The CPU 71 determines an irradiation direction in which a pencil beam is radiated for the input data of target/organ at risk (step S2). This determination can be achieved by appropriate methods including input by an operator, or determination by the CPU 71 in accordance with a preset algorism for determining an irradiation direction.

[0067] The CPU 71 determines an ion species to be radiated (step S3). Here, the number of ion species is determined as M, and ion species is determined as m = 1, M. Since this determination of ion species depends on the ion species that can be radiated from the ion source 2, the determination may be made by reading out data of the ion species that can be radiated, preliminarily stored in the memory 72 of the planning apparatus 70. The determination may be conducted by an appropriate method, for example, by inputting a plurality of kinds of ion species (for example, three kinds) to be used among a plurality of kinds of ion species (for example, four kinds) that are selectable in the charged particle irradiation system 1, by a therapy planner, or by an appropriate algorism.

[0068] The CPU 71 prescribes doses for a target/organ at risk (step S4). Here, a therapy planner inputs a maximum allowable value Dmax, a minimum allowable value Dmin and the like shown in [Mathematical formula 1] to [Mathematical formula 5] at the input part 74 under a physician's direction.

[0069] The CPU 71 determines an irradiation position of a pencil beam (step S5). The irradiation position is determined by arranging beam spots densely three-dimensionally for the entire region of PTV (which is to be a target). The entire irradiation position determined in this manner is a target T, and each one of the irradiation positions is a spot to which a pencil beam of ion species is to be radiated. PTV refers to a planned target volume including CTV and an irradiation error. The CPU 71 sets the part corresponding to GTV in the irradiation position as a high-grade malignant target T', and the periphery of the irradiation position as a protective region O which is OAR.

[0070] The CPU 71 creates a dose kernel d (i, m) of a pencil beam (step S6). Here, i represents an irradiation position (spot ID), and m represents a volume.

[0071] The CPU 71 determines an initial value of a weight w (i, m) of a pencil beam (step S7). This initial value is determined by the CPU 71 on the basis of a rough order regarding the number of nuclides to be radiated to the spot.

[0072] The CPU 71 calculates a dose D based on the weight (step S8). This dose calculation gives candidates for the irradiation parameter data 67 that determines the position, the ion species, and the amount to be radiated.

[0073] The CPU 71 derives an evaluation index f so that the dose is necessary and sufficient to the target, and exposure to organ at risk is not more than allowable values (step S9).

[0074] The CPU 71 repeats steps S8 to S9 while updating the weight w (i, m) of the pencil beam and adding a variable n by 1 (step S11) until the evaluation index f is less than C or the variable n is larger than N (step S10: No). C represents an allowable evaluation value indicating that the evaluation index f is sufficiently small and allowable, and N represents the maximum number of repetition. Therefore, when the evaluation index f is less than C and is sufficiently small, or the maximum number of repetition is reached, the repetitive operation ends. As to updating of the weight w (i, m), it is desired to update the data of the entire region to be irradiated. Besides, the value currently stored and the value obtained by the calculation of this time may be compared for each spot, and the value of the spot may be updated when the value obtained by the calculation of this time is preferred.

[0075] When the evaluation index f is less than C, or the variable n is larger than N (step S10: Yes), the CPU 71 outputs the irradiation parameter data 67 to the controlling apparatus 50 (step S12), and ends the process.

[0076] Through these operations, the planning apparatus 70 can generate the irradiation parameter data 67 using a plurality of kinds of ion species. The controlling apparatus 50 of the charged particle irradiation system 1 can irradiate one target (irradiation region of one patient) with any one of the plurality of kinds of ion species switched in accordance with the irradiation parameter data 67. As described above, by having the ion sources 2A to 2C, and switching the energy and the ion species during a single irradiation from one direction by conducting switching of ion species, acceleration, drawing and irradiation, it is possible to realize any dose/dose distribution in the tumor.

[0077] By the irradiation parameter data 67 thus generated, the arrangement of ion species to be radiated to the tumor is set, for example, in the manner as shown in the irradiation ion species distribution chart of Fig. 3(A). Fig. 3(A) is a longitudinal section of irradiation ion species distribution viewed from the lateral side of the beam traveling direction. Irradiation spots SP are three-dimensionally arranged so that the entire target 80 is filled. In this example, the front side of the irradiation direction (the side closer to a body surface 88) and the peripheral part in the XY direction are set as a first irradiation region 82 mainly composed of a heavy ion species (oxygen O in this example), the center part of the tumor is set as a second irradiation region 83 mainly composed of a lighter ion species (carbon C in this example), and the back side of the irradiation direction is set as a third irradiation region 84 mainly composed of a further lighter ion species (helium He in this example). By irradiating in this manner, it is possible to achieve irradiation with desired quality of radiation for each site (each of the irradiation regions 82, 83, 84) in the target 80 by combining the advantage of the heavy ion species having characteristics of small scattering, large generation quantity of fragments, and high LET, and the advantage of the light ion species having characteristics of large scattering, small generation quantity of fragments, and low LET. In brief, the charged particle irradiation system 1 can concentrate the dose at the target 80 while minimizing exposure to the peripheral normal tissues by irradiating the periphery of the target (peripheral part perpendicular to the irradiation direction) with a heavy ion species to make the scattering small, and irradiating the downstream side of the target (back side of the irradiation direction) with a light ion species to reduce the application of dose to the back side of the target due to fragments, and irradiating the upstream side of the target (front side of the irradiation direction) with a heavy ion species to make LET high.

