Radiation Dosimetry

1. Introduction

1.1 Development of Stereotactic Radiotherapy Technology

In recent years, with the application and development of CT, MRI and PET scanner, the image diagnosis technology of human body has been developed greatly. Human beings have obtained further understanding and cognition of body tissues and intracranial fine structure and complex functions. The early diagnosis detectable rate and abnormal tissue localization precision of body tumor, intracrancial tumor, arteriovenous malformation, and nerve system disease has been improved greatly. The development and utilization of various new stereotactic devices and computer software technology have provided more perfect method for diagnosis and treatment intracranial malfunction, important tissue and organ disease. Up to the eighties of 20th century, in tune with the trend of operation miniaturization, closed loop, and computerization, the stereotactic radiotherapy which regards stereotactic technology as the means and high-energy radial irradiation as the treatment method has been developed very quickly. Stereotactic radiotherapy has many aspects of characteristics, such as precise treatment, simple operation, and non-invasion. Its rise and development is a trans-century revolution in treatment medicine field.

According to stereotactic principle, stereotactic radiotherapy selectively determines targets of normal tissues of abnormal tissues in body and skull to put focus on the target precisely and destroy the target to achieve the treatment purpose. Intracranial target area is usually small and the localization and target planning is relatively strict. According to the size of target and the type of tissues, single focus irradiation treatment or multi foci irradiation treatment can be used. Before the treatment, the dose distribution can be made as conformal as possible to the target with treatment planning. The radiation is expected to be delivered to the target with the surrounding normal tissue spared. Stereotactic radiotherapy can avoid the danger of post-operation hemorrhage, infection, and damaging intracranial important organs that is caused by opening skull operation and general surgical removal. It also can implement effective treatment to tumor or vessel malformation in the deep part of brain, the body (such as internal organ), and esophagus. It established a new radiotherapy method without opening cranium, opening hole, blood, and pain. After the treatment, although ‘target’ still exists from the anatomical images, actually all the tumor cells have become necrosed in solid and the volume will not increase any more. By later stage, all the tumor tissues will be replaced by neuroglial scar tissue and absorbed partially or totally. The patient’s survival time will be lengthened.

Stereotactic radiotherapy is quite different from the traditional radiotherapy. The latter utilizes the sensitiveness of tumor tissue to radioactive rays to treat the disease. The target dosage is greatly smaller than the maximum absorbed dosage of the body surface. The localization

precision of equipment is also far lower than the demand of stereotactic radiotherapy equipment. The additional radiation dosage received by the patient's normal tissues is large, and the clinical radioactive symptom such as alopecia, skin burned often happens. The complicating disease and sequelae after treatment is very relatively serious and the patient's survival time is within five years. By utilizing vernier focusing of radioactive rays, stereotactic radiotherapy can make the dosage of target far more than the absorbed dosage of healthy tissues. The complicating disease and sequelae is lighter and the patient's survival time is longer (there are patients who has survived for 20 years).

Whole-Body Stereotactic Gamma Radiotheraphy System (SGS-I) developed by Shenzhen Hype Technology Incorporation has been successfully installed and been brought into clinical operation. The valuable experience obtained provides good foundation for later producing and extended use.

All the stereotactic radiotherapy equipments (gamma knives, Stereotactic Gamma System, X knives, proton knives, and BNCT) utilize high-energy beams to implement the treatment. In the view of physicists, radiotherapy is essentially a process of producing radiobiological effect. In this process, energy is shaped well and is transferred to small-size body tissues. And thus influence the structure and function of tissues that are selected as the target area, induce corresponding physics, chemistry, and biological effect to enable us obtain expected treatment result.

In the process of stereotactic radiotherapy, selection of target is not restricted and the size of target tissues can be very small or very big, especially body tumor whose diameter can be more than 10cm. Stereotactic radiotherapy selectively irradiate these target tissues, while the surrounding normal tissues will be damaged very little.

