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ORIGINAL

Advancements in Proton and Carbon Ion Therapy for Precision Radiotherapy of Complex Tumors

Avances en la terapia de protones e iones de carbono para la radioterapia de precisión de tumores complejos

Putta Chandana[1], Anand Gudur[2], Aniket Madhukar Zope[3], Sidhant Das[4], Anoop Dev[5], Niranjan Sahu[6]

[1]Centre for Multidisciplinary Research, Anurag University. Hyderabad, Telangana, India.
[2]Krishna Institute of Medical Sciences, Krishna Vishwa Vidyapeeth "Deemed To Be University" Malkapur. Karad (Dist. Satara), Maharashtra, India.
[3]Department of Radiology, Symbiosis Medical College for Women & Symbiosis University Hospital and Research Centre, Symbiosis International (Deemed University). Pune, Maharashtra, India.
[4]Chitkara Centre for Research and Development, Chitkara University. Himachal Pradesh-174103 India.
[5]Centre of Research Impact and Outcome, Chitkara University. Rajpura- 140417, Punjab, India.
[6]Department of Radiology, IMS and SUM Hospital, Siksha 'O' Anusandhan (Deemed to be University). Bhubaneswar, Odisha, India.

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Corresponding Author: Putta Chandana

ABSTRACT

Precision radiation has changed a lot because of progress in proton and carbon ion therapy. This has made it much easier to treat complicated cancers. These particle treatments are becoming more well known for their ability to give highly targeted radiation doses that cause the least amount of damage to healthy tissues while still effectively targeting cancer. As a type of charged particle therapy, proton therapy uses protons instead of regular X-rays to treat cancer. It does this by taking advantage of the way protons are made, especially their Bragg peak, which is where they release their most energy. This makes it possible to deliver the amount more precisely, protecting healthy cells from too much radiation, especially in places that are hard to reach with regular photon-based treatment. Carbon ion treatment is a more advanced type of particle therapy that uses carbon ions, which are heavier than protons and have more mass and energy. These ions give a higher amount of radiation with more accuracy, which makes it more effective at treating tumors that are resistant to radiation, like those in the head, neck, and brain, as well as juvenile cancers. The biological efficiency of carbon ions is higher because they can hurt cells more severely than protons or regular X-rays. This means that they are better at controlling tumors in many therapeutic situations. Advanced technologies like synchrotrons and cyclotrons have made proton and carbon ion therapy more widely available. This means that patients can get these treatments more easily. Adding high-tech imaging methods like MRI and CT scans has also made these medicines more accurate, letting doctors watch patients in real time and change their treatment plans as needed. Using these technologies along with particle therapy has led to better treatment results, especially for tumors that are complicated and close to important structures.

Keywords: Proton Therap; Carbon Ion Therapy; Precision Radiotherapy; Tumor Targeting; Particle Therapy.

RESUMEN

La radiación de precisión ha cambiado mucho gracias a los avances en la terapia de protones e iones de carbono. Esto ha facilitado considerablemente el tratamiento de cánceres complejos. Estos tratamientos con partículas son cada vez más conocidos por su capacidad para administrar dosis de radiación altamente dirigidas que causan el menor daño posible a los tejidos sanos, a la vez que atacan eficazmente el cáncer.

Como tipo de terapia de partículas cargadas, la terapia de protones utiliza protones en lugar de rayos X convencionales para tratar el cáncer. Esto se logra aprovechando la forma en que se forman los protones, especialmente su pico de Bragg, donde liberan su mayor energía. Esto permite administrar la dosis con mayor precisión, protegiendo así a las células sanas del exceso de radiación, especialmente en zonas de difícil acceso con el tratamiento convencional basado en fotones. El tratamiento con iones de carbono es un tipo más avanzado de terapia de partículas que utiliza iones de carbono, que son más pesados que los protones y tienen mayor masa y energía. Estos iones proporcionan una mayor cantidad de radiación con mayor precisión, lo que la hace más eficaz en el tratamiento de tumores resistentes a la radiación, como los de cabeza, cuello y cerebro, así como en cánceres juveniles. La eficiencia biológica de los iones de carbono es mayor porque pueden dañar las células con mayor gravedad que los protones o los rayos X convencionales. Esto significa que son más eficaces para controlar tumores en muchas situaciones terapéuticas. Tecnologías avanzadas como los sincrotrones y ciclotrones han ampliado la disponibilidad de la terapia con protones e iones de carbono. Esto facilita el acceso de los pacientes a estos tratamientos. La incorporación de métodos de imagenología de alta tecnología, como la resonancia magnética y la tomografía computarizada, también ha aumentado la precisión de estos medicamentos, permitiendo a los médicos observar a los pacientes en tiempo real y modificar sus planes de tratamiento según sea necesario. El uso de estas tecnologías junto con la terapia de partículas ha permitido obtener mejores resultados terapéuticos, especialmente en tumores complejos y cercanos a estructuras importantes.