[0078] For the irradiation regions 82, 83, 84, the irradiation setting can be made appropriately, for example, radiating a single ion species to each irradiation spot, or radiating to each irradiation spot a combination of a plurality of kinds of ion species in different proportions of irradiation amounts (the number of radiated charged particles) for different ion species, or making irradiation spots to be irradiated with a single ion species, and irradiation spots to be irradiated with a plurality of kinds of ion species coexist.

[0079] Fig. 3(B) shows a depth dose distribution chart radiated by the controlling apparatus 50 using a plurality of kinds of ion species in accordance with the irradiation parameter data 67 by an intensity modulated composite ion therapy. As described with Fig. 3(A), Fig. 3(B) shows an example of the case where the front side of the irradiation direction (the part of small depth, upstream side) is irradiated with a heavy ion species, and the back side of the irradiation direction (the part of large depth, downstream side) is irradiated with a light ion species.

[0080] As illustrated in the drawing, the charged particle irradiation system 1 keeps gentle distribution of quality (LET) in the target by combining a first ion species irradiation dose 94, a second ion species irradiation dose 95 and a third ion species irradiation dose 96 indicating physical amount of energy for a clinical dose 91 (D_{clin}). In the illustrated example, the charged particle irradiation system 1 irradiates the front side of the irradiation direction with oxygen which is a heavy ion species at a proportion larger than those of other ion species to achieve the first ion species irradiation dose 94, irradiates the center or its periphery of the irradiation direction with carbon which is the second heavy ion species at a proportion larger than those of other ion species to achieve the second ion species irradiation dose 95, and irradiates the back side of the irradiation direction with helium which is a lighter ion species than the above at a proportion larger than those of other ion species to achieve the third ion species irradiation dose 96.

[0081] In this manner, the charged particle irradiation system 1 can realize a uniform clinical dose distribution in the target while appropriately changing the quality of radiation (particle species and LET) by combining a plurality of kinds of ion species. As a result, the distribution of quality of radiation (LET) in the target can be kept gentle by combination of the plurality of kinds of ion species, and distortions 91a, 91b in the distribution of the clinical dose 91 can be suppressed to low levels even when errors 92a, 92b occur in a RBE 92.

[0082] By optimizing the quality distribution by means of the plurality of kinds of ion species in accordance with the radiation sensitivity of normal cells or cancer cells in a tumor, the charged particle irradiation system 1 can kill only the cancer cells while conserving the normal cells.

[0083] By using a light ion species for irradiation of a deep site, the charged particle irradiation system 1 can treat a deep site of the body with an accelerator of low acceleration energy. Generally, high acceleration energy is required for a heavy ion species to reach a deep site, however, according to the present invention, a deep site can be treated with low acceleration energy by using a light ion species, and thus the acceleration energy required as a whole can be reduced. Therefore, it is possible to achieve cost reduction and downsizing of the accelerator, which contributes to the spread of the heavy charged particle therapy.

[0084] In addition, by using the plurality of kinds of ion species, the charged particle irradiation system 1 can desirably set spatial distribution of not only dose but also quality even in the single field irradiation from one direction, and improve the concentration of dose to the tumor compared with the conventional case using a single ion species. The charged particle irradiation system 1 can provide a therapy that is insusceptible to relative biological effectiveness (RBE) and irradiation, and registration error. The charged particle irradiation system 1 can also provide an effective therapy depending on the difference in radiation sensitivity between normal cells and cancer cells contained in a tumor. The charged particle irradiation system 1 can realize the dose distribution and the quality distribution to be given into the target without necessity of a large-scale apparatus like a rotary gantry.

[0085] The present invention is not limited to the configuration of the aforementioned embodiment, but many embodiments are available.

INDUSTRIAL APPLICABILITY

[0086] The present invention is applicable to a charged particle irradiation system that radiates a beam of charged particles to a target.

DESCRIPTION OF REFERENCE SIGNS

[0087]

1: Charged particle irradiation system
2: Ion source
2A: First ion source
2B: Second ion source
2C: Third ion source
4: Linear accelerator
5: Synchrotron
67: Irradiation parameter data
68: Maximum depth data
70: Planning apparatus
71: CPU
72: Memory
73: Planning program

Claims

1. A charged particle irradiation system (1) comprising:

an ion source (2) for generating charged particles;
an accelerator for accelerating the charged particles generated by the ion source (2);
an irradiation device for irradiating a target with charged particles drawn from the accelerator; and
a controlling apparatus (50) configured to control operations of the ion source (2), the accelerator, and the irradiation device, wherein
the ion source (2) includes a plurality of kinds of ion sources (2A, 2B, 2C) that generate different ion species as the charged particles, and **characterized in that** the controlling apparatus (50) includes:

a current pattern memory (52) configured to store current values to be flown in an electromagnet provided in the accelerator defined for individual ion species; and
a multiple ion species irradiation controller configured

to switch a current value to be flown in the electromagnet of the accelerator based on the ion source to be used and a current value with respect to the one target stored in the current pattern memory, and to control the ion source to radiate a plurality of kinds of ion species while the plurality of kinds of ion species are switched selectively.