At present, with the development of stereotactic radiotherapy technology and the invention of gamma knives, SGS, and body X knives, implementing stereotactic radiotherapy to the whole-body tissues and organs of patients is gradually widely used in clinic, which has brought greater hope to the recovery and cure of patients.

1.2 Application of Stereotactic Radiotherapy Technology

Stereotactic radiotherapy is a kind of very safe treatment technology which has no risk of bleeding or infection. It can treat pathologic changes of any part of human body and brain. However, some tissues and organs of human body, such as skin, eye lens, optic nerve, brain stem, spinal cord, coronal nerve, are sensitive to radioactive rays. Due to the meticulous functions of these tissues, the obvious side-effect, such as vision obstacle, invalid in coronal nerve, sectional paralysis, may be caused even though they are irradiated by very small dosage. Therefore, dose distribution must be planed perfectly. Strictly and accurately select the transmission route and shield to avoid or minimize the received irradiation of these sensitive tissues. This is just the advantage of stereotactic radiotherapy technology.

The irradiation bearing capability of normal tissues around the target will decrease with the increasing of

target zone. Therefore, we should consider the relation between dosage and irradiation zone in stereotactic radiotherapy dose planning. In the process of radiotherapy, setting the upper limit of corresponding bearable dosage according to the size of treated target and planning the dosage distribution of target zone and the shape of dosage field according to the shape and size of bigger-volume target to achieve highly uniform is most important thing. In addition, it is also necessary to have superb medical technology and planning software.

On the whole, the above are some problems that concern the technical performance and treatment method to realize stereotactic radiotherapy. In addition, the precise stereo localization of target area and its complete consistency on the treatment equipment is also very important. SGS realizes localization of head tumor through mask technology and realizes localization of body tumor through vacuum cushion, localization couch, and 3-dimension coordinate system which is set by 3-D treatment bed. Thus the target is closely connected with the coordinate system of the equipment on geometrical relation. Meanwhile, it is necessary to use the same set of coordinate system to finish the localization to patients in the process of MRI/CT localization scan and treatment.

Stereotactic radiotherapy technology is totally different from localization technology in conventional radiotherapy process. In the conventional radiotherapy process, physicians make fiducial markers on the patients skin. The target connects with coordinate system of treatment equipment through these markers and the localization accuracy is not very good. The 3-dimesional localization process of stereotactic radiotherapy technology is composed of a series of configuration, including stereotactic system, MRI/CT frame, MRI/CT scanning, 3-dimesion image reconstruction, and stereotactic localization of SGS. Each process has very strict requirements and rules. Therefore, the target localization precision in stereotactic radiotherapy is improved greatly.

Moreover, in conventional radiotherapy, the target tissues are positioned in different coordinate system and thus the coordinates transformation may incur greater systematic deviation. To conventional radiotherapy equipment, randomness and uncertainty of this kind of localization generally can be ignored, which can not be accepted in stereotactic radiotherapy that requires highly accurate localization.

In order to realize selectively absorbing dosage, it is required to focus energy on radiotherapy target area through narrow radioactive rays distributed in 3-dimension space. This kind of energy transmission can be realized by several or dozens of rotating sources around head and human body, or by hundreds of static source. There is another kind of design which make patients swing regarding target area as the center, or make patients move around target area together with radiation sources. This kind of irradiation technology has been applied and realized in X knives and other equipments. The purpose of all the above designs is to make radioactive rays focus on the target and to increase the absorbed dosage rate on the focus.

In a word, the following requirements are very important to stereotactic radiotherapy equipment:

1) Accuracy of localization. In the process of target localization, treatment planning, and treatment, the totally geometrical deviation caused by various factors must be within stipulated range and must have quite high repositioning precision.

2) Selectively transmit higher radiation dosage to targets through multi-rays focusing and equal-center rotary irradiation technology without endangering or strongly impacting the function and structure of normal tissues around targets. Avoid big irradiation deviation caused by patients breathing and organgs wriggling.