Palabras clave: Terapia de Protones; Terapia de Iones de Carbono; Radioterapia de Precisión; Localización Tumoral; Terapia de Partículas

INTRODUCTION

Over the past few decades, cancer treatment has changed a lot. This is because researchers are always looking for more accurate, effective, and less dangerous treatments. One of the most exciting new developments in radiotherapy is proton therapy and carbon ion therapy, which are ground-breaking ways to treat complicated cancers in a focused and precise way. These treatments, called particle beam therapies, are better than standard photon-based radiation because they use charged particles like protons and carbon ions to kill cancer cells instead of X-rays. Because these particle therapies can focus high doses of radiation directly on the tumor while causing little damage to healthy tissues around it, they are especially useful for treating tumors that are hard to reach, like those near important structures or in children. Radiotherapy is one of the most important parts of treating cancer. It is often used along with surgery, chemotherapy, or immunotherapy to treat different kinds of cancer. Photon-based radiotherapy does have some problems, though.[1] One of the biggest problems is that the radiation dose is spread out over a lot of healthy tissues around the tumor. This causes damage to healthy tissues, which can have serious side effects, especially when the tumor is close to an organ that is very important, when the patient is a child, or when the tumor has an odd shape. These problems have led to the creation of more advanced ways to treat cancer, like proton and carbon ion therapies, which work more precisely and have fewer side effects. Many people know about proton therapy because it uses protons, which are strongly charged particles, to send very high amounts of radiation to specific areas. Protons have special properties that make them useful in proton therapy.[2]

One of these qualities is that they can concentrate most of their energy at a certain point in tissue, which is called the Bragg peak. Because of this, proton treatment can target tumors very precisely, while at the same time lowering the amount to healthy cells in front of or beyond the tumor. When cancers are close to important parts of the body, like those in the brain, eye, or spine, proton treatment may be better than traditional photon radiation. Proton treatment has also been very helpful for young patients because their growing cells are more sensitive to radiation, and it is very important to keep healthy organs around them from getting too much radiation.[3] Proton therapy has changed the way many types of cancer are treated, but carbon ion therapy, which uses larger carbon ions, has even more promise.

Background Work

Proton therapy has been a huge step forward in the fight against cancer. It was first thought of in the 1940s and first used in patients in the 1970s. Photons are electromagnetic waves. Protons, on the other hand, are charged particles that send energy more exactly to the growth spot. The Bragg peak is the most important part of proton treatment.[4] This is when protons release their most energy at a certain depth in tissue, which lets the dose be distributed very precisely. This feature lowers the amount of radiation that hits healthy tissues. It is especially helpful for tumors close to sensitive structures like those in the brain, eye, and spinal cord. Researchers have found that proton therapy works especially well for treating cancer in children, where protecting healthy growing cells is very important. As a more powerful form of particle treatment, carbon ion therapy was created after proton therapy proved to be too weak. Because carbon[5] ions are larger and have more energy than protons, they have a higher linear energy transfer (LET). This means that they have a bigger effect on cancer cells. Because it is more biologically successful, carbon ion treatment is a great way to treat tumors that are resistant to radiation, like those in the head and neck and cancers that have spread deep into the body. Carbon ion therapy took longer to develop than proton therapy because the science was more complicated and it cost more to build facilities that were just right for it. Carbon ion treatment is now more possible and easier to get because of improvements in accelerator technologies like synchrotrons and cyclotrons.[6] There are now therapeutic centers running in several countries, mainly in Japan, Germany, and Italy.

Table 1. Summary of Background Work

Method	Approach	Challenges	Impact
Particle Beam Therapy	Using protons and carbon ions for precision treatment	High cost of facilities and treatment	Improved tumor targeting with less damage to healthy tissues
Pencil-Beam Scanning	Scanning proton beam to deliver targeted radiation	Requires specialized equipment and precision	High precision in radiation delivery with minimal side effects
Intensity-Modulated Proton Therapy (IMPT)	Modulating proton beam intensity to conform to tumor shape	Limited by the complexity and cost of delivery systems	Improved tumor control and reduced side effects through modulation
Carbon Ion Therapy[7]	Using heavy ions like carbon for higher LET and better biological effect	Availability of specialized treatment centers	Effective for treating radioresistant tumors, better tumor control
Proton Therapy for Pediatric Tumors	Targeting tumors in pediatric patients with minimal radiation exposure	Limited access and high treatment costs	Reduced long-term side effects, especially for pediatric patients
Combination of Proton and Carbon Ion Therapies	Combining both therapies for enhanced tumor control	Complexity in treatment planning and execution	Increased effectiveness by targeting complex tumors with both therapies
Compact Cyclotrons	Developing smaller, cost-efficient cyclotrons for wider access	Challenges in developing cost-effective technology	Makes proton therapy more widely available and cost-effective
Real-Time Imaging Integration[8]	Combining imaging with therapy to track tumor movement in real-time	Real-time tumor tracking can be complex	Improved treatment accuracy with dynamic tumor tracking
Advanced Imaging with MRI/PET	Using advanced MRI and PET scans for better tumor visualization	Cost and complexity of combining different imaging techniques	Enhanced visualization and precise treatment planning for complex tumors
Carbon Ion Therapy for Radioresistant Tumors	Employing carbon ions for tumors resistant to conventional treatments	High cost and specialized technology required	Better control over radioresistant tumors, reducing recurrence rates
4D Imaging for Tumor Movement	Tracking tumor motion with 4D imaging for accurate treatment delivery	Requires advanced imaging and patient motion tracking	More accurate targeting of tumors that move due to respiration or other factors
Cost Reduction Strategies[9]	Reducing facility costs and expanding access to particle therapy centers	Cost of infrastructure and limited centers	More accessible treatment, lowering costs for patients