2. An irradiation planning apparatus (70) for determining an irradiation parameter of the charged particle irradiation system (1) of claim 1, the apparatus comprising:
composite irradiation parameter determining means (71) arranged to determine the irradiation parameter with respect to one target patient body (80) while varying the kind of the ion species to be radiated, or a ratio of the plurality of kinds of ion species to be radiated to each site of the target patient body (80).

3. The irradiation planning apparatus (70) according to claim 2, further comprising memory means (72) for storing maximum depth data (68) defining a maximum depth of irradiation in a target patient body (80) for individual ion species radiated by the charged particle irradiation system (1), wherein
the composite irradiation parameter determining means (71) is arranged to determine, using the stored maximum depth data (68), an ion species which is able to be radiated to a position located deeper in the target patient body (80) than the maximum depth of another ion species for which the maximum depth is defined in the maximum depth data (68).

4. The irradiation planning apparatus (70) according to claim 2 or 3, wherein
the composite irradiation parameter determining means (71) is configured to execute a repetitive operation for determining a preferred irradiation parameter, using a formula for calculating a dose of radiation by the charged particles of the plurality of kinds of ion species for each irradiation spot in the target patient body (80), in a mathematical formula of evaluation index for evaluating irradiation parameters in order to determine the preferred irradiation parameter.

5. The irradiation planning apparatus (70) according to claim 2, 3 or 4, wherein
the composite irradiation parameter determining means (71) is configured to define a plurality of irradiation spots for the target patient body (80) by three-dimensional positions, and make a determination so that within the depth distribution of the ions irradiated in the target patient body (80), an ion species which is lighter than the ion species forming the relatively shallow portion of the depth distribution is assigned for the ion species to be abundantly radiated to the relatively deep portion of the depth distribution.

6. An irradiation planning program (73) for making a computer function as an irradiation planning apparatus (70) for determining an irradiation parameter of the charged particle irradiation system (1) according to claim 1 , wherein
the computer is made to function as composite irradiation parameter determining means (71) that are configured to determine the irradiation parameter with respect to one target patient body (80) while varying the kind of the ion species to be radiated, or a ratio of the plurality of kinds of ion species to be radiated from each site of the target.

7. An operation method for an irradiation planning apparatus (70) for determining an irradiation parameter of the charged particle irradiation system (1) according to claim 1 , wherein
the irradiation parameter with respect to one target patient body (80) is determined while the kind of the ion species to be radiated, or a ratio of the plurality of kinds of ion species to be radiated is varied to each site of the target patient body (80).

Patentansprüche

1. System zur Bestrahlung mit geladenen Teilchen (1), umfassend:

   eine Ionenquelle (2) zum Erzeugen von geladenen Teilchen;
   einen Beschleuniger zum Beschleunigen der durch die Ionenquelle (2) erzeugten, geladenen Teilchen;
   eine Bestrahlungsvorrichtung zum Bestrahlen eines Targets mit geladenen Teilchen, die dem Beschleuniger entnommen werden; und
   eine Steuerungsvorrichtung (50), die konfiguriert ist, Arbeitsvorgänge der Ionenquelle (2), des Beschleunigers und der Bestrahlungsvorrichtung zu steuern, worin
   die Ionenquelle (2) eine Vielzahl von Arten von Ionenquellen (2A, 2B, 2C) umfasst, die unterschiedliche Ionenspezies als die geladenen Teilchen erzeugen, und
   dadurch gekennzeichnet, dass
   die Steuerungsvorrichtung (50) Folgendes umfasst:

      einen Strommusterspeicher (52), der konfiguriert ist, Stromwerte, die in einem Elektromagnet fließen sollen, zu speichern, welcher in dem für einzelne Ionenspezies definierten Beschleuniger bereitgestellt ist; und
      eine Mehrfach-Ionenspezies-Bestrahlungssteuerungseinheit, die konfiguriert ist,
      einen Stromwert, der in dem Elektromagnet des Beschleunigers auf Basis der anzuwendenden Ionenquelle fließen soll, und einen Stromwert mit Bezug auf das eine Target, der im Strommusterspeicher gespeichert ist, zu schalten, und
      die Ionenquelle zu steuern, um eine Vielzahl von Ionenspeziesarten abzustrahlen, während die Vielzahl von Ionenspeziesarten wahlweise geschaltet werden.