3) Stereotactic radiotherapy equipments should be able to transfer irradiation through static or rotary collimators and evenly distribute dosage field in the targets. Radiation beams must be collimated rigorously and their axis must highly and precisely intersect in the center of stereotactic system.

4) The design of radiotherapy equipment system and relevant operation process must consider the security of patients and medical personnel. The equipment itself must be highly reliable and can be used in clinic simply, conveniently, and easily.

SGS-I is the third generation of radiotherapy equipment which is developed by Shenzhen Hyper Technology Incorporation. 18 sealed Co-60 radiation source is installed on its fan-shape ball shell. The radiation beams of each radiation source focus on the center of sphere to form focus in radial direction via the guidance of specified-diameter collimators. When doing treatment, radiation beams will rotate simultaneously around a cross-focus axis and form a lot of different focus scanning conical surface. The focus on the target is continuously irradiated by many radiation beams, while the healthy tissues outside the focus are momentarily irradiated by single radiation beam. The focus dosage field has enough strength (the focus dosage rate is high enough) and the edge of focus dosage field has very big dosage attenuation gradient. This ensures that the target is killed with little radiation to adjacent normal tissues, resulting in so-called non-invasive treatment.

SGS-I is a kind of whole-body stereotactic gamma radiotherapy system which is meticulously designed based on the above principles. In the following chapters, we will separately elaborate the physical mechanism design, dosimetry index, radiation protection of SGS-I.

2 Basis of Radiophysics

2.1 Atom Structure and Nuclear Disintegration

2.1.1 Atom Structure

Various materials in nature are made up of different elements. Elements are composed of atom and atom is composed of atomic nucleus and extranuclear electron. The centre of atom is atomic nucleus with positive charge, and extranuclear electron moves round atom nucleus

on different paths. Atom nucleus is composed of proton and neutron. Proton and neutron are both elementary particles that are often called nucleon and the total amount of them is called mass number of atom nucleus. The protons bring positively charged and one proton brings one positive charge. The total number of protons in atom nucleus is the nuclear charge number of this atom nucleus. The neutrons are not charge. The electrons bring negatively charged and one electron brings one negative charge. The nuclear charge number of extranuclear electron is equal with the nuclear charge number in atom nucleus, so the whole atom presents electroneutrality.

Atoms have the same nuclear charge number are called elements. Although atomic nucleus of the same class of elements has the same number of protons, the number of neutrons in the atomic nucleus might not be the same. Atoms that have same number of protons but different number of neutrons are at the same position on Mendeleev's periodic table of elements, which is called isotope. For example, ^{59}Co and ^{60}Co are both isotope. The nuclear charge number of atom nucleus is equal with the number of extranuclear electron, which is atomic number Z on Mendeleev's periodic table of elements. All the atom nucleus that have different number of nucleons are called different nuclide. For example, ^{1}H , ^{14}C , ^{59}Co , ^{60}Co and ^{60}Ni are five different nuclide. At present, more than one hundred of elements have been found, while more than 1900 kinds of nuclide has been found. Atoms compose molecules in order. Some molecules only contain a few atoms, for example water molecule only contains one oxygen atom and two hydrogen atoms. Some complicated molecules may contain hundreds of or hundreds of thousands of atoms, such as protein molecule, enzyme, and ribonucleic acid (DNA, RNA). Different objects associated by different molecule groups include forming human body. The human body may contain large number of atoms, most of which are carbon, hydrogen, and oxygen atoms. The problem of radiation protection is essentially considering the interaction problem of atoms in radioactive rays and human body.