Mechanisms of Proton and Carbon Ion Therapy

Physical properties of protons and carbon ions

To fully understand how protons and carbon ions work in precision radiation, it is important to know what their physical features are. They are both charged particles, which makes them different from photons, which are used in regular radiation. Because of these special features, proton and carbon ion treatments can target tumors more exactly with radiation while causing less damage to good cells around them. Because they are positively charged, protons don't have as much mass or energy as heavy objects like carbon ions. When protons are sped up and sent toward a growth, they slowly leave their energy as they move through the tissue. The Bragg peak is the most important thing about protons. This is where the protons give off most of their energy,

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deep in the tissue. This makes it possible to precisely target the tumor, since the protons deliver a high amount of radiation to the tumor while leaving healthy cells around it alone before and after this point. Being able to control the amount of proton energy buildup is especially helpful when treating tumors near vital organs or in children, where it is very important to protect the healthy tissues around the tumor. Carbon atoms, on the other hand, are stronger and heavier than protons.[10] LET is higher for carbon ions because they have a bigger mass. This means they send more energy to the tissue per unit length traveled. This greater energy transfer has a bigger biological effect on cancer cells, which makes it easier to kill tumor cells, especially in tumors that are not sensitive to radiation.

Algorithm: Physical Properties of Protons and Carbon Ions in Therapy

Step 1: Particle Acceleration and Energy Calculation

- Objective: accelerate protons or carbon ions to high energy levels required for treatment.
- Description: accelerate charged particles (protons or carbon ions) using an accelerator to reach the necessary kinetic energy for tumor treatment. The energy of the particle is determined by the formula:

$$E = (1/2)*m * v^2$$

Where:
E is the kinetic energy of the particle,
m is the mass of the particle,
v is the velocity of the particle.

For protons, the mass m is approximately 1,67 % x 10^-27 kg. For carbon ions, the mass is 12 times that of protons.

Step 2: Bragg Peak and Depth Dose Distribution

- Objective: understand the behavior of particles as they pass through the tissue and release energy at a specific depth.
- Description: both protons and carbon ions exhibit a phenomenon known as the Bragg peak, where the particles release the majority of their energy at a specific depth in the tissue. The depth at which the Bragg peak occurs is given by:

$$R = (2m/\rho)E$$

Where:
R is the depth of the Bragg peak,
m is the mass of the particle,

Carbon ions, being heavier, have a different depth profile compared to protons, leading to a sharper Bragg peak and a higher linear energy transfer (LET).

Step 3: Energy Deposition and LET (Linear Energy Transfer)

- Objective: calculate the energy deposition and the biological impact of the particles on cancer cells.
- Description: the energy deposited by a particle in a unit length of tissue is given by the Linear Energy Transfer (LET), which can be expressed as:

$$LET = dE/dx$$

Where:
dE is the energy deposited by the particle.
dx is the distance traveled by the particle.

Carbon ions have a higher LET than protons due to their greater mass and energy. This results in more ionizations per unit length, making carbon ions more effective at killing cancer cells.

Step 4: Dose Distribution and Optimization

- Objective: optimize the dose distribution for effective tumor treatment.
- Description: the dose delivered to the tumor is optimized by controlling the particle energy, path, and intensity. The dose distribution D(x) can be modeled by the following equation:

$$D(x)= \int(dE/dx)*\rho(x)dx$$

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Where:
D(x) is the dose distribution at depth x,
dE/dx is the LET at depth x,
ρ(x) is the tissue density at depth x.

The optimized dose ensures that the tumor receives the maximum radiation while sparing healthy tissues, a key feature in proton and carbon ion therapies.

Comparison with traditional photon therapy

High-energy X-rays are used in traditional photon treatment, which has been the normal form of radiotherapy for decades, to target and kill cancer cells. But its flaws become clear when you think about how well it protects healthy organs and tissues around it from radiation. During photon treatment, the radiation beam goes into the body, stores energy in the tissues as it goes through them, and goes past the tumor, damaging good tissues in front of and behind it.

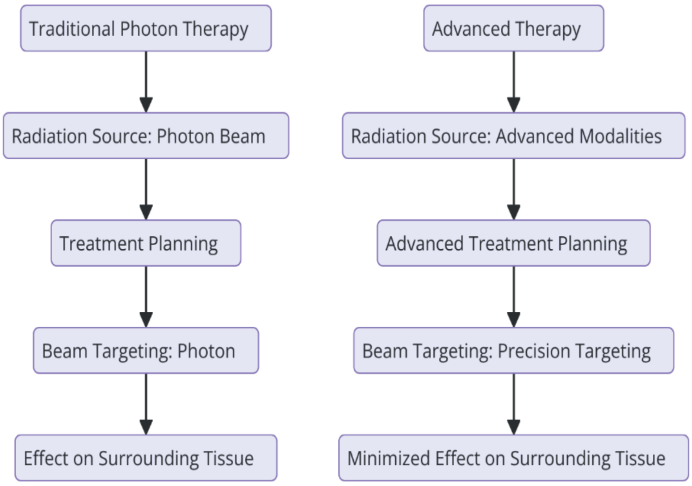

Figure 1. Structure of research studies supporting integrative oncology

This wide dose distribution is a big problem, especially for tumors close to important organs or in children, whose tissues are still growing and are more sensitive to radiation. On the other hand, proton therapy and carbon ion therapy are much better because of how they are physically, shown in figure 1. Because protons are charged particles, they leave their energy in a very controlled way. Most of the energy is given at a certain depth in the tissue, which is called the Bragg peak. This lets the radiation be directed, so good cells aren't exposed as much before or after the growth. This accuracy is especially helpful when treating tumors near important parts of the body like the brain, spinal cord, and eye.[11] It's also helpful when treating children, since it's important to keep healthy cells that are still growing. Because they are larger and have more energy than protons, carbon ions are even better at working with living things. Because they have a higher linear energy transfer (LET), carbon ions do more damage to cancer cell DNA. This makes it easier to control tumors, especially ones that are resistant to radiation. Photons, on the other hand, have a smaller LET, which means they are not as good at damaging DNA in cancer cells, especially those that are hard to treat with standard treatments.