2. Bestrahlungsplanungsvorrichtung (70) zum Bestimmen eines Bestrahlungsparameters des Systems zur Bestrahlung mit geladenen Teilchen (1) nach Anspruch 1, wobei die Vorrichtung Folgendes umfasst:

   ein Kombinationsbestrahlungsparameterbestimmungsmittel (71), das so angeordnet ist, dass es den Bestrahlungsparameter mit Bezug auf einen Target-Patientenkörper (80) bestimmt, wobei die auf jede Stelle des Target-Patientenkörpers (80) abzustrahlende Ionenspeziesart oder ein Verhältnis aus der Vielzahl von abzustrahlenden Ionenspeziesarten variiert wird.

3. Bestrahlungsplanungsvorrichtung (70) gemäß Anspruch 2, ferner umfassend Speichermittel (72) zum Speichern von Maximaltiefendaten (68), welche eine Maximaltiefe von Bestrahlung in einem Target-Patientenkörper (80) für einzelne, durch das System zur Bestrahlung mit geladenen Teilchen (1) abgestrahlte Ionenspezies definieren, worin das Kombinationsbestrahlungsparameterbestimmungsmittel (71) so ausgebildet ist, unter Verwendung der gespeicherten Maximaltiefendaten (68) eine Ionenspezies zu bestimmen, die geeignet ist, an eine Stelle abgestrahlt zu werden, die tiefer im Target-Patientenkörper (80) als die Maximaltiefe einer anderen Ionenspezies angeordnet ist, für welche die Maximaltiefe in den Maximaltiefendaten (68) definiert ist.

4. Bestrahlungsplanungsvorrichtung (70) gemäß Anspruch 2 oder 3, worin
   das Kombinationsbestrahlungsparameterbestimmungsmittel (71) konfiguriert ist, einen Wiederholungsvorgang zum Bestimmen eines bevorzugten Bestrahlungsparameters unter Anwendung einer Formel zum Berechnen einer Strahlungsdosis durch die geladenen Teilchen aus der Vielzahl von Ionenspeziesarten für jede Bestrahlungsstelle im Target-Patientenkörper (80) in einer mathematischen Formel eines Evaluierungsindexes zum Evaluieren von Bestrahlungsparametern auszuführen, um den bevorzugten Bestrahlungsparameter zu bestimmen.

5. Bestrahlungsplanungsvorrichtung (70) gemäß Anspruch 2, 3 oder 4, worin
   das Kombinationsbestrahlungsparameterbestimmungsmittel (71) konfiguriert ist, eine Vielzahl von Bestrahlungsstellen für den Target-Patientenkörper (80) durch dreidimensionale Positionen zu definieren, und eine Bestimmung dahingehend durchzuführen, dass innerhalb der Tiefenverteilung der im Target-Patientenkörper (80) bestrahlten Ionen eine Ionenspezies, die leichter als die Ionenspezies, welche den relativ oberflächennahen Abschnitt der Tiefenverteilung bildet, ist, derjenigen Ionenspezies zugewiesen wird, die reichlich auf den relativ tiefen Abschnitt der Tiefenverteilung abzustrahlen ist.

6. Bestrahlungsplanungsprogramm (73), um einen Computer als eine Bestrahlungsplanungsvorrichtung (70) funktionieren zu lassen, um einen Bestrahlungsparameter des Systems zur Bestrahlung mit geladenen Teilchen (1) gemäß Anspruch 1 zu bestimmen, worin

der Computer veranlasst wird, als ein Kombinationsbestrahlungsparameterbestimmungsmittel (71) zu funktionieren, das konfiguriert ist, den Bestrahlungsparameter mit Bezug auf einen Target-Patientenkörper (80) zu bestimmen, wobei die abzustrahlende Ionenspeziesart oder ein Verhältnis aus der Vielzahl von Ionenspeziesarten, die von jeder Target-Stelle abzustrahlen sind, variiert wird.

7. Verfahren zum Betrieb einer Bestrahlungsplanungsvorrichtung (70) zum Bestimmen eines Bestrahlungsparameters des Systems zur Bestrahlung mit geladenen Teilchen (1) gemäß Anspruch 1, worin
der Bestrahlungsparameter mit Bezug auf einen Target-Patientenkörper (80) bestimmt wird, wobei die abzustrahlende Ionenspeziesart oder das Verhältnis aus der Vielzahl von abzustrahlenden Ionenspeziesarten für jede Stelle des Target-Patientenkörpers (80) variiert wird.

Revendications

1. Système d'irradiation de particules chargées (1) comprenant :

une source d'ions (2) pour générer des particules chargées ;
un accélérateur pour accélérer les particules chargées générées par la source d'ions (2) ;
un dispositif d'irradiation pour irradier une cible avec des particules chargées attirées à partir de l'accélérateur ; et
un appareil de commande (50) configuré pour commander des opérations de la source d'ions (2), de l'accélérateur, et du dispositif d'irradiation, dans lequel
la source d'ions (2) comprend une pluralité de types de sources d'ions (2A, 2B, 2C) qui génèrent différentes espèces d'ions en tant que particules chargées, et
caractérisé en ce que l'appareil de commande (50) comprend :

une mémoire de motifs de courant (52) configurée pour stocker des valeurs de courant devant être mis en circulation dans un électroaimant prévu dans l'accélérateur définies pour des espèces d'ions individuelles ; et
une commande d'irradiation d'espèces d'ions multiples configurée
pour commuter une valeur de courant devant être mis en circulation dans l'électroaimant de l'accélérateur sur la base de la source d'ions à utiliser et une valeur de courant par rapport à la cible stockée dans la mémoire de motifs de courant, et
pour commander la source d'ions pour irradier une pluralité de types d'espèces d'ions tandis que la pluralité de types d'espèces d'ions sont commutés sélectivement.