Isotope can be divided into two classes: 1. Stable isotope. Atomic nucleus of this kind of isotope will not decay spontaneously and can exist steadily; 2. Radioactive isotope. Atomic nucleus of this kind of isotope will decay spontaneously and turn to another kind of atomic nucleus, and emit rays at the same time. Radioactive isotope can be divided into natural radioactive isotope and artificial radioactive isotope according its different mode of production. Natural radioactive isotope exits in nature naturally, while artificial radioactive isotope is produced through artificial method. For example, ^{60}Co is a kind of artificial radioactive isotope which is produced by natural stable isotope ^{59}Co irradiating via neutrons in nuclear reactor. Almost all the radioactive isotope used in clinic is artificial radioactive isotope.

2.1.2 Mode of Nuclear Decay

The nuclear decay of radioactive nuclide has many modes. We will only have a brief introduction of α decay and β decay.

α decay means emitting α ray in nuclear decay process. The decay mode is shown in below formula:

$$^{A}X \rightarrow {}^{A-4}Y + \alpha + Q \qquad (2.1)$$

^{A}X means mother nucleus; ^{A-4}Y means child nucleus; α is α particle; Q is the energy emitted in nuclear decay process.

β decay means emitting β ray in nuclear decay process. The decay mode is in below formula:

$$_{z}X \rightarrow {}_{z+1}Y + \beta + Q \qquad (2.2)$$

$_{z}X$ means mother nucleus; $_{z+1}Y$ means child nucleus; β is β particle; Q is the energy emitted in nuclear decay process.

What should be pointed out here is that some radioactive nuclide has more than one decay mode. Most radioactive nuclide radiates α ray or β ray followed along with radiating γ ray. Further study found that α ray is helium atomic nucleus with high-speed movement which is called α particle. It is made up of two protons and two neutrons, and it brings two pieces of positive charge. Because it brings two electric charges and the mass is big, it has the characteristics of high ionization ability and low impenetration ability. α ray is very easy to be shielded, even a piece of paper can block it. A α particle with 5 Mev energy only has 3.5mm range in the air. Therefore, the most important thing of α ray protection is protecting internal irradiation. β ray is high-speeding moving electron stream which is called β particle. Electron brings a negative charge and its rest mass is only 1/1840 of proton mass. Therefore, comparing with α ray, the ionization ability of β is low, but the impenetration ability is high. A β particle with 5 MeV energy has 20mm range in the air. Use light materials to shield β, such as lucite and aluminium. Bremsstrahlung (X ray) will be produced in the process of stopping β particle, and the intensity of bremsstrahlung will increase along with the increasing of atomic number of shield materials. To β ray with high average energy, add heavy materials with proper thickness behind light materials in order to shield X ray produced by bremsstrahlung. γ ray is neutral particle flows which does not bring charge. γ particle is also called γ photon and its rest mass is zero. The inpenetration ability of γ is very strong and it can not make materials ionize and excite directly. The interaction between γ ray and materials and the protection of γ ray will be introduced in detail later.

2.1.3 Decay Laws of Radioactive Nuclide

The decay modes of radioactive nuclide are varied, but they all comply with the common law of decay. In the process of decay, the atomic nucleus amount of any kind of radioactive nuclide will decay according to index law, namely:

$$N = N_0 e^{-\lambda t} \qquad (2.3)$$

N_0 is the atomic nucleus amount of radioactive nuclide when t=0, N is the number of atomic nucleus that do not decay after time t, λ is decay constant which is the characteristic constant of radioactive nuclide. Each kind of radioactive nuclide has its own decay constant. Obviously, if time t is in terms of second, the unit of λ will be 1/second. If time t is in terms of day, the unit of λ will be 1/day, and the rest may be deduced by analogy. In the above formula, the decay of atomic nucleus amount is only half of original amount, which means the time needed by $N= N_0/2$ is called half life of this radioactive nuclide that is usually expressed in $T_{1/2}$. Half life $T_{1/2}$ is another characteristic constant of radioactive nuclide.

$$T_{1/2}= ln2/\lambda=0.693/\lambda \qquad (2.4)$$

The atomic nucleus that the radioactive nuclide decays within unit time is called radioactive activity and is usually expressed in A. The expression is:

$$A = -dN/ dt \qquad (2.5)$$

Increment dN of the atomic nucleus amount is a negative value, so there is negative sign in the formula.

