Improvement of carbon ion therapy technique with modeling the dose distribution in tail region.

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Abstract

One of prominent disadvantages of Carbon ion therapy compared with proton therapy is the Bragg peak tail caused by Carbon ion nuclear interactions in tumor. This is attributed to recoil nucleons and neutrons produced in the Bragg peak. The tail is extended into the healthy tissue located at the posterior part of the tumor. To assess the harms due to extra dose imposed by the Bragg peak tail, an analytical approach is presented. At first, elastic and non-elastic interactions of Carbon ion from the major target nuclides (H, O, C, N) are precisely investigated. Each product nucleus is treated as a secondary projectile charged particle. Computational results are obtained for each relevant Bragg peak appearing behind the major peak. Many reactions are studied; among them some products are not of sufficient energy to evolve out of the tumor. On the other hand, computer code SRIM is invoked to calculate the range and LET of secondary fragments.

Keywords: Hadrontherapy; Carbon ion; Bragg peak; Tail; Secondary particles.

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IMPROVEMENT OF CARBON ION THERAPY TECHNIQUE WITH MODELING THE DOSE DISTRIBUTION IN TAIL REGION.

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Contents

Introduction

- Importance of Cancer Treatment

Currently, more than 25 million people are suffering from cancer around the world and 7 million people lose their lives due to cancer each year.

Because of changes made in lifestyles towards a lazy life; increases in meat, fat, and smoke consumption; increases in life expectancy in society and high proportion of old people; industrialization of the society and high ecological and biological pollution; it is predicted that 27 million people will suffer from cancer until 2030 and deaths due to cancer will increase to 17 million people a year.

So, this statistics reveals the significance of cancer treatment and this is the reason to address the new methods of cancer treatment.

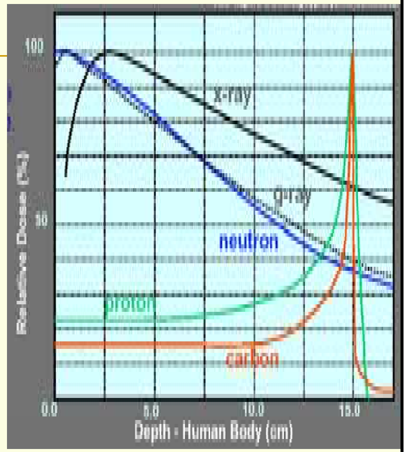
New methods in Cancer Treatment

- Brachytherapy (requires surgery);
- Hadron Therapy (suitable for progressive tumors);
- Radioactive Nanoparticles (still under research);
- The main problem in radiotherapy is to leave the healthy tissue intact. When the tumor is located in sensitive parts of body (like retinal cancer or cancer of the base of brain), due to fine targeting of charged particle beam, proton or carbon ion is applied.

Particle	Energy Interval	Application
Proton	60-70 (MeV)	Retina
Proton	180-250 (MeV)	Brain, Lungs and Prostate
Carbon Ion	80-400 (AMeV)	Retina, Brain, Lungs and Prostate

History and Specifications of Hadron Therapy

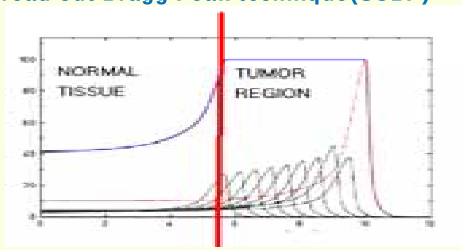
- Hadron Therapy was first suggested by Robert Wilson in 1946;
- Losing the maximum part of energy at the end of the path;
- Possibility of precise defining of penetration angle;
- Minimizing the dose received by healthy tissue;



Specifications of Hadron Therapy

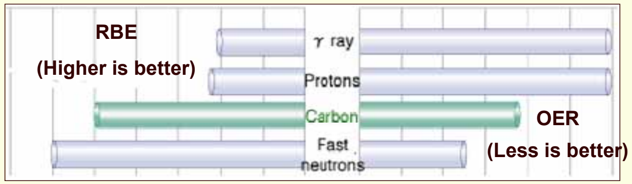
- Administering no dose to the region after tumor is removed;
- The ability to treat tumors in different sizes and shapes.

Spread out Bragg Peak technique(SOBP)



Specifications of Hadron Tehrapy

- Higher LET(linear energy transfer) and RBE (radiobiological effectiveness) in ions heavier than proton;
- Lower dependence to OER (oxygen enhancement ratio) parameter in ions heavier than proton (to treat Radioresistant tumors).