2. Appareil de planification d'irradiation (70), pour déterminer un paramètre d'irradiation du système d'irradiation de particules chargées (1) selon la revendication 1, l'appareil comprenant :
un moyen de détermination de paramètre d'irradiation composite (71) agencé pour déterminer le paramètre d'irradiation par rapport à un corps de patient cible (80) tout en modifiant le type d'espèce d'ions à irradier, ou un rapport de la pluralité de types d'espèces d'ions devant être rayonnées sur chaque site du corps du patient cible (80) .

3. Appareil de planification d'irradiation (70) selon la revendication 2, comprenant en outre des moyens de mémoire (72) pour stocker des données de profondeur maximale (68) définissant une profondeur maximale d'irradiation dans un corps de patient cible (80) pour des espèces d'ions individuelles rayonnées par le système d'irradiation de particules chargées (1), dans lequel
le moyen de détermination de paramètre d'irradiation composite (71) est agencé pour déterminer, en utilisant les données de profondeur maximale stockées (68), une espèce d'ions pouvant être rayonnée vers une position située plus profondément dans le corps de patient cible (80) que la profondeur maximale d'une autre espèce d'ions pour laquelle la profondeur maximale est définie dans les données de profondeur maximale (68).

4. Appareil de planification d'irradiation (70) selon la revendication 2 ou 3, dans lequel
le moyen de détermination de paramètre d'irradiation composite (71) est configuré pour exécuter une opération répétitive pour déterminer un paramètre d'irradiation préféré, en utilisant une formule pour calculer une dose de rayonnement par les particules chargées de la pluralité de types d'ions pour chaque point d'irradiation dans le corps de patient cible (80), dans une formule mathématique d'indice d'évaluation pour évaluer des paramètres d'irradiation afin de déterminer le paramètre d'irradiation préféré.

5. Appareil de planification d'irradiation (70) selon la revendication 2, 3 ou 4, dans lequel le moyen de détermination de paramètre d'irradiation composite (71) est configuré pour définir une pluralité de points d'irradiation pour le corps de patient cible (80) par des positions tridimensionnelles, et effectuer une détermination de sorte que dans la distribution de profondeur des ions irradiés dans le corps de patient cible (80), une espèce d'ions qui est plus légère que les espèces d'ions formant la partie relativement peu profonde de la distribution de profondeur est assignée pour que les espèces d'ions soient rayonnées abondamment dans la partie relativement profonde de la distribution de profondeur.

6. Programme de planification d'irradiation (73) pour faire fonctionner un ordinateur en tant qu'appareil de planification d'irradiation (70) pour déterminer un paramètre d'irradiation du système d'irradiation de particules chargées (1) selon la revendication 1, dans lequel
l'ordinateur est conçu pour fonctionner en tant que moyen de détermination de paramètre d'irradiation composite (71) qui est configuré pour déterminer le paramètre d'irradiation par rapport à un corps de patient cible (80) tout en modifiant le type d'espèces d'ions à rayonner ou un rapport de la pluralité de types d'espèces d'ions à rayonner à partir de chaque site de la cible.

7. Procédé de fonctionnement pour un appareil de planification d'irradiation (70) pour déterminer un paramètre d'irradiation du système d'irradiation de particules chargées (1) selon la revendication 1, dans lequel
le paramètre d'irradiation par rapport à un corps de patient cible (80) est déterminé tandis que le type de des espèces d'ions à rayonner, ou un rapport de la pluralité de types d'espèces d'ions à rayonner, est modifié vers chaque site du corps de patient cible (80).