According to the suggestion of International Commission on Radiation Units and Measurements (ICRU), adopt International System of Units Beckler as the unit of radioactive activity which is expressed in Bq. Moreover, if the radioactive nuclide decays once per second, its radioactive activity will be 1 Beckler. Namely:

$$1B_q = 1\text{decay/second}$$

In practice, Curie is usually used as the unit of radioactive activity and the symbol is Ci. The activity of 1 Curie means there are $3.7X10^{10}$ times decay per second. Namely:

$$1 \quad C_i = 3.7X10^{10}\ B_q$$

2.1.4 Decay of Co-60

^{60}Co is a kind of commonly used artificial radioactive isotope and it has widely used in many fields, such as industry, agriculture, and health care, etc. γ ray used in SGS-I is generated from the decay process of ^{60}Co. In the decay process, the ^{60}Co atomic nucleus with 27 nuclear charges emits one β particle with negative electricity (electron), and then it changes into ^{60}Ni atomic nucleus with 28 nuclear charges. ^{60}Ni nuclear energy is in excited state at this moment. Excited state is a kind of unstable energy state which can emit two γ photons (one is 1.17Mev, the other is 1.33Mev) to achieve stable ground state via two times of energy level transition. **<u>The half-life of ^{60}Co is 5.27 years</u>**. The decay process of radioactive nuclide ^{60}Co can be reflected more clearly from its decay scheme (Figure 6. 1).

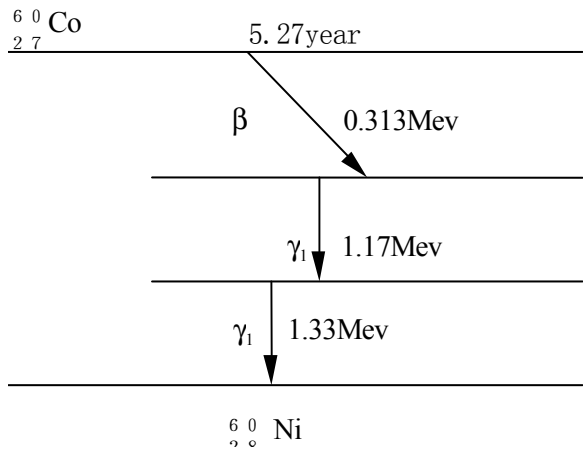

Figure 6.1 ^{60}Co Decay Scheme

2.2 Interaction between γ Ray and Materials

When γ ray interacts with materials, it can not make materials directly ionize and excite. The interaction between γ ray and materials has three main forms, namely photoelectric effect, Compton effect (Compton scattering), and electron pair effect. The mode of interaction relates to energy of incident photons and features of medium. γ ray with lower energy mainly generate photoelectric effect in materials; γ ray with higher energy mainly generate electron pair effect; Compton effect is the main form of interaction between moderate-energy γ ray and materials.

2.2.1 Photoelectric Effect

When low-energy γ photons interact with materials, photoelectric effect is easily to be generated. Photoelectric effect means that γ photons collide with atoms to hit out an electron on the innerorbit and the energy of γ photons are all absorbed by electrons. Electrons emitted in the process of photoelectric effect are called photoelectron, while the atom itself turns into cation.

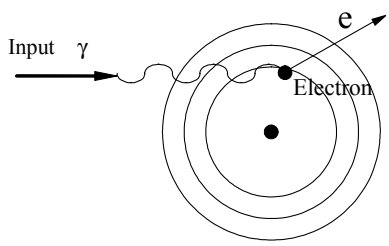

Figure 6.2 Sketch Map of Photoelectric Effect

2.2.2 Compton Effect

When moderate-energy photons interact with materials, Compton effect is easily to be generated. Incident photons collide with electrons of outer orbit to transfer some energy to electrons. The electrons that get every fly out of the electron orbit and these electrons are called recoil electrons. The atom itself turns into cation. Photons whose energy has been reduced will change the original movement direction to continue flying. This kind of photon is called scattering photon.