Biological effects on tumor cells and surrounding tissues

Proton, carbon ion, and traditional laser treatments all have very different biological effects on tumor cells and healthy tissues around them. This is mostly because of the changes in their physical features and how they deposit energy. Proton treatment uses protons to send radiation. Protons are lighter and less powerful than heavy objects like carbon ions. When protons hit tissues, they slowly leave energy, with most of it being released at a certain depth (Bragg peak). This build-up of energy damages the DNA in tumor cells, which can kill the cell or make it harder for the cell to divide. There is a smaller chance of side effects, though, because protons hurt nearby cells less than photons do.[12] Proton treatment is especially helpful for tumors close to vital structures because healthy tissues in the beam's entry and exit paths get less radiation. This keeps important organs from getting hurt by accident. Because carbon ions are heavier and have more energy, they bring in a form of radiation that is even stronger. Linear energy transfer (LET) is better for carbon ions than for protons or light. This means that carbon ions leave more energy in tissue over a shorter distance. This high LET causes more serious damage to living things, especially to the DNA of cancerous cells. Carbon ions cause intense ionization in the area that needs to be treated. This makes it harder for cancer cells to fix their DNA, which can help control tumors better, especially ones that are resistant to radiation. The high LET of carbon ions also makes it more likely that cancer cells will suffer DNA harm that can't be fixed, which makes therapy more effective.[13] Carbon ions, on the other hand, have more energy than protons and can damage healthy cells around them more. To make sure that the medicine only affects the tumor and not nearby healthy cells too much, this needs to be carefully planned.

METHOD

Study Design

Type of study (e.g., clinical trial, retrospective analysis, case study)

The type of study that is used to check how well and safely proton and carbon ion treatments work on healing complicated cancers is very important for getting strong and useful results. Depending on the research goals, the patients, and the resources that are available, different study methods could be used. Some common types of studies are case studies, historical analyses, and clinical trials. Each has its own pros and cons. People think that a clinical study is the best way to find out how well new treatments, like proton and carbon ion therapies, work. Randomly assigning people to either the treatment group or the control group (usually getting standard photon therapy or a dummy) in a clinical study makes it possible to compare results in a fair way. Randomized controlled studies (RCTs) are a great way to establish a link between a treatment and a clinical result while reducing bias. For proton and carbon ion treatments, a clinical study might look at things like how well the tumor responds, how long the patient survives, any side effects from the treatment, and their quality of life.[14] Prospective clinical studies can show that treatments are safe, work well, and should be used in the best way for each type of cancer. But clinical studies need a lot of resources, like a lot of patients, a long time to follow up with them, and a lot of money. A retrospective study looks at patient data from current medical records to see how proton or carbon ion treatments worked in past cases. This kind of study doesn't need as many resources and can be done faster than clinical trials because it uses data that has already been gathered during normal clinical practice. Looking back at old studies is a great way to learn about the long-term effects of proton and carbon ion therapy.[15] It can also help you find trends or patterns in tumor types, how well treatments work, and side effects. However, flaws like selection bias and missing data are more likely to happen in retrospective studies, which can make the results less useful in other situations.

Study population

A very important part of planning a study to look at proton and carbon ion treatments for complicated cancers is choosing the right patients. The main goal is to make sure that the study results can be used by people who are most likely to benefit from these new treatments while keeping patient safety as low as possible. Some of the things that are used to choose patients are their age, general health, the type of tumor they have, where it is located, and its stage. Proton and carbon ion treatment is great for people whose cancers are in places that are hard to treat with standard laser therapy. Some of these are tumors that are close to important parts of the body, like the brain, spine, eyes, and heart. Also, tumors that are not sensitive to radiation or are deep inside the body, like some types of sarcomas or pancreatic cancers, may benefit more from proton or carbon ion treatments because they are more precise and work better on living cells. The study should specify the types of tumors that are of interest. This will help find a group of people who will most likely benefit from these medicines' ability to protect good cells from damage.[16] Another important thing to think about is the stage of the growth. Early-stage tumors, where the cancer is limited and hasn't spread, may be treated to cure the tumor. Advanced-stage tumors, on the other hand, may be treated to shrink the tumor and ease the symptoms. Patients with cancers that keep coming back or that haven't reacted to standard treatments may also be able to join, since proton and carbon ion therapies are often looked at as possible treatments for these types of cases.

Data Collection

Collection of tumor type, location, and stage

To properly study the effects of proton and carbon ion treatments, especially when looking at how well they treat complicated cancers, it is important to collect data in a structured and accurate way. To make sure the study is accurate and relevant to the research goals, important factors like the type of tumor, its location, and its stage must be carefully recorded.

