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[Continued on next page]

(54) Title: REVOLVING COLLIMATOR FOR PROTON STEREOTACTIC BODY RADIOTHERAPY

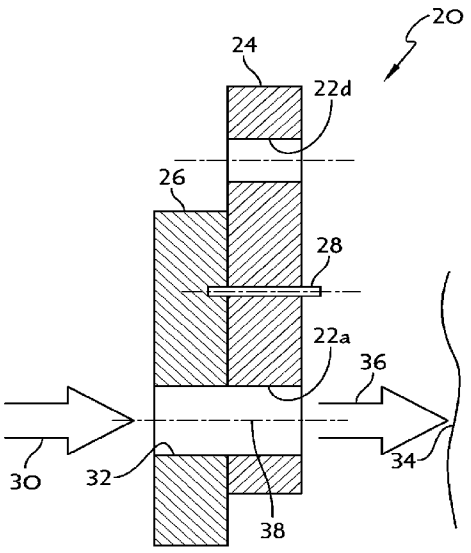


FIG. 1A

(57) Abstract: Methods and apparatus for performing at least one of proton stereotactic radiosurgery (pSRS) and proton hypofractionated therapy (pHT). A base and a cylinder are movably coupled. The base defines an aperture at which a proton beam is aimed. The cylinder defines a plurality of openings having different sizes and/or different shapes. The openings are oriented in the cylinder so that a selected one of the openings can be aligned generally with the aperture to permit irradiating tissue with the proton beam after passage of the beam through the aperture and the selected opening.

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REVOLVING COLLIMATOR FOR PROTON STEREOTACTIC BODY RADIOTHERAPY

Cross Reference to Related Applications

This application claims the benefit of the May 30, 2013 filing date of U. S. S. N. 61/653,145. The entire disclosure of U. S. S. N. 61/653,145 is hereby incorporated herein by reference.

Background

Stereotactic radiosurgery (hereinafter sometimes SRS), particularly image-guided stereotactic body radiation therapy (hereinafter sometimes SBRT) or hypofractionated radiotherapy (hereinafter sometimes HT) has been shown to be a successful non-invasive therapy for a wide variety of tumors, in particular of early-stage non-small cell lung cancer (hereinafter sometimes NSCLC) (see, for example: R. Timmerman, R. Paulus, J. Galvin, J. Michalski, W. Straube, J. Bradley, A. Fakiris, A. Bezjak, G. Videtic, D. Johnstone, J. Fowler, E. Gore, H. Choy, Stereotactic Body Radiation Therapy for Inoperable Early Stage Lung Cancer, JAMA-J. Am. Med. Assoc., 303 (2010) 1070-1076; and, Z.X. Liao, S.H. Lin, J.D. Cox, Status of particle therapy for lung cancer, Acta Oncol., 50 (2011) 745-756), vestibular schwannomas, meningiomas, arteriovenous malformations (hereinafter sometimes AVMs), pituitary adenomas, select cases of limited metastatic central nervous system (hereinafter sometimes CNS) disease, and base of skull tumors including paragangliomas, recurrent chondrosarcomas or chordomas. Recent small studies and trials have shown that proton therapy has clear advantages over megavoltage photon SBRT or photon hypofractionated radiotherapy. See, for example: Z.X. Liao, S.H. Lin, J.D. Cox, Status of particle therapy for lung cancer, Acta Oncol., 50 (2011) 745-756; and, S.P. Register, X.D. Zhang, R. Mohan, J.Y. Chang, Proton stereotactic body radiation therapy for clinically challenging cases of centrally and superiorly located stage I non-small-cell lung cancer, Int. J. Radiat. Oncol. Biol. Phys., 80 (2011) 1015-1022. Proton hypofractionated radiotherapy has shown less toxicity than photon therapy, and it has shown encouraging early results in small studies

in the terms of local control and overall survival. See, for example: Z.X. Liao, S.H. Lin, J.D. Cox, Status of particle therapy for lung cancer, Acta Oncol., 50 (2011) 745-756; J.Y. Chang, R. Komaki, H.Y. Wen, B. De Gracia, J.B. Bluett, M.F. McAleer, S.G. Swisher, M. Gillin, R. Mohan, J.D. Cox, Toxicity and pattern of failure of adaptive/ablative proton therapy for early-stage, medically inoperable non-small cell lung caner, Int. J. Radiat. Oncol. Biol. Phys., 80 (2011) 1350-1357; and, J.P.C. Grutters, A.G.H. Kessels, M. Pijls-Johannesma, D. De Ruysscher, M.A. Joore, P. Lambin, Comparison of the effectiveness of radiotherapy with photons, protons and carbon-ions for non-small cell lung cancer: A meta-analysis, Radiother. Oncol., 95 (2010) 32-40. Combinations of the proton hypofractionated therapy (hereinafter sometimes pHT) with concurrent chemotherapy and utilization of the tumor motion control systems have demonstrated the positive outcome of the therapy. See, for example: Z.X. Liao, S.H. Lin, J.D. Cox, Status of particle therapy for lung cancer, Acta Oncol., 50 (2011) 745-756; and, J.Y. Chang, R. Komaki, H.Y. Wen, B. De Gracia, J.B. Bluett, M.F. McAleer, S.G. Swisher, M. Gillin, R. Mohan, J.D. Cox, Toxicity and pattern of failure of adaptive/ablative proton therapy for early-stage, medically inoperable non-small cell lung caner, Int. J. Radiat. Oncol. Biol. Phys., 80 (2011) 1350-1357. Proton SRS (hereinafter sometimes pSRS) or pHT alone or in combination with chemotherapy is an attractive option to reduce or eliminate effects associated with acquired resistance to treatment. See, for example, Z.X. Liao, S.H. Lin, J.D. Cox, Status of particle therapy for lung cancer, Acta Oncol., 50 (2011) 745-756.