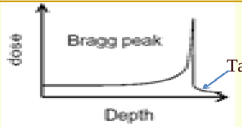
Comparative diagrams of RBE and OER in different radiations

Approach to the problem

- Finding the reactions and products of the nuclear interactions of carbon ion with C, H, O, and N nuclei; (tissue formula $C_5H_{40}O_{18}N$) and calculating their cross section.
- Calculating produced secondary particles' energy, range, and angular distribution.
- Calculating rate of reactions.
- Calculating flux of secondary particles.
- Modeling of dose distribution curve according to particles' penetration depth.

Stages of the research activities

- Investigating amount of secondary particles' penetration after Bragg Peak region.



- Calculating total absorbed dose resulted from produced secondary particles and investigating amount of dose received by patient.
- Investigating biological effects of produced second particles from health physics perspective.

Activities performed till present

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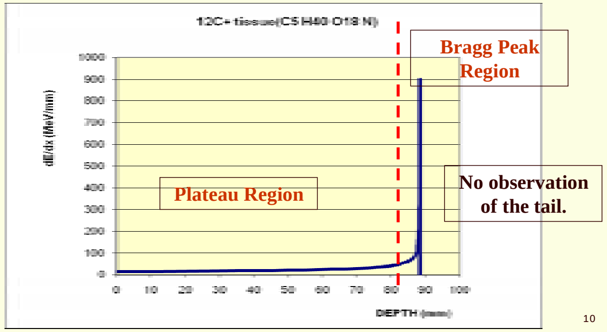

Activities performed till present (continue)

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Reaction	Reaction	Reaction	Reaction
12C+12C→p+23Na	12C+14N→5Li+21Ne	12C+14N→p+25Mg	12C+16O→5He+23Mg
12C+12C→d+22Na	12C+16O→p+27Al	12C+14N→d+24Mg	12C+16O→6He+22Mg
12C+12C→t+21Na	12C+16O→t+25Al	12C+14N→t+23Mg	12C+16O→4Li+24Na
12C+12C→4H+20Na	12C+16O→4H+24Al	12C+14N→α+22Mg	12C+16O→5Li+23Na
12C+12C→α+20Ne	12C+16O→2p+26Mg	12C+14N→α+22Na	12C+16O→6Li+22Na
12C+12C→6Li+18F	12C+16O→α+24Mg	12C+14N→5He+21Na	12C+16O→7Li+21Na

Activities performed till present

- Calculating produced second particles' energy resulting from nuclear interaction according to under mentioned equation

$$a+X \Rightarrow Y+b$$

$$Q=(m_a+m_b-m_Y-m_b)c^2$$

a = Incident Ion
X=Target
Y & b =Produced Particles
θ=Angle of Incident Ion

$$T_b^{0.5}=\frac{(m_a m_b T_a)^{0.5}\cos\theta+[(m_a m_b T_a \cos^2\theta+m_Y+m_b)(m_Y Q+(m_Y-m_a)Ta)]^{0.5}}{m_Y+m_b}$$

$$T_Y = T_a + Q - T_b$$

T_a = Incident Ion Energy
T_X = Target Energy
T_a &T_b = Produced Particles energy

- **And calculating their range by SRIM code.**

Activities performed till present (continue)

- Investigating the amount of particles’ penetration resulted from nuclear interaction to the area after Bragg Peak.

Maximum Energy of Reaction 's products	100MeV
Location of 100 MeV Carbon Ion (start of Bragg Peak)	88.19 mm
Maximum Range of 2400 MeV Carbon Ion	88.5 mm
Range of Reaction 's Products at least	0.31 mm

Activities performed till present (continue)

- Reaction products’ range in maximum energy condition (Carbon ion’s energy equals 100MeV and its scattering angle is 00).

Reaction	Range (mm)
12C+12C → p+23Na	40.58
12C+12C → d+22Na	20.29
12C+12C → t+21Na	13.53
12C+12C → 4H+20Na	10.15
12C+12C → α+20Ne	4.91
12C+12C → 6Li+18F	1.77
12C+14N → p+25Mg	39.54
12C+14N → d+24Mg	43.74
12C+14N → t+23Mg	31.51
12C+14N → α+22Mg	24.96
12C+14N → α+22Na	5.02
12C+14N → 5He+21Na	4.45