FIG. 1

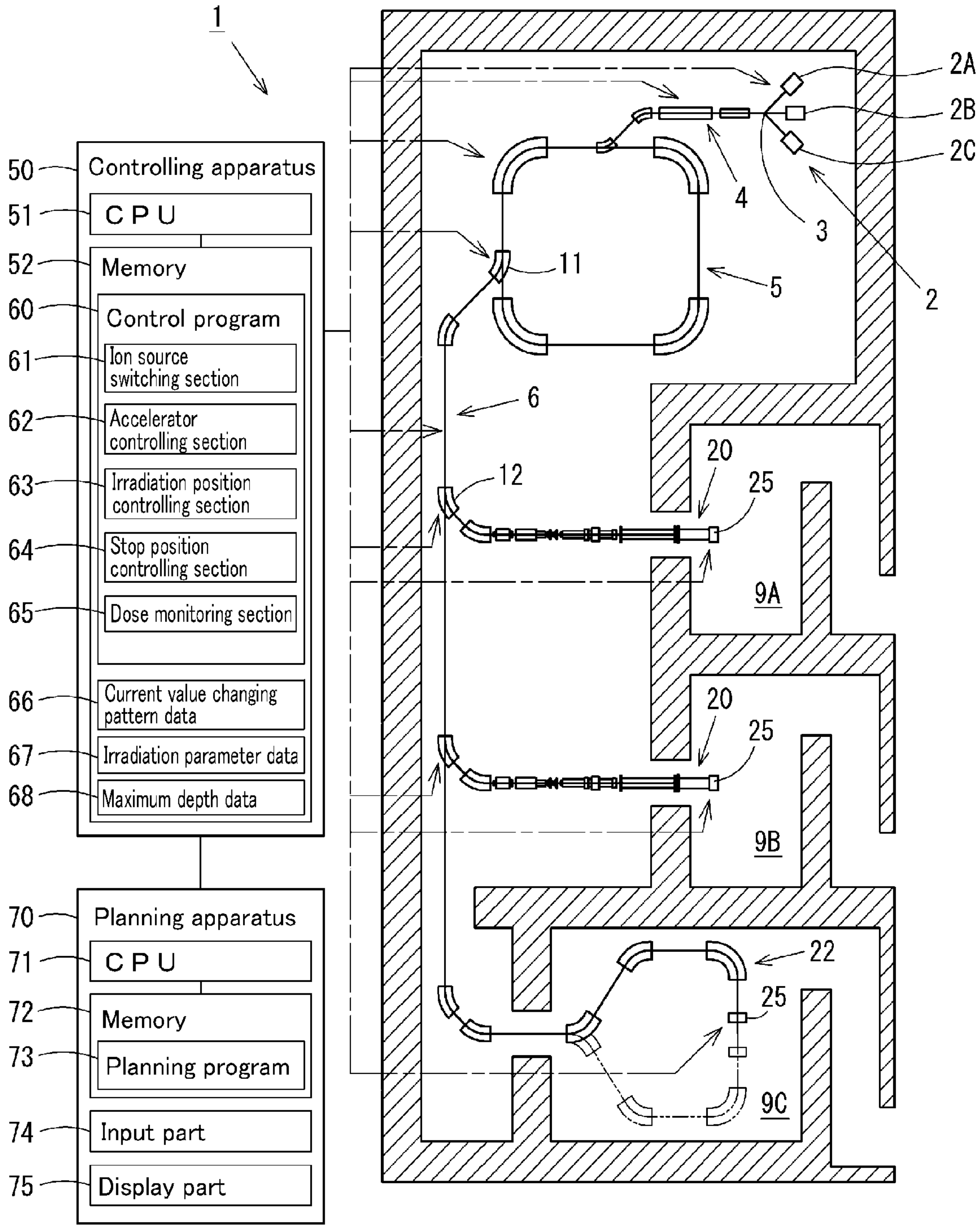

1
50 Controlling apparatus
51 CPU
52 Memory
60 Control program
61 Ion source switching section
62 Accelerator controlling section
63 Irradiation position controlling section
64 Stop position controlling section
65 Dose monitoring section
66 Current value changing pattern data
67 Irradiation parameter data
68 Maximum depth data
70 Planning apparatus
71 CPU
72 Memory
73 Planning program
74 Input part
75 Display part
2A
2B
2C
2
3
4
5
6
11
12
20
25
9A
9B
9C
22