Proton therapy has been gaining recognition worldwide due to its large dosimetric advantage over photons by forming the energy deposition peak (hereinafter sometimes the Bragg peak). See, for example, M.W. McDonald, M.M. Fitzek, Proton Therapy, Curr. Probl. Cancer, 34 (2010) 257-296. The spread-out Bragg peak (hereinafter sometimes SOBP) can confine the targeting area (tumor) with the relatively low entrance dose and zero dose behind the tumor. See, for example, B.S. Hoppe, S. Huh, S. Flampouri, R.C. Nichols, K.R. Oliver, C.G. Morris, N.P. Mendenhall, Z. Li, Double-scattered proton-based stereotactic body radiotherapy for stage I lung cancer: A dosimetric comparison with photon-based stereotactic body radiotherapy, Radiother. Oncol., 97 (2010) 425-430. Applying multiple non-conformal beams with the tumor

motion control mechanism may permit utilization of the discovered advantages of proton therapy in reducing side effects from treatment, and improve survival. Recent progress in accelerator development dramatically reduces the cost of a proton facility. See, for example: D.R. Olsen, J. Overgaard, Leveraging clinical performance by technological excellence - The case of particle therapy, Radiother. Oncol., 95 (2010) 1-2; and, M. Pijls-Johannesma, P. Pommier, Y. Lievens, Cost-effectiveness of particle therapy: Current evidence and future needs, Radiother. Oncol., 89 (2008) 127-134. The number of proton therapy facilities commissioned or in various stages of the construction has increased dramatically over the past few years. The single-vault options permit establishment of community based facilities.

There are two main approaches in current proton therapy development: shaping the beam with the patient-specific collimator, or aperture, and spot scanning. Spot scanning the proton beam seems to be an attractive option. However it is not suitable for producing small SOBP of about 1 cm required for pSRS. The proton beam in spot scanning spreads up to about 18 mm in air for high energies and up to about 3 cm for low energies while passing the treatment nozzle. The current approach in proton radiosurgery is usage of circular brass collimators with diameters ranging from 2 to 30 mm, without compensators (Loma Linda) (see, for example, S.M. Vatnitsky, D.W. Miller, M.F. Moyers, R.P. Levy, R.W. Schulte, J.D. Slater, J.M. Slater, Dosimetry techniques for narrow proton beam radiosurgery, Phys. Med. Biol., 44 (1999) 2789-2801) or tungsten micro-multileaf collimators (hereinafter sometimes MLCs) (Massachusetts General Hospital). See, for example, J. Daartz, M. Bangert, M.R. Bussiere, M. Engelsman, H.M. Kooy, Characterization of a mini-multileaf collimator in a proton beamline, Med. Phys., 36 (2009) 1886-1894). A micro-MLC system would be more flexible for irregularly shaped targets. However, a micro-MLC system itself requires a dedicated treatment room installation, thereby increasing the cost of the facility. The experience with Gamma Knife in utilization of the finite size and number of collimators showed the efficacy of the cone approach for cranial SRS. Photon SBRT of the lung has used elliptical-shaped, custom-designed collimators and was substituted later with an elliptical-shaped MLC opening. The MLC for photon therapy is manufactured from tungsten. See, for example, L. Papiez, V. Moskvin, R. Timmerman,

Chapter 8. The Physics and Dosimetry of SBRT: Dosimetry of Stereotactic Body Radiation Therapy, in: B.D. Kavanaugh, R.D. Timmerman (Eds.) Stereotactic Body Radiation Therapy, Lippincott Williams & Wilkins, NY, 2004, pp. 160.

Our preliminary study has shown that MLC proton therapy increases the neutron dose 1.6 times. See, for example: V. Moskvin, C.W. Cheng, Q.Y. Zhao, I.J. Das, Comment on "Comparison of secondary neutron dose in proton therapy resulting from the use of a tungsten alloy MLC or a brass collimator system" Med. Phys. 38(11), 6248-6256 (2011), Med. Phys., 39 (2012) 2303-2305; and, V. Moskvin, C.W. Cheng, I.J. Das, Pitfalls of tungsten multileaf collimator in proton beam therapy, Med. Phys., 38 (2011) 6395-6406. The measured neutron dose from a tungsten leaf micro-MLC is found to be in the range of 1.5-1.8 times higher than for a brass aperture. See, for example, J. Daartz, M. Bangert, M.R. Bussiere, M. Engelsman, H.M. Kooy, Characterization of a mini-multileaf collimator in a proton beamline, Med. Phys., 36 (2009) 1886-1894.

The significant increase in the number of long-term survivors among radiation therapy patients gives rise to a concern about the risk of radiation-induced cancer appearing as a late post-treatment effect. See, for example: S. Agosteo, C. Birattari, M. Caravaggio, M. Silari, G. Tosi, Secondary neutron and photon dose in proton therapy, Radiother. Oncol., 48 (1998) 293-305; and, D.J. Brenner, E.J. Hall, Secondary neutrons in clinical proton radiotherapy: A charged issue, Radiother. Oncol., 86 (2008) 165-170. The activation of the MLC and impact of the secondary neutron on MLC controller electronics both contribute to the conclusion that current MLC design is not appropriate for proton therapy. See, for example, V. Moskvin, C.W. Cheng, I.J. Das, Pitfalls of tungsten multileaf collimator in proton beam therapy, Med. Phys., 38 (2011) 6395-6406.

U. S. Patent 6,389,108 describes a system which was designed for photon radiation assuming that the thickness of the collimator should be enough to attenuate the photon/gamma radiation of given wavelength. The U. S. Patent 6,389,108 collimator includes a set of revolving plates characterized by large variation in collimator downstream surface-to-patient distance.

The proton beam passing through the narrow collimator opening shows a

strong effect on the air/collimator interface that may lead to perturbation of the Bragg peak and plateau part of the dose distribution. This effect can limit the minimum size of the collimator system in the cone approach, and may significantly limit the alternative micro-MLC application. Utilization of exchangeable cones may be an attractive option, but will make the pSRS procedure time consuming and therefore more expensive.

Summary

According to one aspect, apparatus for performing a proton treatment comprises a base and a cylinder movably coupled to the base. The base defines at least one aperture at which a proton beam is aimed. The cylinder defines at least one divergent or non-divergent opening oriented in the cylinder so that a selected one of the at least one opening can be aligned generally with a selected one of the at least one aperture to permit irradiating tissue with the proton beam after passage of the beam through the selected aperture and the selected opening.

Illustratively, the at least one opening comprises a plurality of openings of different sizes.

Illustratively, the at least one opening comprises a plurality of openings of different shapes.

Illustratively, the plurality of openings are selected from circular openings and elliptical openings.

Illustratively, the apparatus comprises an apparatus for performing pSRS. Illustratively, the pSRS is image-guided SBRT.

Illustratively, the base and the cylinder are constructed from titanium alloy.

Illustratively, the base and the cylinder are constructed from Ti-6Al-4V or Ti-6Al-5V or another titanium alloy containing no high atomic number elements.

According to another aspect, a method is provided for performing a proton treatment. The method comprises aiming a proton beam at an aperture provided in a base, aligning with the aperture a selected one of at least one divergent or non-divergent opening provided in a cylinder movably coupled to the base to permit irradiating tissue with the proton beam after passage of the beam through the aperture

and the selected opening.