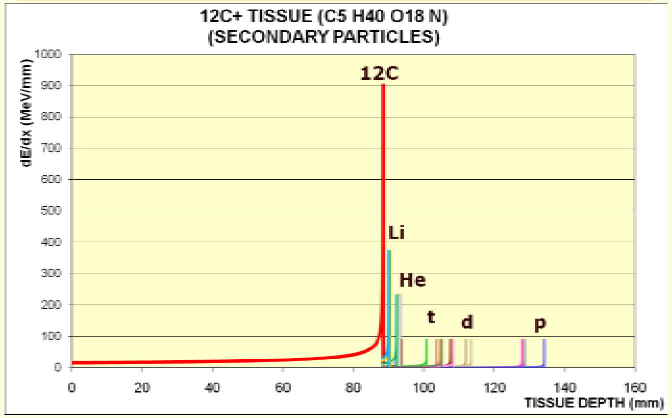
Activities performed till present (continue)

Reaction products’ range in maximum energy condition (Carbon ion’s energy equals 100MeV and its scattering angle is 0 degree).

Reaction	Range (mm)
12C+14N → 5Li+21Ne	1.97
12C+16O → p+27Al	45.92
12C+16O → t+25Al	15.31
12C+16O → 4H+24Al	12.33
12C+16O → 2p+26Mg	14.77
12C+16O → α+24Mg	5.12
12C+16O → 5He+23Mg	4.54
12C+16O → 6He+22Mg	3.92
12C+16O → 4Li+24Na	2.27
12C+16O → 5Li+23Na	2.01
12C+16O → 6Li+22Na	1.81
12C+16O → 7Li+21Na	0.8

Activities performed till present (continue)

dE/dx diagrams according to penetration depth of produced secondary particles and carbon ion in the tissue



Activities performed till present (continue)

- Reactions that lead to neutron production by interaction of carbon ion with body tissue.

Reaction
12C+12C → n+23Mg
12C+12C → 2n+22Mg
12C+12C → 3n+21Mg
12C+14N → n+25Al
12C+14N → 2n+24Al
12C+14N → 3n+23Al
12C+16O → n+27Si
12C+16O → 2n+26Si
12C+16O → 3n+25Si

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Activities performed till present (continue)

Results:

Comparing the range of heavy nuclei and required maximum range to pass the Bragg Peak area, we conclude that heavy nuclei don’t pass the Bragg Peak.

- Passage of light nuclei of the Bragg Peak area depends on their energy, except for neutrons. Making any comment on the produced neutrons and their effects needs more research by more advanced methods (advanced codes).

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Activities performed till present (continue)

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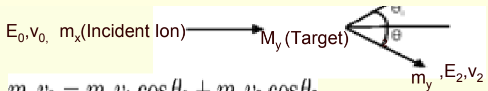

$$m_x v_0 = m_x v_1 \cos\theta_1 + m_y v_2 \cos\theta_2$$

$$E_1 = E_0 \left(\frac{m_x \cos\theta_1 \pm \sqrt{m_y^2 - m_x^2 \sin^2\theta_1}}{m_1 + m_2} \right)^2$$

$$E_2 = E_0 \left(\frac{4 m_x m_y \cos^2(\theta_1)}{(m_x + m_y)^2} \right)$$

Considering that

$\theta_1 = 0$,

E_C=100 MeV

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Activities performed till present (continue)

- Investigating the amount of penetration of scattered proton after Bragg Peak region.

cross section of 12C(H,p)12C reaction (EC=100MeV)	1380.319 mb
Energy of scattered proton	28.400 MeV
Range of scattered proton	7.950 mm

- Some studies are conducted in the field of predicting models of cross section including Sihver,Kox and Shen, Tripathi models.

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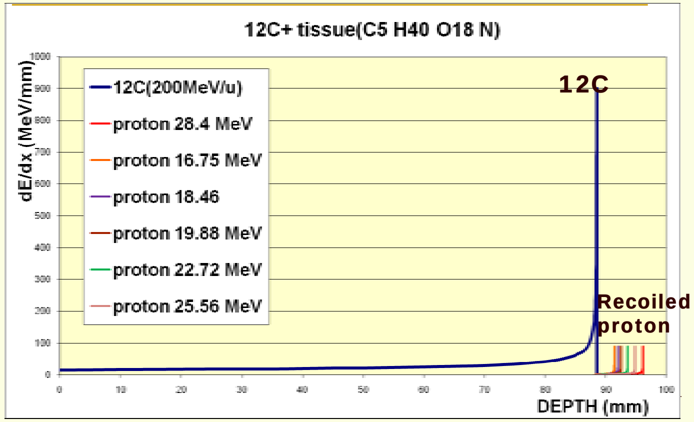
Activities performed till present (continue)

dE/dx diagrams according to penetration depth of proton and carbon ion in the tissue



Activities performed till present (continue)

Results:

- In the energy range of 0 ~ 100 MeV of carbon ion (in the Bragg Peak area), origination of tail in the area after the Bragg Peak is due to recoiled protons and light nuclei produced by the nuclear reaction (fragmentation) of carbon ion with the tissue. Making any comments on the effect of produced neutrons on the origination of the tail needs more study which is going to be studied in the next stages of the research.