FIG. 2

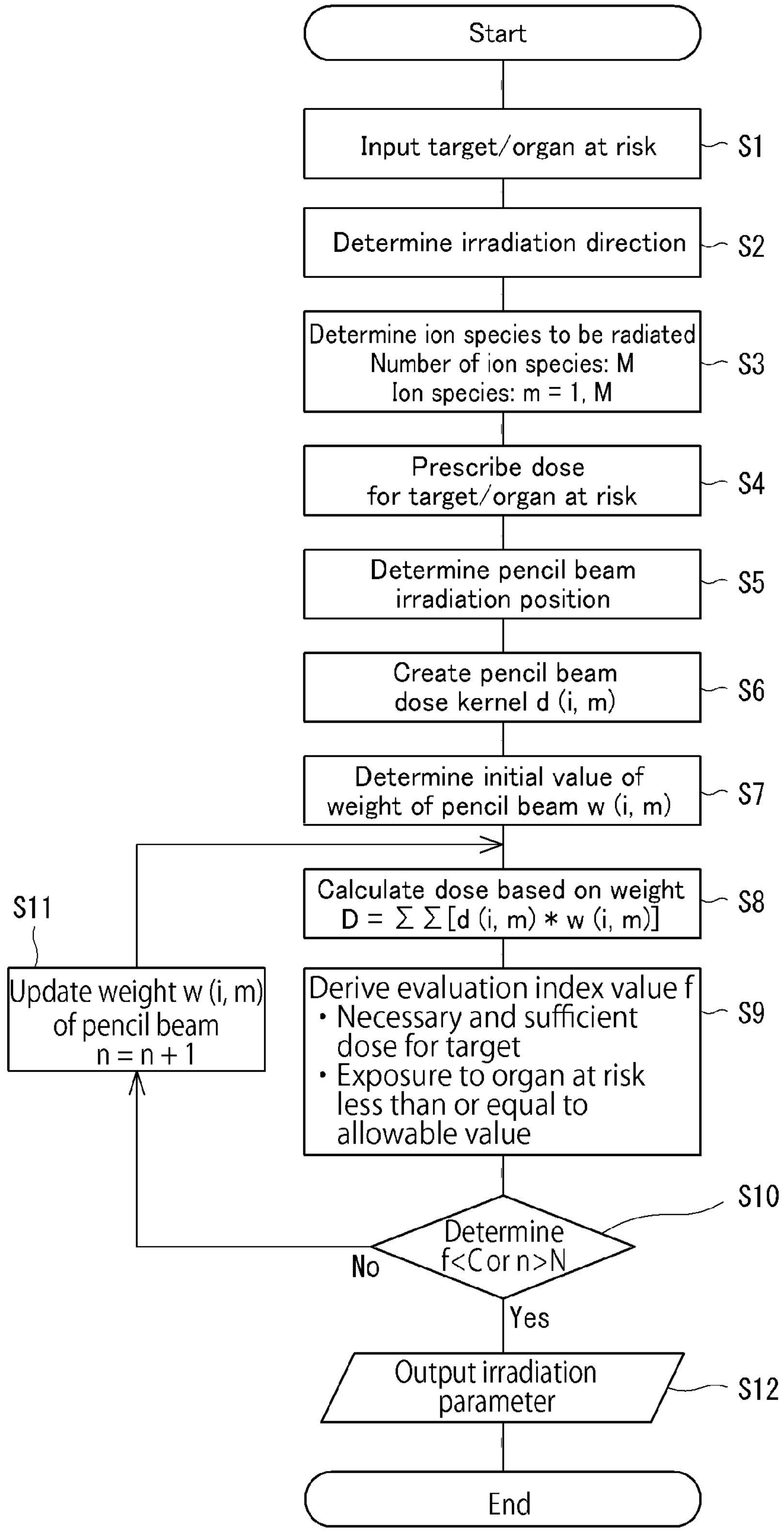
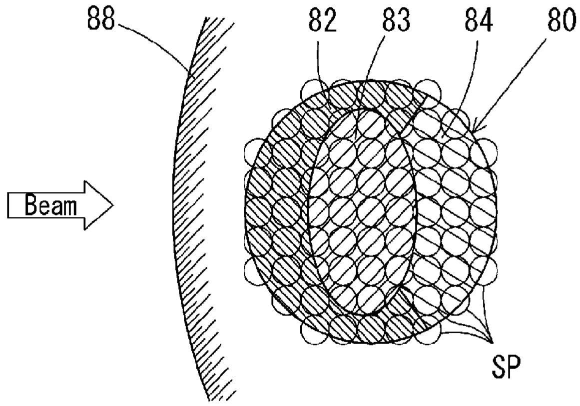

Start
Input target/organ at risk
S1
Determine irradiation direction
S2
Determine ion species to be radiated
Number of ion species: M
Ion species: m = 1, M
S3
Prescribe dose
for target/organ at risk
S4
Determine pencil beam
irradiation position
S5
Create pencil beam
dose kernel d (i, m)
S6
Determine initial value of
weight of pencil beam w (i, m)
S7
Calculate dose based on weight
D = Σ Σ [d (i, m) * w (i, m)]
S8
Derive evaluation index value f
• Necessary and sufficient
dose for target
• Exposure to organ at risk
less than or equal to
allowable value
S9
Determine
f<C or n>N
S10
No
Yes
S11
Update weight w (i, m)
of pencil beam
n = n + 1
Output irradiation
parameter
S12
End

FIG. 3

(A)


88
82
83
84
80
Beam
SP

(B)