Illustratively, aligning a selected one of at least one opening with the aperture comprises aligning a selected one of a plurality of openings of different sizes with the aperture.

Illustratively, aligning a selected one of at least one opening with the aperture comprises aligning a selected one of a plurality of openings of different shapes with the aperture.

Illustratively, aligning a selected one of a plurality of openings of different shapes with the aperture comprises aligning a selected one of a plurality of openings selected from circular openings and elliptical openings with the aperture.

Illustratively, performing a proton treatment comprises performing at least one of pSRS and pHT.

Illustratively, aiming a proton beam at an aperture provided in a base and aligning a selected one of at least one opening provided in a cylinder with the aperture comprises aiming a proton beam at an aperture provided in a base constructed from titanium alloy and aligning a selected one of at least one opening provided in a cylinder constructed from titanium alloy with the aperture.

Illustratively, aiming a proton beam at an aperture provided in a base and aligning a selected one of at least one opening provided in a cylinder with the aperture comprises aiming a proton beam at an aperture provided in a base constructed from Ti-6Al-4V or Ti-6Al-5V or another titanium alloy containing no high atomic number elements and aligning a selected one of at least one opening provided in a cylinder constructed from Ti-6Al-4V or Ti-6Al-5V or another titanium alloy containing no high atomic number elements with the aperture.

According to a further aspect, apparatus for performing at least one of pSRS and pHT comprises a base and a cylinder movably coupled to the base. The base defines an aperture at which a proton beam is aimed. The cylinder defines a plurality of openings of at least one of different sizes and different shapes. The openings are oriented in the cylinder so that a selected one of the openings can be aligned generally with the aperture to permit irradiating tissue with the proton beam after passage of the beam through the aperture and the selected opening.

Illustratively, the plurality of openings are of different sizes.

Illustratively, the plurality of openings are of different shapes.

Illustratively, the plurality of openings are selected from circular openings and elliptical openings.

Illustratively, the apparatus is for performing pSRS. Illustratively, the pSRS is image-guided SBRT.

Illustratively, the base and the cylinder are constructed from titanium alloy.

Illustratively, the base and the cylinder are constructed from Ti-6Al-4V or Ti-6Al-5V or another titanium alloy containing no high atomic number elements.

According to another aspect, a method is provided for performing at least one of pSRS and pHT. The method comprises aiming a proton beam at an aperture provided in a base, aligning a selected one of a plurality of openings provided in a cylinder movably coupled to the base with the aperture to permit irradiating tissue with the proton beam after passage of the beam through the aperture and the selected opening.

Illustratively, aligning a selected one of a plurality of openings with the aperture comprises aligning a selected one of a plurality of openings of different sizes with the aperture.

Illustratively, aligning a selected one of a plurality of openings with the aperture comprises aligning a selected one of a plurality of openings of different shapes with the aperture.

Illustratively, aligning a selected one of a plurality of openings of different shapes with the aperture comprises aligning a selected one of a plurality of openings selected from circular openings and elliptical openings with the aperture.

Illustratively, performing at least one of pSRS and pHT comprises performing image-guided SBRT.

Illustratively, aiming a proton beam at an aperture provided in a base and aligning a selected one of a plurality of openings provided in a cylinder with the aperture comprise aiming a proton beam at an aperture provided in a base constructed from titanium alloy and aligning a selected one of a plurality of openings provided in a cylinder constructed from titanium alloy with the aperture.

Illustratively, aiming a proton beam at an aperture provided in a base and aligning a selected one of a plurality of openings provided in a cylinder with the aperture comprises aiming a proton beam at an aperture provided in a base constructed from Ti-6Al-4V or Ti-6Al-5V or another titanium alloy containing no high atomic number elements and aligning a selected one of a plurality of openings provided in a cylinder constructed from Ti-6Al-4V or Ti-6Al-5V or another titanium alloy containing no high atomic number elements with the aperture.

Brief Description of the Drawings

The invention may best be understood by referring to the following detailed description and accompanying drawings which illustrate the invention. In the drawings:

Fig. 1a illustrates a sectional side elevational view of a revolving pSRS collimator system taken generally along section lines 1a-1a of Fig. 1b;

Fig. 1b illustrates a front elevational view of a revolving pSRS collimator system taken generally along section lines 1b-1b of Fig. 1a;

Fig. 2a illustrates neutron flux Φ_n from a titanium alloy, Ti-6Al-4V, stainless steel brass and tungsten alloy blocks during irradiation with a 204 MeV proton beam; the spectra computed for the detector having 0.5 cm radius placed at 10 cm distance along the beam axis from the downstream surface of he block modeling a MLC;

Fig. 2b illustrates the neutron weighting factors from Recommendations of the International Commission on Radiological Protection (ICRP Publication 60, or ICRP 60), (Oxford: Pergamon) (1990)) and The 2007 Recommendations of the International Commission on Radiological Protection (ICRP Publication 103 or ICRP 103), (Oxford: Pergamon) (2007)); and,

Fig. 3 illustrates the ambient neutron dose equivalents from various collimator materials along the proton beam axis.

Detailed Descriptions of Illustrative Embodiments

A revolving pSRS collimator system 20 with multiple collimator openings 22a, 22b, . . . 22n of various sizes and shapes, for example, circular and elliptical shapes,

in a cylinder 24 is illustrated in Figs. 1a-b. The revolving pSRS collimator 20 includes exchangeable cylinders 24 which may have openings 22a, 22b, . . . 22n of the same or different sizes, that is, cross-sectional areas transverse to their longitudinal extents through cylinders 24, and shapes, that is, cross-sectional shapes transverse to their longitudinal extents through cylinders 24. The system 20 includes, in addition to the multiport 22a, 22b, . . . 22n cylinder 24 a base 26 to which cylinder 24 is rotatably coupled by an axle 28 onto which cylinder 24 readily can be placed and from which cylinder 24 readily can be removed and replaced with another cylinder 24 of the same or a different configuration (that is, number, sizes and shapes of openings 22a, 22b, . . . 22n). The proton beam 30 is incident from the left in Fig. 1a, passes through the aperture 32 in base 26, through the selected opening 22a, 22b, . . . 22n in cylinder 24, and thence to the target 34.