Activities performed till present (continue)

- Now, to simulate the tail region produced by mentioned particles, we have to calculate the reaction rate leading to production of fragments and scattered particles in each point of the target, and this calculation is performed for the Bragg Peak area of the target in which carbon's beam energy equals 0 ~ 100 MeV.

Activities performed till present (continue)

- Calculating the total reaction rate leading to production of mentioned reactions to calculate the dose resulting from them according to this equation:

$$\text{Reaction Rate} = \int_{E2}^{E1} N(cm^{-3}) \times \sigma(cm^{2}) \times \Phi(cm^{-2}.s^{-1})$$

δ=cross section

Φ= no. of carbon/sec/cm2

$$N = \frac{\rho \times NA}{M}$$

Beam current of carbon is considered 0.3nA.

Activities performed till present (continue)

Calculating total reaction rate in the energy range of 0 ~ 100 MeV

Reaction	Total Reaction Rate ($cm^{-3}s^{-1}$)	Reaction	Total Reaction Rate ($cm^{-3}s^{-1}$)
12C(1H,n)13N	3562784925	12C(12C,t)21Na	24469362.57
12C(1H,p)12C	2583548330	12C(12C,4H)20Na	42827.80543
12C(12C,n)23Mg	27890756.47	12C(12C,6Li)18F	43131611.13
12C(12C,2n)22Mg	1167931.075	12C(14N,n)25Al	474323.3363
12C(12C,3n)21Mg	8701.419683	12C(14N,2n)24Al	226329.6406
12C(12C,d)22Na	161772287.7	12C(14N,3n)23Al	5744.877828

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Activities performed till present (continue)

Calculating total reaction rate in the energy range of 0 ~ 100 MeV

Reaction	Total Reaction Rate ($cm^{-3}s^{-1}$)	Reaction	Total Reaction Rate ($cm^{-3}s^{-1}$)
12C(14N,4He)22Mg	65813.7862	12C(16O,t)25Al	83437208.17
12C(14N,α)22Na	17690641.79	12C(16O,4H)24Al	879665.009
12C(14N,5He)21Na	1683784.012	12C(16O,5He)23Mg	58959991.68
12C(16O,n)27Si	45233304.81	12C(16O,6He)22Mg	8576947.33
12C(16O,2n)26Si	3499406.932	12C(16O,4Li)24Na	12893058.52
12C(16O,3n)25Si	91258.16063	12C(16O,6Li)22Na	165368714.9
12C(16O,d)26Al	437432853.5	12C(16O,7Li)21Na	50706737.17

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Prediction of the future activities

- Calculating angular distribution and energy of scattered protons in the Bragg Peak area.
- Calculating angular distribution of flux and energy of the produced secondary particles in the Bragg Peak area.
- Calculating the dose resulted from aforementioned produced particles using above information to distribute 3 dimensional of dose in tail region.
- Implementing the nuclear code of FLUKA to calculate nuclear reactions, scatterings and their cross section in the energy range of 0 ~ 200 MeV/u.

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Why FLUKA?

Code	Projected Ion or Particle	Target	Energy Range	Output
TALYS	n, γ, p, d, t, α	All elements with mass of 12 to 339	1 keV–200 MeV	Cross section of the reaction, angular distribution of energy, cross section of the produced and recoiled particles
EMPIRE II	Nucleons, heavy ions, and photons	All composite targets and elements	Up to couple of hundreds MeV	Total elastic cross section,elastic and nonelastic angular distribution of reactions, cross section for nonelastic scatteringst, gamma spectrum and radiative particles and recoiled particles' spectrum.

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Why FLUKA?

Code	Projected Ion or Particle	Target	Energy Range	Output
FLUKA	Photons, electrons, neutrinos, neutrons and hadrons	All composite targets and elements	1 KeV ~ couple of thousands TeV, and for heavy ions up to 20 TeV	Calculating particle transfer and its interaction with materials, calculations related to design of shields and target design in proton and electron accelerators, calorimeter, activation, dosimeter, designing detectors, accelerators, cosmic beams, neutrinos, radiotherapy and … 29

THANK YOU FOR YOUR ATTENTION.