The energy of γ ray emitted in the decay process of ^{60}Co is 1.17Mev and 1.33Mev which belongs to moderate energy and its interaction with medium is mainly Compton effect.

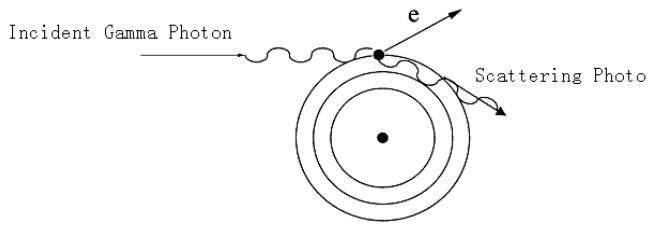

Figure 6.3 Sketch Map of Compton Effect

2.2.3 Electron Pair Effect

When the energy of incident γ ray is more than 1.02MeV, electron pair effect is easily to be generated. When photons pass by atomic nucleus, they will be acted upon by nuclear electric field and photons will disappear suddenly to turn into positive and negative electron, which is called electron pair effect. When high-energy photons interact with materials, electron pair effect will be in the ascendant.

From the above discussion, it can be found out that when γ ray interacts with materials, all the three effects can generate secondary electrons which can make atoms of absorbing material ionize or excite. The range of secondary electrons in materials is not long, so there is no need to take protection measures when considering shield of γ ray. The generation time of the three effects is the symbol of the amount of γ radiation absorbed by materials. Both theory and practice prove that the occurring probability of photoelectric effect is proportional to atomic number of absorbing materials to the fourth power; the occurring probability of Compton effect is proportional to Z/A (A is the total amount of nucleons in absorbing materials which is called mass number of atomic nucleus); the occurring probability of electron pair effect is proportional to square of Z. Therefore, it is best to choose heavy materials that have high atomic number to shield γ ray.

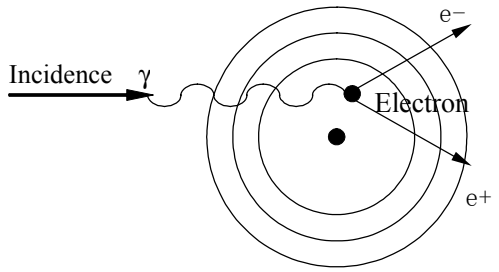

Figure 6.4 Sketch Map of Electron Pair Effect

2.4 Fundamental Principleof Radiophysics and Radiobiology

When biological cell are irradiated by γ ray, a series of change will take place. First is primary action of rays. When γ ray interacts with atoms of biomacromolecule, atoms will be ionized or excited, which causes the structure of macromolecule compounds and some tiny structures of cells destroyed. Second is secondary action of rays. The ionization of water molecule is caused by rays irradiate water, which forms free radical. These very lively free radicals will destroy biomacromolecule indirectly. Cells have various kinds of molecules, however the biomacromolicule and water molecule is most important considering from the view of radiobiology. Biomacromolicule includes proteins and ribonucleic acid which are the basic of cell function and biological heritage. After radiation, biological cells can cause: albumen chain rupturing, DNA or RNA chain rupturing, some enzyme or coenzyme destroyed directly, structure of biological enzyme destroyed, obstruction of mitochondria energy system, lysosome rupturing, etc. And thus cause the variation of cell function, function loss, or cell's death. The reaction of biology cells and damage degree after irradiation is related to the amount of absorbed dose. Radiation can cause cancer, but it also can kill cancer cells.

SGS-I utilizes γ rays irradiated by Co-60, concentrates the irradiation of targets in human body, and destroys target tissues after strict plan to achieve the purpose of curing diseases.