This permits application of the revolving pSRS collimator 20-collimated proton beams 36 to a wider range of tumor sizes and shapes. The combination of the non-coplanar multiport 32, 22a, 22b, . . . 22n scheme of pSRS with the revolving pSRS collimator 20 produces smaller numbers of secondary neutrons. It is believed that an accurate method of narrow proton beam 36 dosimetry, treatment plan algorithm and methods of accounting for tumor motion may increase positive outcomes of pSRS. The revolving pSRS collimator system 20 may be constructed from titanium alloy to minimize the secondary radiation dose to the target 34.

Fig. 2 illustrates the spectra of secondary neutrons at 10 cm distance from downstream collimator surface, the downstream surface of cylinder 24, for various collimator materials.

Fig. 3 illustrates the ambient dose equivalent from various collimator materials along the beam axis 38. It is clear that titanium alloy will benefit the patient treatment with the use of pSRS by minimizing the impact of secondary neutrons. That in turn will reduce the risk of the later effects, in particular, secondary cancers.

A set of collimator cylinders 24 having divergent or non-divergent openings 22a, 22b, . . . 22n of various sizes in various shapes, for example, circular and elliptical shapes, is provided. The collimator 20 is sized to replace mechanically the 10 cm snout of the IBA SA proton beam treatment nozzle and will conform to the IBA

snout design.

The revolving pSRS collimator 20 is designed for proton beam therapy. It is constructed from low atomic number material, illustratively, a titanium alloy such as, for example, Ti-6Al-4V or Ti-6Al-5V, that is not suitable for photons. This permits significant reduction of the secondary neutron radiation which would pose a risk of secondary cancer in proton therapy. The revolving pSRS collimator includes an exchangeable revolver providing a wide range of the collimator opening sizes in both circular and elliptical shapes. The collimator thickness is defined by the range R of the protons in the low atomic number material, and is planned to be of the order 1.2 R.

Simulations were performed utilizing FLUKA Monte Carlo general purpose code. The details of the simulation model customization, methods of the neutron transport simulation activation of the MLC material and neutron dose equivalent calculations were all described in U. S. S. N. 13/429,559, the disclosure of which is hereby incorporated herein by reference. See also, V. Moskvin, C.-W. Cheng, I. J. Das, Pitfalls of tungsten multileaf collimator in proton beam therapy, Medical Physics, 38 (2011) 6395-6406.

The thickness of the block representing the collimator was selected as the value of the proton range in a given material with some additional material thickness to assure complete absorption of the proton beam in the block. The titanium alloy is represented by annealed Ti-6Al-5V Grade 5 alloy. Tungsten and stainless steel blocks are analyzed for illustrative purposes as typical shielding design materials. The illustrative thicknesses of blocks were 10 cm for titanium alloy, and 5.54 cm for stainless steel. Tungsten blocks of 6.5 cm and 9 cm were considered in: V. Moskvin, C.-W. Cheng, I. J. Das, Pitfalls of tungsten multileaf collimator in proton beam therapy, Medical Physics, 38 (2011) 6395-6406; and, V. Moskvin, C.-W. Cheng, Q. Zhao, I.J. Das, Comment on "Comparison of secondary neutron dose in proton therapy resulting from the use of a tungsten alloy MLC or a brass collimator system" [Med. Phys. 38(11), 6248-56 (2011)], Medical Physics, 39 (2012) in press. The 3.3 cm tungsten alloy block corresponds to the 10 cm titanium alloy block of one proton range plus additional material. This tungsten thickness is used in the following "Neutron flux and neutron dose equivalent from titanium alloy pSRS collimator" discussion where data on the

neutron dose equivalent is analyzed.

Neutron flux and neutron dose equivalent from titanium alloy pSRS collimator

Fig. 2a illustrates the spectra of neutrons $\Phi_n(E)$ from titanium alloy (Ti-6Al-4V), stainless steel, brass and tungsten alloy blocks during irradiation with a 204 MeV proton beam. The spectra computed for a detector of 0.5 cm radius placed at 10 cm distance along the beam axis from the downstream surface of the block used to imitate the collimator in this study. The neutron weighting factors from the ICRP 60 and ICRP 103 are illustrated in Fig. 2b.

Neutron dose equivalent was calculated for a Ti-6Al-4V alloy block representing a collimator magnitude in the energy interval where the neutron weighting factor reaches a maximum of 10 cm thickness and compared to the dose equivalent from neutrons generated in a 5.54 cm thick stainless steel block, a 6.5 cm thick brass block, a 3.3 cm thick tungsten alloy block and a 6.5 cm thick tungsten alloy block. Fig. 3 illustrates the results of these calculations.

In proton therapy, the patient is positioned at 5 cm distance skin-to-treatment nozzle. Fig. 3 illustrates that a titanium alloy collimator 20 produces a smaller neutron dose equivalent at the patient position than a tungsten collimator or a stainless steel collimator. It should be noted that utilization of the titanium alloy will reduce the dose equivalent from neutrons compared to the current state of the art brass aperture beam shaping device.

The results presented in Table 1 illustrate that Ti alloy exhibits only 4-6% of the tungsten MLC activation after one year of irradiation. In contrast, stainless steel exhibits 8-21% of the tungsten MLC activation after one year of irradiation. Titanium alloy thus provides at least a 50% reduction in activation over stainless steel as a MLC material after one year of irradiation.

Cooling Time	Titanium alloy Ti-6Al-4V	Stainless Steel
Immediately after beam off, < 1 s	4.86	8.588
15 min	5.94	12.08
1 hour	6.48	12.866
6 hours	6.63	15.06
12 hours	6.48	16.20
24 hours	6.52	17.64
10 days	4.97	21.14
40 days	4.46	21.59

Table 1. Activity of the irradiated part of the collimator material for various cooling times in percentage of the activity exhibited by a Tungsten MLC at the same cooling times

Almost 60% of the activity in a titanium alloy (Ti-6Al-5V) block irradiated over one year is attributable to $^{46}_{21}Sc$, with a half-life of 83.79 days, after 40

days of cooling. The rest, about 40%, will be attributable to all other isotopes. See Table 3. The isotopes $^{48}_{23}V$ and $^{37}_{18}Ar$ have relatively short half-lives and so do not affect the long term requirement for titanium alloy (Ti-6Al-5V) storage. Isotopes of $^{45}_{20}Ca$ and $^{49}_{23}V$ with half-lives of 162.61 and 330 days, and tritium accumulation will require prolonged storage for cooling. However, the data on total activity suggest that the absolute yields of $^{45}_{20}Ca$ and $^{49}_{23}V$ are small (1.4 and 1.5% of total activity after 15 min. cooling time of the alloy block irradiated over one year) and they will not made a major impact on the radiation environment around the collimator in storage. Taking into account that total activity in a titanium alloy collimator is only 4-6% of the activity in a tungsten MLC after one year irradiation, the impact of these isotopes may be considered minimal.