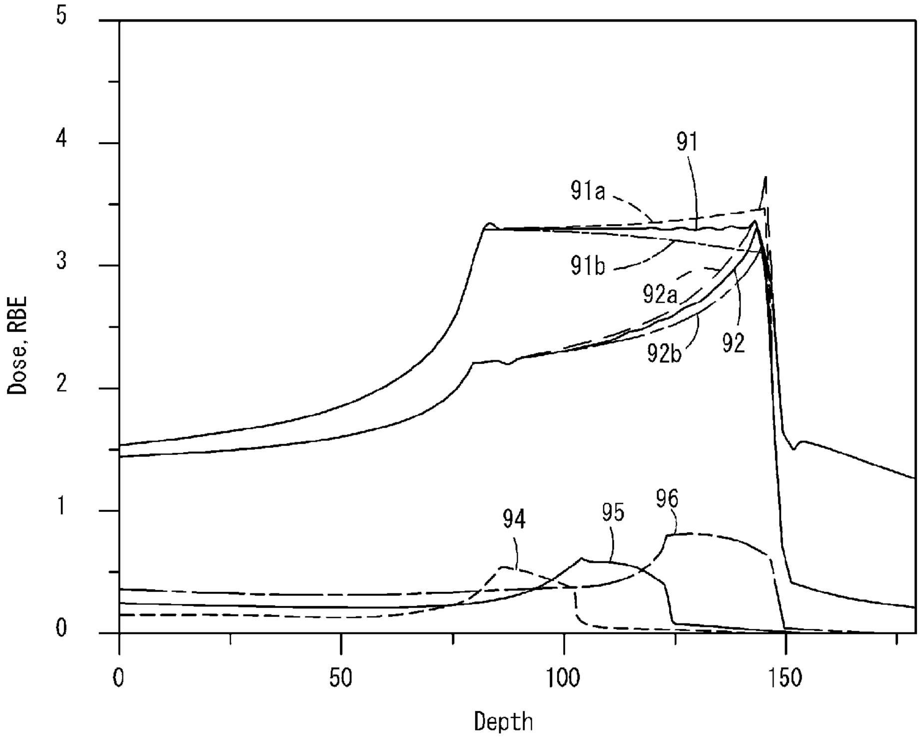
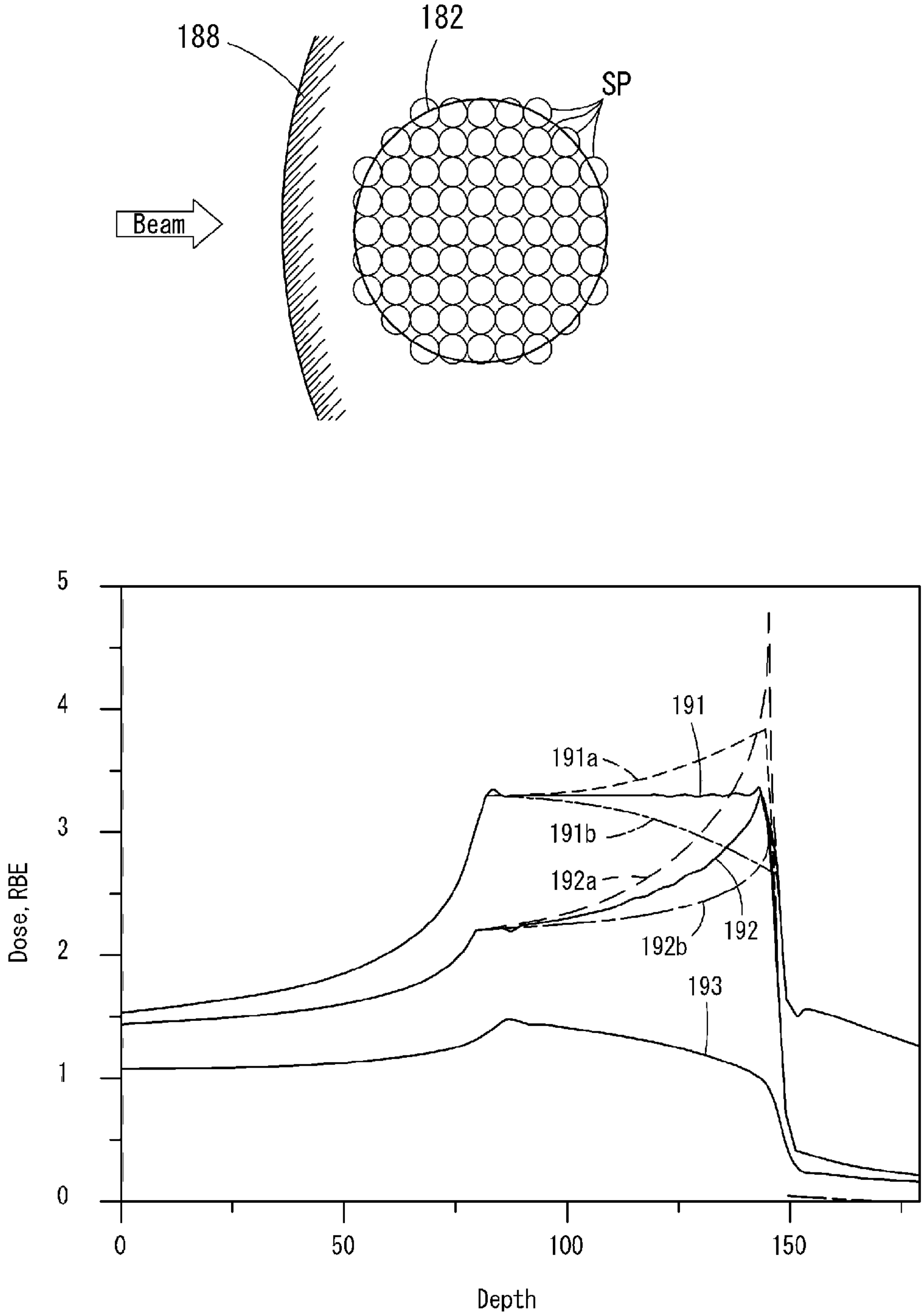

5
4
3
2
1
0
Dose, RBE
91
91a
91b
92a
92
92b
94
95
96
0
50
100
150
Depth

FIG. 4

(A)

(B)


188
182
SP
Beam
Dose, RBE
Depth
191
191a
191b
192a
192
192b
193
0
1
2
3
4
5
0
50
100
150

REFERENCES CITED IN THE DESCRIPTION

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