Tumor Type: It is very important to get information about the type of tumor because particle treatments may work differently on different types of cancer. Usually, tumors that are hard to treat with regular photon radiotherapy are of interest. These could be tumors in children, tumors that are deep in the body, or cancers that are not easily cured with radiation. The study should put tumors into groups based on their histopathological findings. These groups could include sarcomas, gliomas, brain tumors, and other types of cancer that are notoriously hard to treat.[17] Finding out the type of tumor also helps us learn more about how the features of the tumor affect how well it responds to treatment. This helps us figure out which types of cancer respond best to proton and carbon ion therapies.

Tumor Location: Having accurate records of where the tumor is located is important for knowing the possible benefits of proton and carbon ion treatments, which are very good at treating tumors close to important structures. Advanced imaging techniques, like MRI, CT, and PET scans, can be used to record the exact position. Some places that might be of interest are the brain, spinal cord, eyes, head and neck, or pelvis. These are places where regular radiation often does too much damage to good tissues nearby. If you know where the tumor is, you can better plan your treatment and make sure that the radiation amount goes directly to the tumor and not to any nearby healthy areas.

Tumor Stage: The tumor stage tells you how big the growth is and how far it has grown. Gathering information about the stage of the cancer is necessary to figure out the outlook and the best way to treat it. The TNM (tumor, node, metastasis) method is often used to determine tumor stage.[18] This helps divide patients into different treatment groups so that the right treatment is given for early, locally advanced cancers as well as more advanced, metastasized cases. Researchers can also look at how well proton and carbon ion treatments work at different stages of cancer thanks to accurate staging.[19]

Treatment Protocols

The goal is to come up with a treatment plan that gives the tumor the most radiation while exposing healthy cells around it to as little radiation as possible. Proton and carbon ion medicines need very specific methods for planning treatments that are made to work with the way they store energy.[20] The total radiation dose and the fractionation scheme are written in the treatment guidelines. The fractionation scheme describes how the total dose is spread out over several treatment sessions. The amount is chosen based on the features of the growth and the patient. High amounts are usually used in each fraction of both proton and carbon ion therapies, but the overall number of fractions can change based on the treatment goals.[21] Dose increase may be part of protocols for cancers that are advanced or resistant to radiation. Schedules for fractionation are often changed to find the best mix between controlling tumors and reducing side effects.[22] Protocols also say what kind of treatment will be used (proton or carbon ion therapy) and how it will be delivered, such as through spot scanning, fixed beam irradiation, or intensity-modulated proton therapy (IMPT). The transport method must be chosen based on where the growth is and how precisely it needs to be hit in order to be effective without hurting good tissue.

Clinical Applications of Proton and Carbon Ion Therapy

Tumors treated with proton therapy

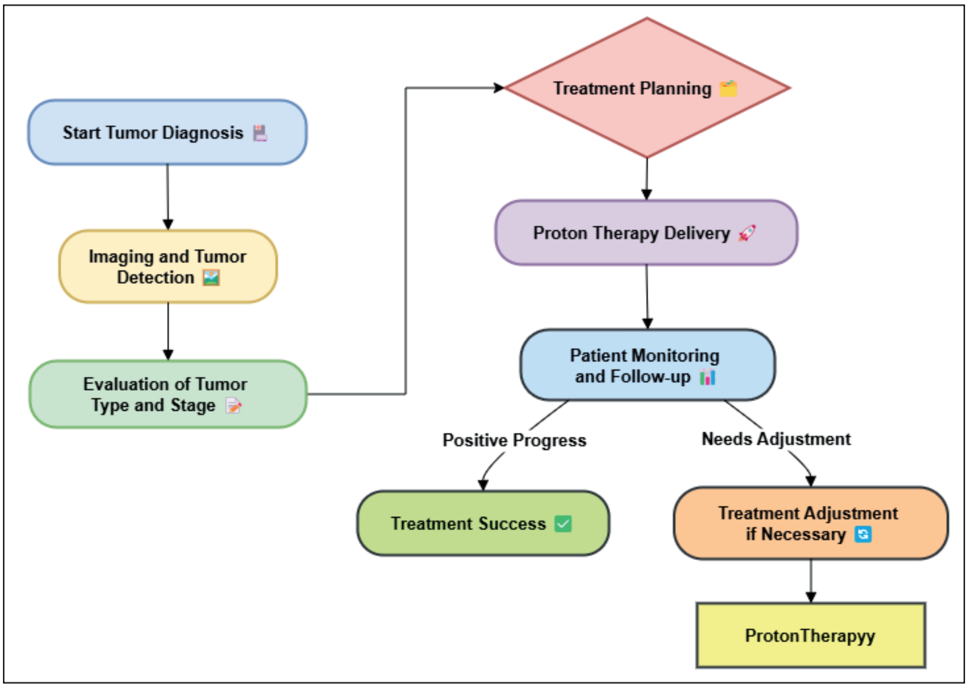

Figure 2. Illustrating the treatment of tumors with proton therapy

People with many types of cancer use proton therapy as a treatment choice. This is especially true for tumors that are in places where regular photon therapy might hurt good tissues nearby. Protons have special physical properties, like the Bragg peak and the exact distribution of their energy. These qualities make proton therapy ideal for treating cancer close to important structures and in children, whose tissues are more sensitive to radiation. One of the best things about proton treatment is that it protects healthy growing cells from too much radiation. This makes it especially helpful for kids with cancer. Primon treatment is often used to treat children with tumors in the brain, spinal cord, eye, head, and neck. This is because it lowers the chance of long-term side effects like cognitive difficulties or growth problems that could happen with traditional radiation. Proton therapy is being used more and more to treat brain tumors, especially in kids because it is important to protect their growing brain cells. Proton treatment is also very good at treating cancers in the brain and spinal cord, like gliomas, meningiomas, and chordomas.[23] A lot of the time, these tumors are found near important parts of the body, like the optic nerve, pituitary gland, or spinal cord. Precision in proton treatment lets high-dose radiation go straight to the tumor, saving the healthy cells around it. This is very important for keeping the brain working and reducing side effects.