Isotope	% of total activity	Half-life	Decay mode
$^{44}_{21}Sc$	17.8	3.97 h 58.61 h	EC- 100% IT -98%, EC-2%
$^{46}_{21}Sc$	15.1	83.79 d 18.25 s	β-- 100% IT -100%
$^{45}_{22}Ti$	14.0	184.3 m	EC- 100%
$^{47}_{21}Sc$	12.9	3.35 d	β-- 100%
$^{48}_{23}V$	7.8	15.97d	EC- 100%
$^{43}_{21}Sc$	4.4	3.89 h	EC- 100%

Table 2. Isotopes contributing to the residual activity of a unit irradiated volume of the Ti-6Al-5V alloy collimator. The irradiation duration is 1 year. Activity is given in % of total activity after 15 min. of cooling. Here notations are h - hours, d - days, EC - electron capture β- - beta decay IT –internal conversion.

Isotope	% of total activity	Half-life,	Decay mode
$^{46}_{21}Sc$	59.7	83.79 d 18.25 s	β-- 100% IT -100%
$^{49}_{23}V$	8.5	330 d	EC- 100%
$^{45}_{20}Ca$	7.8	162.61 d	β-- 100%
$^{48}_{23}V$	7.6	15.97d	EC- 100%
$^{37}_{18}Ar$	5.6	35.04 d	EC- 100%
$^{3}_{1}H$	2.8	12.32 y	β-- 100%

Table 3. Isotopes contributing to the residual activity of a unit irradiated volume of the Ti-6Al-5V alloy c. The irradiation duration is 1 year. Activity is given in % of total activity after 40 days of cooling. Here notations are h - hours, d - days, EC - electron capture and β- - beta decay IT –internal conversion.

The revolving pSRS collimator reduces the secondary neutron dose to the patient, reducing later effects, and ultimately improving survival and quality of life.

The revolving pSRS collimator permits the establishment of the pSRS system and methodology without the need for a dedicated treatment vault, making the revolving pSRS collimator system an attractive option for hospitals with single vaults.

The implementation of the revolving pSRS collimator also reduces side effects from treatment. The revolving pSRS collimator system makes possible proton radiosurgery on a wider range of tumors, including but not limited to NSCLC, vestibular schwannomas, meningiomas, AVMs, pituitary adenomas, select cases of limited metastatic CNS disease, and base of skull tumors including paragangliomas, recurrent chondrosarcomas or chordomas.

The disclosures of all of the references identified herein are hereby incorporated herein by reference.

What is claimed is:

1. Apparatus for performing a proton treatment, the apparatus comprising a base, a cylinder movably coupled to the base, the base defining at least one aperture at which a proton beam is aimed, the cylinder defining at least one divergent or non-divergent opening, the at least one opening being oriented in the cylinder so that a selected one of the at least one opening can be aligned generally with a selected one of the at least one aperture to permit irradiating tissue with the proton beam after passage of the beam through the selected aperture and the selected opening.

2. The apparatus of claim 1 wherein the at least one divergent or non-divergent opening comprises a plurality of openings of different sizes.

3. The apparatus of claim 1 wherein the at least one divergent or non-divergent opening comprises a plurality of openings of different shapes.

4. The apparatus of claim 3 wherein the plurality of divergent or non-divergent openings are selected from circular and elliptical.

5. The apparatus of claim 1 for performing at least one of proton stereotactic radiosurgery (pSRS) and proton hypofractionated therapy (pHT).

6. The apparatus of claim 1 wherein the base and the cylinder are constructed from titanium alloy.

7. The apparatus of claim 6 wherein the the base and the cylinder are constructed from Ti-6Al-4V or Ti-6Al-5V or another titanium alloy containing no high atomic number elements.

8. A method for performing a proton treatment, the method comprising aiming a proton beam at an aperture provided in a base, aligning a selected one of at least one opening provided in a cylinder movably coupled to the base with the aperture to permit irradiating tissue with the proton beam after passage of the beam through the aperture and the selected opening.

9. The method of claim 8 wherein aligning a selected one of at least one opening with the aperture comprises aligning a selected one of a plurality of openings of different sizes with the aperture.

10. The method of claim 8 wherein aligning a selected one of at least one opening with the aperture comprises aligning a selected one of a plurality of

divergent or non-divergent openings of different shapes with the aperture.

11. The method of claim 10 wherein aligning a selected one of a plurality of openings of different shapes with the aperture comprises aligning a selected one of a plurality of openings selected from circular openings and elliptical openings with the aperture.

12. The method of claim 8 wherein performing a proton treatment comprises performing at least one of proton stereotactic radiosurgery (pSRS) and proton hypofractionated therapy (pHT).

13. The method of claim 8 wherein aiming a proton beam at an aperture provided in a base and aligning a selected one of at least one divergent or non-divergent opening provided in a cylinder with the aperture comprises aiming a proton beam at an aperture provided in a base constructed from titanium alloy and aligning a selected one of at least one opening provided in a cylinder constructed from titanium alloy with the aperture.

14. The method of claim 13 wherein aiming a proton beam at an aperture provided in a base and aligning a selected one of at least one opening provided in a cylinder with the aperture comprises aiming a proton beam at an aperture provided in a base constructed from Ti-6Al-4V or Ti-6Al-5V or another titanium alloy containing no high atomic number elements and aligning a selected one of at least one opening provided in a cylinder constructed from Ti-6Al-4V or Ti-6Al-5V or another titanium alloy containing no high atomic number elements with the aperture.

15. Apparatus for performing at least one of proton stereotactic radiosurgery (pSRS) and proton hypofractionated therapy (pHT), the apparatus comprising a base, a cylinder movably coupled to the base, the base defining an aperture at which a proton beam is aimed, the cylinder defining a plurality of openings of at least one of different sizes and different shapes, the openings being oriented in the cylinder so that a selected one of the openings can be aligned generally with the aperture to permit irradiating tissue with the proton beam after passage of the beam through the aperture and the selected opening.

16. The apparatus of claim 15 wherein the plurality of openings are of different sizes.

17. The apparatus of claim 15 wherein the plurality of openings are of different shapes.

18. The apparatus of claim 17 wherein the plurality of openings are selected from circular openings and elliptical divergent or non-divergent openings.

19. The apparatus of claim 15 for performing pSRS wherein the pSRS is image-guided stereotactic body radiation therapy (SBRT).