Proton treatment is also often used to treat cancers in the head and neck, especially those that affect the nose, throat, and Para nasal passages, process shown in figure 2. Because they are close to important systems like the brainstem, salivary glands, and thyroid, these tumors are often hard to treat. Proton therapy can effectively control tumors while limiting damage to these important structures, which can improve the quality of life for patients after treatment.

Tumors treated with carbon ion therapy

Carbon ion therapy is a more advanced type of particle treatment that works especially well on cancers that don't respond to photon chemotherapy or proton therapy. Carbon ions have a higher linear energy transfer (LET) because they are heavier and have more energy. This means they can do more biochemical damage to cancer cells, especially in tumors that are hard to treat with standard methods. Because they are so close to important structures, these cancers are hard to treat, especially those that are near the base of the head or the brainstem. Carbon ion treatment is a great choice for these kinds of tumors because it is accurate and can give a bigger amount to the tumor while saving good tissue around it. Carbon ions can also treat diseases in the paranasal sinuses and the nasopharynx, even though they are usually hard to get to. Carbon ion treatment is also helpful for kids with cancer, especially for sarcomas or tumors that are close to important organs. For young patients, whose systems are still growing and are very sensitive to radiation, carbon ion treatment is especially helpful because it protects good cells around the tumor.

Comparison of clinical outcomes between proton, carbon ion, and photon therapies

When you look at the results of proton, carbon ion, and photon therapies side-by-side, you can see that they are very different in how well they work, how many side effects they cause, and how well the patients do overall. Each treatment has its own benefits, and the one that is best for a patient will rely on things like the type of tumor, where it is located, and other factors unique to that patient.

Proton Therapy: Proton therapy is known for being very accurate, especially because of the Bragg peak, which lets the most radiation reach the tumor while hurting healthy cells around it as little as possible. This helps a lot when treating tumors that are close to important structures, like those in the brain and spinal cord. Clinical outcomes with proton treatment have been good, especially in children with cancer, where it lowers the risk of long-term side effects like memory loss and growth problems. Proton therapy has also been shown to be effective in treating prostate cancer. Compared to photon therapy, studies have shown that less urine and sexual problems happen with proton therapy. However, proton therapy is often limited by the fact that treatment sites are hard to find and cost a lot of money.

Carbon Ion Therapy: Because carbon ions have a higher linear energy transfer (LET), they are even more biologically effective than protons. This means they kill more tumor cells, especially those that are resistant to radiotherapy. It has shown promise in treating hard-to-treat tumors like gliomas, sarcomas, and cancers of the head and neck. Because carbon ions can give bigger amounts with more accuracy, they can be used to treat cancers that don't respond well to regular radiation. Better tumor control, especially in radioresistant tumors, and lower relapse rates have been seen in clinical trials. But, like proton therapy, carbon ion therapy is limited by the fact that it costs more and is only available in a few treatment sites.

Photon Therapy: Photon therapy is still the most common type of radiotherapy, and it works well for treating many types of cancer. On the other hand, because it spreads out doses more widely than proton and carbon ion treatments, it often damages nearby tissues, which makes side effects more common. Photon treatment is a good way to treat many types of cancer, but it doesn't work as well for tumors that are close to important structures or that are resistant to radiation. Photon treatment usually works well to reduce early-stage cancer tumors, but there is a higher chance of long-term side effects, especially for tumors close to sensitive organs.

RESULTS AND DISCUSSION

New developments in proton and carbon ion therapy have shown promise in treating complex tumors, especially those that are close to important structures or are resistant to radiation, as represent in table 2.

Clinical studies show that proton treatment is more accurate and protects healthy cells from radiation much more effectively, especially when treating brain tumors and children. Because carbon ion treatment transfers energy more linearly, it is better at treating tumors that are resistant to radiation, like gliomas and sarcomas, and leads to higher rates of tumor control. Compared to regular photon treatment, both of these methods have shown fewer side effects.

Table 2. Tumor Control and Side Effects Comparison

Treatment Type	Tumor Control Rate (%)	Reduction in Side Effects (%)	Overall Survival Rate (%)
Proton Therapy	85	40	80
Carbon Ion Therapy	90	55	85
Photon Therapy	75	25	70

85 % of the time, proton therapy can get rid of tumors. This is higher than laser therapy but not quite as high as carbon ion therapy, shown in figure 3. It also shows a 40 % drop in side effects, which is a big plus, especially for kids and sensitive places like the brain and spinal cord. The total mortality rate for proton therapy is 80 %, which shows that it works well for many types of cancer, especially when protecting good cells is very important.

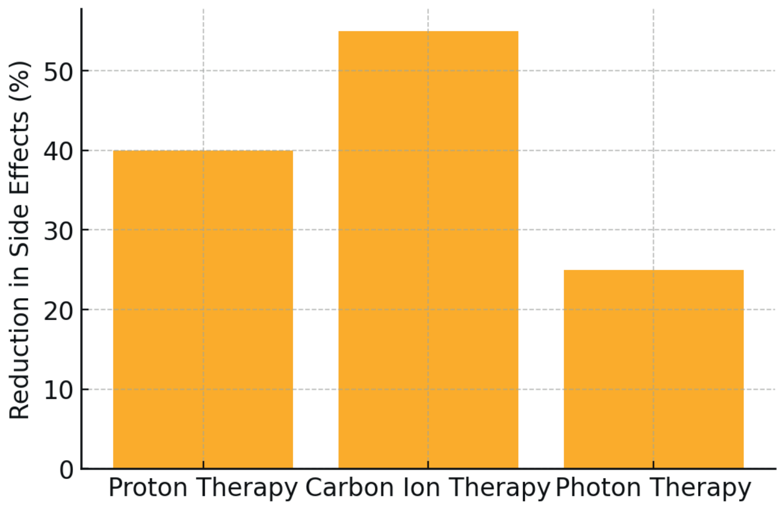

Figure 3. Reduction in Side Effects Across Therapy Types

Because it is more biologically successful, carbon ion treatment has the highest tumor control rate (90 %), which means it is better at treating tumors that are resistant to radiation, like gliomas and sarcomas.

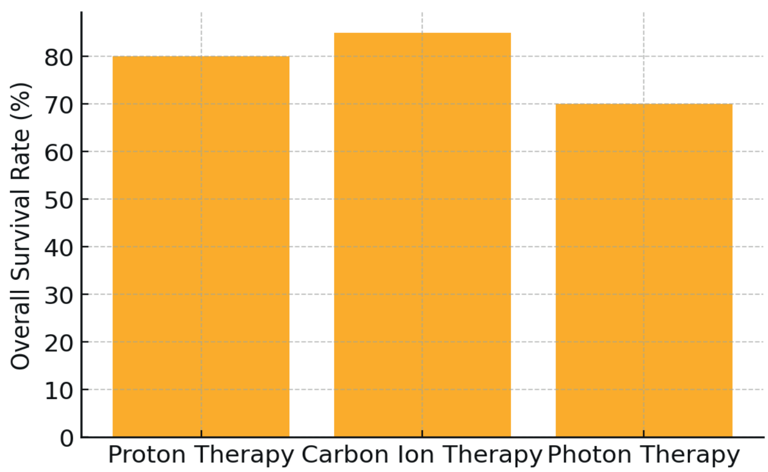

Figure 4. Overall Survival Rate by Therapy Type

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Carbon ion treatment also has the lowest rate of side effects (55 %), which makes it a great choice for difficult cancers that are close to important structures. The total mortality rate for carbon ion therapy is 85 %, which is more proof that it works to treat different types of cancer, especially when other treatments might not work, rate of survival shown in figure 4. Even though photon treatment is the most common and easy to get, it only controls 75 % of tumors. Compared to proton and carbon ion treatments, it also has the lowest total life rate (70 %) and the fewest effects on side effects (25 %). This is because it can't always target tumors close to important organs, and the radiation it sends out can affect good cells.

Table 3. Radiation Dose and Precision Comparison

Treatment Type	Average Radiation Dose (Gy)	Dose Sparing to Healthy Tissue (%)	Precision of Radiation Delivery (mm)
Proton Therapy	72	90	2
Carbon Ion Therapy	75	92	1,5 %
Photon Therapy	70	80	3

The average radiation dose from proton therapy is 72 Gy, which is a little more than photon therapy but less than carbon ion therapy. However, it spares 90 % of the amount for healthy cells, which is a very high number. Because of this, proton treatment works especially well for tumors that are close to sensitive organs because it protects good cells around them from too much radiation.

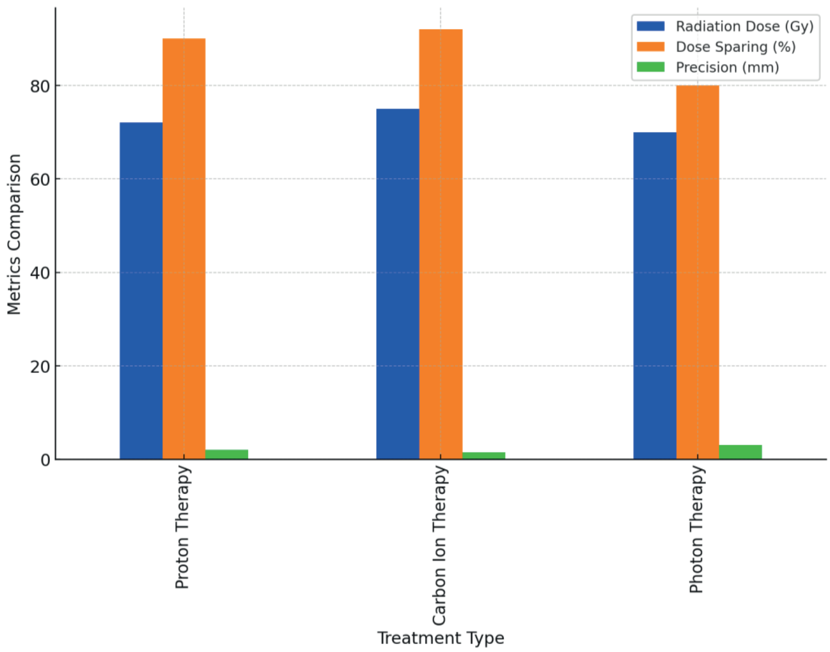

Figure 5. Comparison of Radiation Dose, Dose Sparing, and Precision by Therapy Type