20. The apparatus of claim 15 wherein the base and the cylinder are constructed from titanium alloy.

21. The apparatus of claim 20 wherein the base and the cylinder are constructed from Ti-6Al-4V or Ti-6Al-5V or another titanium alloy containing no high atomic number elements.

22. A method for performing at least one of proton stereotactic radiosurgery (pSRS) and proton hypofractionated therapy (pHT), the method comprising aiming a proton beam at an aperture provided in a base, aligning a selected one of a plurality of openings provided in a cylinder movably coupled to the base with the aperture to permit irradiating tissue with the proton beam after passage of the beam through the aperture and the selected opening.

23. The method of claim 22 wherein aligning a selected one of a plurality of openings with the aperture comprises aligning a selected one of a plurality of openings of different sizes with the aperture.

24. The method of claim 22 wherein aligning a selected one of a plurality of openings with the aperture comprises aligning a selected one of a plurality of openings of different shapes with the aperture.

25. The method of claim 24 wherein aligning a selected one of a plurality of openings of different shapes with the aperture comprises aligning a selected one of a plurality of openings selected from circular openings and elliptical openings with the aperture.

26. The method of claim 22 wherein performing at least one of pSRS and pHT comprises performing image-guided stereotactic body radiation therapy (SBRT).

27. The method of claim 22 wherein aiming a proton beam at an

aperture provided in a base and aligning a selected one of a plurality of openings provided in a cylinder with the aperture comprises aiming a proton beam at an aperture provided in a base constructed from titanium alloy and aligning a selected one of a plurality of openings provided in a cylinder constructed from titanium alloy with the aperture.

28. The method of claim 27 wherein aiming a proton beam at an aperture provided in a base and aligning a selected one of a plurality of openings provided in a cylinder with the aperture comprises aiming a proton beam at an aperture provided in a base constructed from Ti-6Al-4V or Ti-6Al-5V or another titanium alloy containing no high atomic number elements and aligning a selected one of a plurality of openings provided in a cylinder constructed from Ti-6Al-4V or Ti-6Al-5V or another titanium alloy containing no high atomic number elements with the aperture.

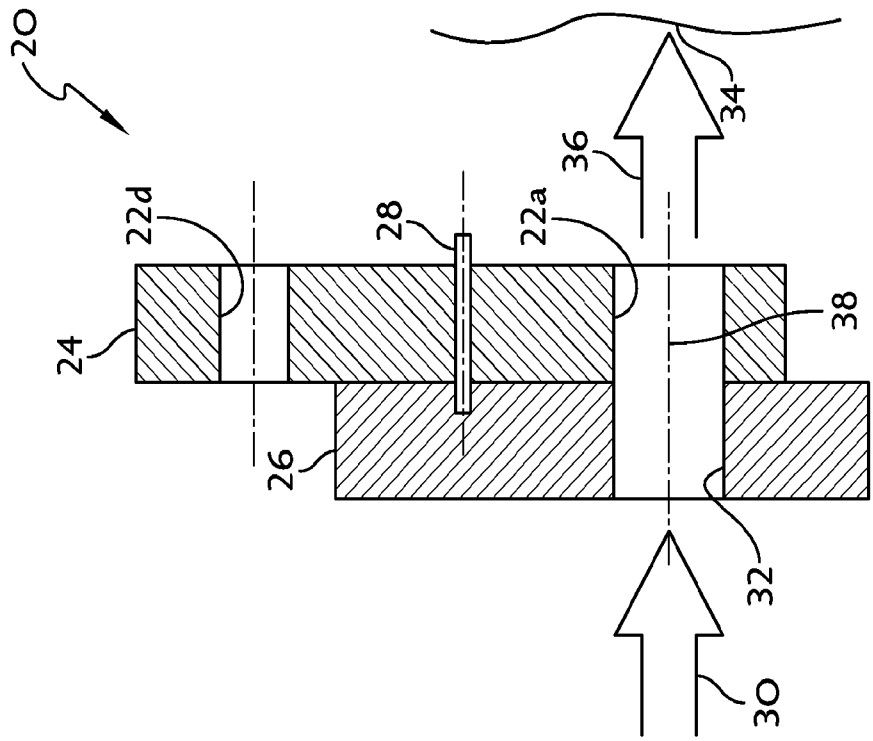


FIG. 1A

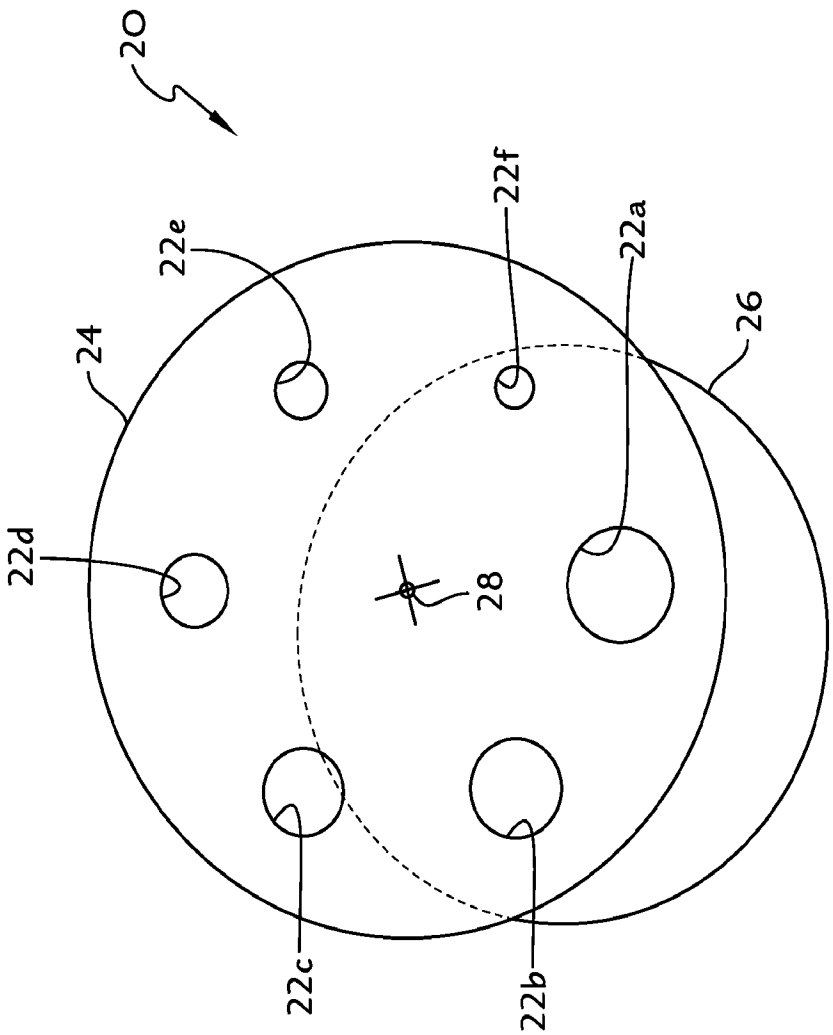


FIG. 1B

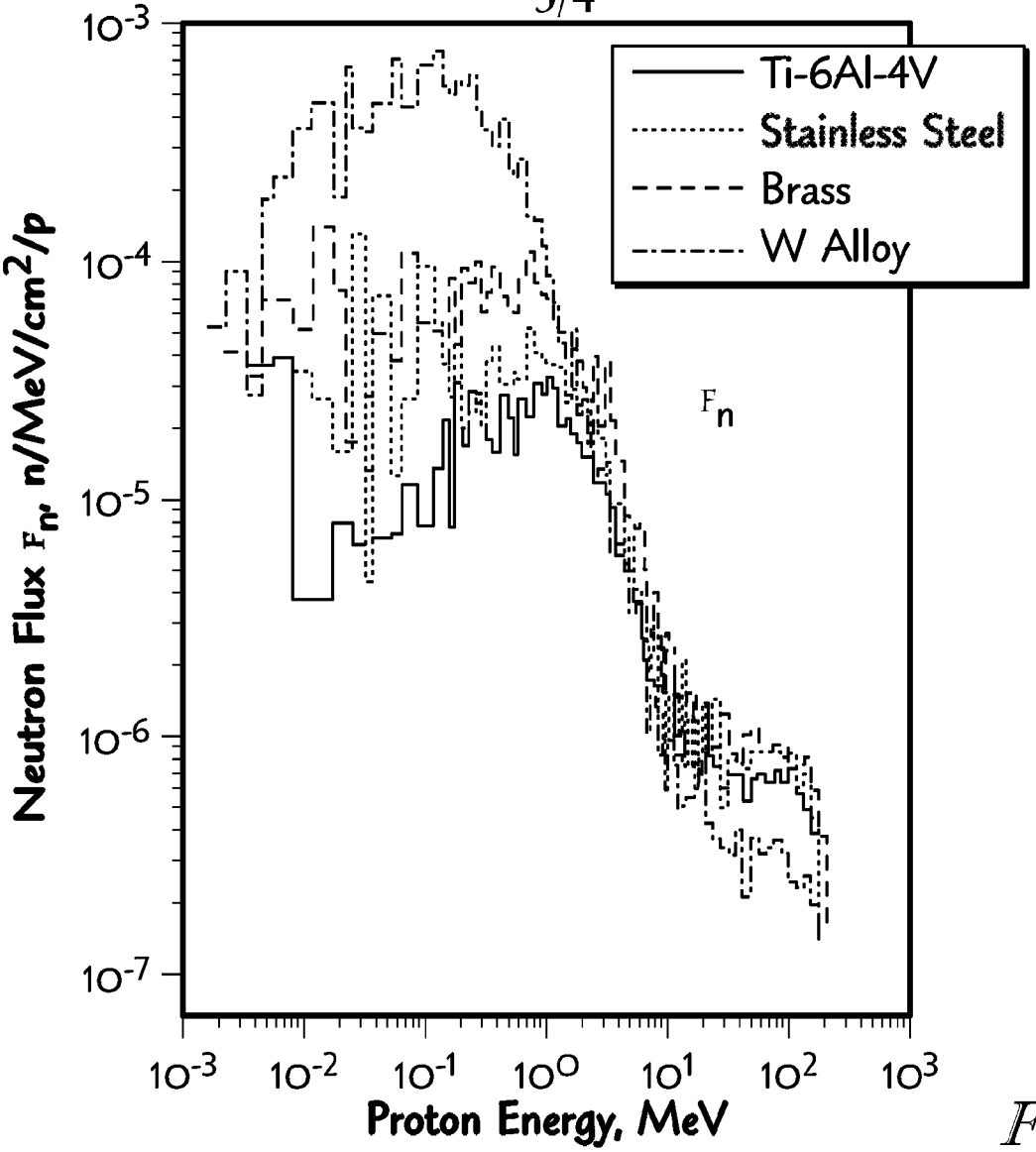

Ti-6Al-4V
Stainless Steel
Brass
W Alloy
F_n
Neutron Flux F_n, n/MeV/cm^2/p
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
Proton Energy, MeV

FIG. 2A

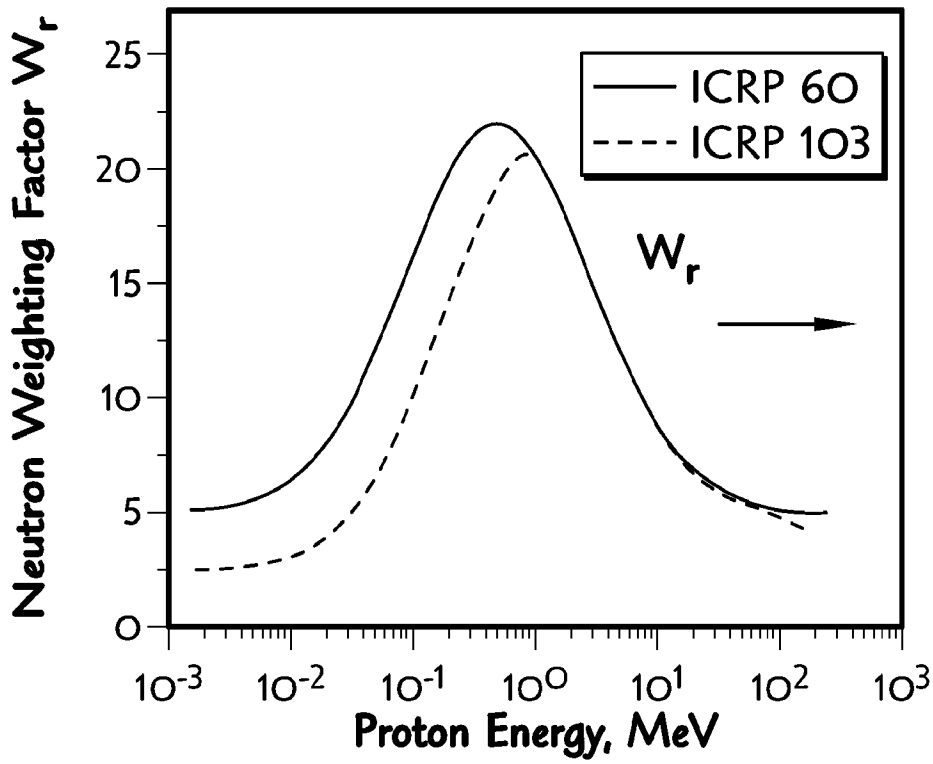

ICRP 60
ICRP 103
W_r
Neutron Weighting Factor W_r
25
20
15
10
5
0
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
Proton Energy, MeV