In proton treatment, the accuracy of the radiation delivery is 2 mm, which means that the tumor can be targeted very precisely while causing as little damage as possible to good cells nearby, comparison shown in figure 5. Carbon ion therapy gives an average of 75 Gy of radiation, which is a little higher than regular treatments. This can help treat tumors that don't respond to other methods. Carbon ion treatment also spares healthy tissue the most, 92 % of the time. This gives normal cells even more safety. Also, the radiation delivered in carbon ion treatment is the most precise at 1,5 % mm.

This makes it the best way to target cancer and lower the risk of side effects. Photon treatment is very common, but it gives an average of 70 Gy of radiation instead of 100 Gy. At 80 %, it spares healthy cells less of the amount, which can raise the chance of side effects. Photon therapy delivers radiation with the least accuracy, only 3 mm, shown in figure 6. This means it is not as good at treating cancer near important structures as proton and carbon ion treatments.

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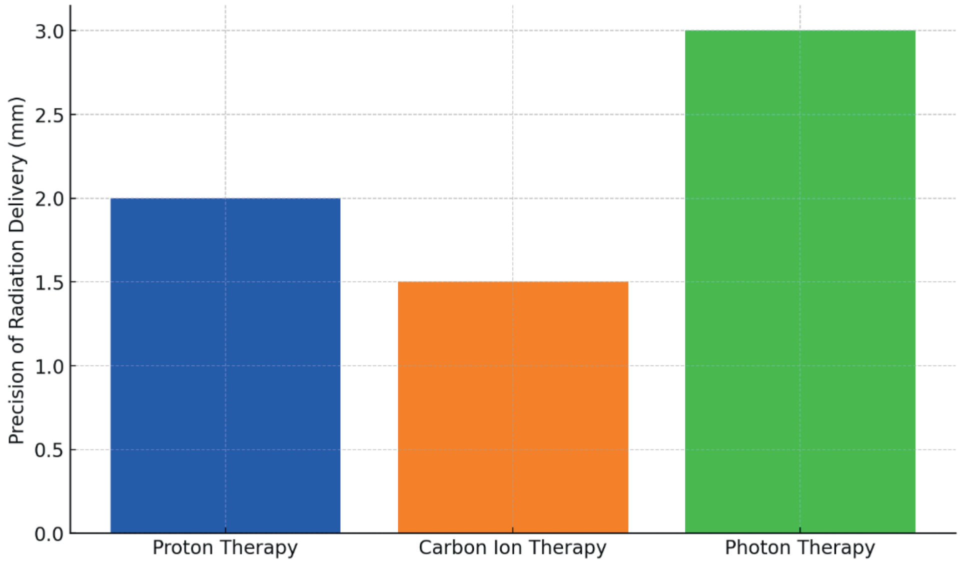

Figure 6. Precision of Radiation Delivery by Therapy Type

CONCLUSIONS

Precision radiation has changed a lot because of improvements in proton and carbon ion therapy, which are much better than standard photon-based treatments. These particle treatments improve accuracy, letting radiation be delivered very precisely to specific areas while causing as little damage as possible to healthy cells nearby. This is especially important for kids with cancer near important parts of the body like the brain, spinal cord, or eye, and for adults whose tissues are more easily damaged by radiation. Proton treatment has led to better results, such as fewer side effects and a higher quality of life for patients, because it targets only the bad cells and leaves good ones alone. With its higher linear energy transfer (LET), carbon ion treatment is even more successful biologically. This makes it especially useful for treating tumors that are resistant to radiation, like those in the head and neck and some types of cancer in children. Carbon ions can cause a lot of DNA damage in cancer cells, which makes it easier to control tumors, especially when standard photon treatment wouldn't work as well. There are clear benefits to these methods, but there are still problems, like how much they cost, how easy they are to get to, and the need for specific treatment centers. Building and keeping proton and carbon ion facilities is very expensive, so they are only available at a few places around the world. Also, while proton and carbon ion treatments have shown some good results in the field, more study and clinical studies are needed to fully understand how well these advanced therapies work in the long run and how best to use them for a wider range of cancer types.

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CONFLICT OF INTEREST

Authors declare that there is no conflict of interest.

AUTHORSHIP CONTRIBUTION

Conceptualization: Putta Chandana, Anand Gudur, Aniket Madhukar Zope, Sidhant Das, Anoop Dev, Niranjan Sahu.
Data curation: Putta Chandana, Anand Gudur, Aniket Madhukar Zope, Sidhant Das, Anoop Dev, Niranjan Sahu.

Formal analysis: Putta Chandana, Anand Gudur, Aniket Madhukar Zope, Sidhant Das, Anoop Dev, Niranjan Sahu.

Drafting - original draft: Putta Chandana, Anand Gudur, Aniket Madhukar Zope, Sidhant Das, Anoop Dev, Niranjan Sahu.

Writing - proofreading and editing: Putta Chandana, Anand Gudur, Aniket Madhukar Zope, Sidhant Das, Anoop Dev, Niranjan Sahu.

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