FIG. 2B

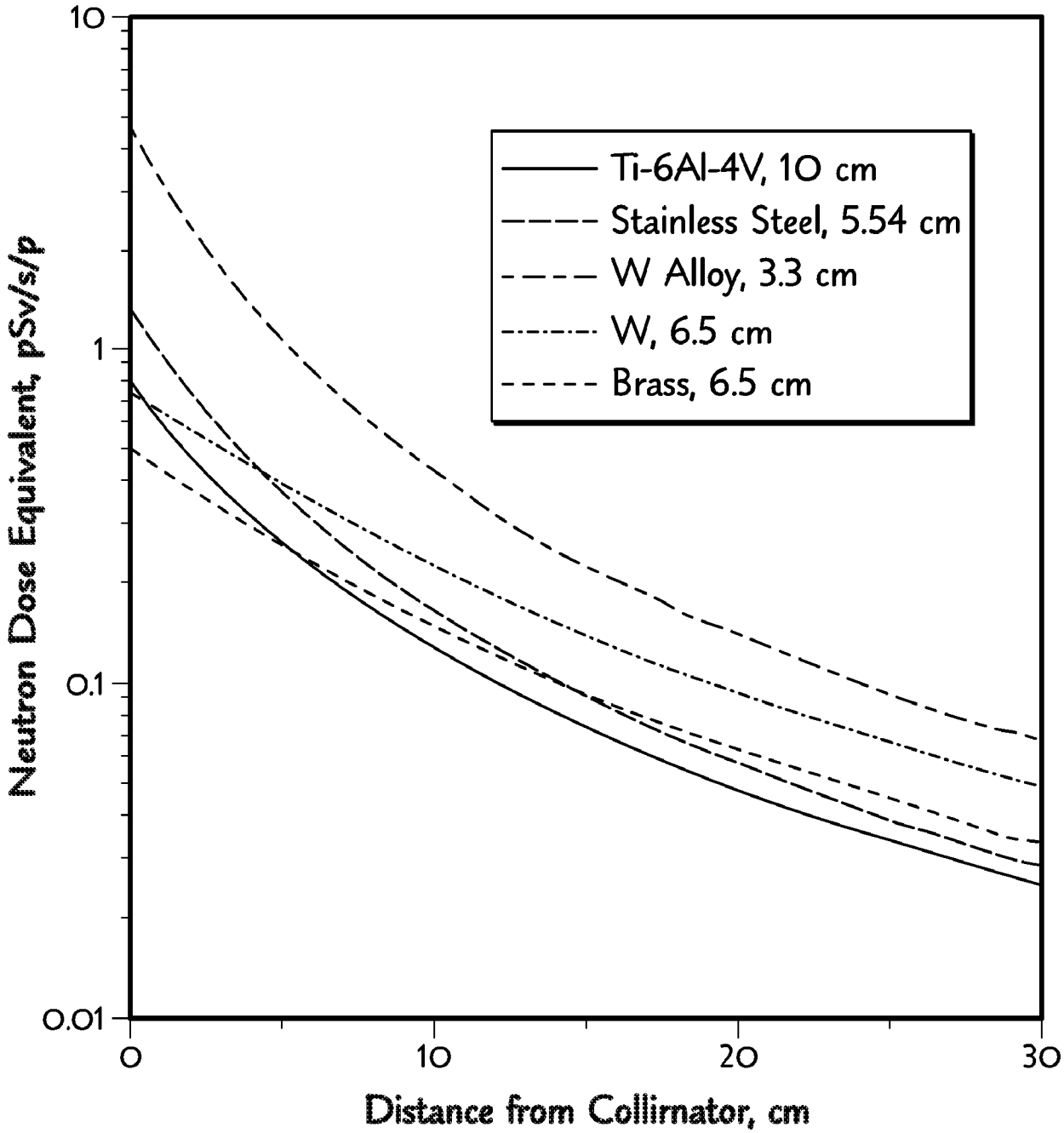

10
1
0.1
0.01
0
10
20
30
Neutron Dose Equivalent, pSv/s/p
Distance from Collimator, cm
Ti-6Al-4V, 10 cm
Stainless Steel, 5.54 cm
W Alloy, 3.3 cm
W, 6.5 cm
Brass, 6.5 cm

FIG. 3

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US13/38995

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G21K 1/02, 1/04 (2013.01)
USPC - 378/65, 147, 149
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) Classification(s): G21K 1/02, 1/04 (2013.01)
USPC Classification(s): 378/65, 119, 125, 138, 147, 149-153; 250/492.1; 600/1

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
MicroPatent (US-G, US-A, EP-A, EP-B, WO, JP-bib, DE-C,B, DE-A, DE-T, DE-U, GB-A, FR-A); DialogPro (Derwent, INSPEC, NTIS, PASCAL, Current Contents Search, Dissertation Abstracts Online, Inside Conferences); IP.com; IEEE: Search terms: collimator, proton, surgery, treatment

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2012/0039444 A1 (BAIC, D. et al.) February 16, 2012, Figures 1, 2, 4, 11-69, paragraphs [0024], [0027], [0038], [0039]	1,2, 8, 9 ---------- 3-7, 10-28
Y	US 5,216,255 A (WEIDLICH, G.) June 1, 1993, column 2, lines 45-60, column 5, lines 15-45	3, 4, 10, 11, 17, 18, 24, 25
Y	EP 0 395 711 B1 (BOVA, F. et al.) March 8, 1995, column 1, lines 1-15, column 2, lines 2-10, column 2, lines 55, 57, column 3, lines 1-15	5, 12, 15-28
Y	US 7,783,010 B2 (CLAYTON, J.) August 24, 2010, Figure 2, column 4, lines 30-40, Table I, column 8, lines 55-60, column 10, lines 25-35	6, 7, 13, 14, 20, 21, 27, 28
Y	US 2011/0257457 A1 (GRAF, A. et al.) October 20, 2011, paragraphs [0002], [0024], [0026]	19, 26

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 August 2013 (26/08.2013)	06 SEP 2013
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Shane Thomas PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774