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**Do all the linear accelerators comply with the ICRU 91's constraints for stereotactic body radiation therapy treatments?**

**Tous les accélérateurs répondent t'ils aux contraintes du rapport 91 de l'ICRU pour les traitements en conditions stéréotaxiques des tumeurs extracrâniennes?**

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## **Résumé**

Pour assurer la qualité et la sécurité des radiothérapies en conditions stéréotaxiques (SRT), la Commission internationale sur les unités de rayonnement (ICRU) propose des recommandations dans son rapport 91, axé sur les traitements hypofractionnés par faisceaux de photons de petites dimensions. Cette revue propose de répondre à la question de l'éligibilité des accélérateurs disponibles commercialement, à la réalisation de radiothérapies en conditions stéréotaxiques extracrâniennes (SBRT) par rapport aux recommandations de ce rapport. Ce rapport préconise : l'utilisation d'un faisceau de photons de haute intensité, un système d'imagerie intégré gérant les mouvements entre et pendant les fractions une précision mécanique de l'accélérateur linéaire élevée, un collimateur performant avec une dimension de lames réduite une table permettant de corriger les mouvements en six dimensions. La plupart des accélérateurs linéaires actuels répondent à ces recommandations, comme ceux dédiés à la radiothérapie stéréotaxique ou ceux classiques modernes équipés d'imagerie par tomographie à faisceau conique tridimensionnelle et d'imagerie stéréoscopique bidimensionnelle. Les accélérateurs linéaires à «tunnel» commercialement disponibles ont certaines limites : ils n'offrent que des traitements coplanaires, les mouvements de la table sont limités aux translations et certains ont un système d'imagerie peu adapté à la technique et aucune solution pour gérer les mouvements pendant les fractions. Cependant, pour la radiothérapie en conditions stéréotaxiques extracrâniennes, les irradiations non coplanaires ne sont pas obligatoires, contrairement à celle intracrânienne. De plus, sur les «IRM-linacs», les rotations des patients peuvent être corrigées grâce à la radiothérapie adaptative en temps réel. Enfin, des améliorations importantes sont attendues à court terme pour compenser les faiblesses des modèles actuels.

**Mots clés:** SBRT, ICRU 91

## **Abstract**

Recent technological developments in linear accelerators (linacs) and their imaging systems have made it possible to routinely perform stereotactic radiotherapy (SRT) treatments. To ensure the security and quality of the treatments, national and international recommendations have been written. This review focuses on the recommendations of the report 91 of the International Commission on Radiation Units (ICRU) on stereotactic treatments with small photon beams and proposes to answer the question of the eligibility of the commercially available accelerators for the treatment of extra-cranial SRT (SBRT). The ICRU 91 report outlines important features needed to respect the constraints, which are high intensity photon beam, integrated image-guidance, high mechanical accuracy of the linac, multileaf collimator with reduced leaf width, bundled motion management and bundled 6 Dimensional “robotic” couch tabletop. Most of the contemporary linacs meet these recommendations, in particular, stereotactic dedicated linacs, or modern gantry-based linacs equipped with 3 dimensional cone-beam CT imaging and 2D-stereoscopic planar imaging. Commercially available ring-based linacs have some limitations: they offer only coplanar treatments, and couch movements are limited to translations and, some have limited imaging equipment and no ability to manage intrafraction motion. However, for performing SBRT, non-coplanar irradiations are not mandatory, contrarily to intracranial stereotactic irradiations. Furthermore, patients’ rotations can be corrected, thanks to real-time adaptive radiotherapy available on MRI-linacs. Finally, significant improvements are expected in the short term to compensate the weaknesses of the current devices.

**Keywords:** SBRT, ICRU 91

## **1. Introduction**

Stereotactic radiotherapy (SRT) is based on the use of stereotactic localization techniques combined with the delivery of multiple small photon beams in one or few high-dose fractions. Originally, the SRT only concerned small brain lesions of a few mm<sup>3</sup>. Accurate positioning was ensured by an invasive frame attached to the patient's skull, allowing for precise tracking of the lesion in the three spatial dimensions and thus ensuring the delivery of the dose with millimeter precision [1]. This technique consisted in delivering large doses in either one fraction, called radiosurgery (SRS), or few fractions, with treatment ballistics using non-coplanar small conical photon beams. Initially, this type of treatment was reserved for so-called dedicated machines such as the Gamma Knife® (Elekta, Sweden) for intracranial irradiations only, or could be performed on standard accelerators equipped with additional systems such as circular collimators, or micro-multileaf collimators (MLC) with leaves as narrow as 3mm [2-3]. With the recent improvements made in linac technologies and in their imaging devices, SRT is now extended to extra-cranial treatments (SBRT).

The new generation linacs have an increased mechanical precision which concerns the isocentric rotation of the arm, the MLC (leaf thickness, transmission, leaves' speed, and positioning accuracy), and the positioning accuracy of the table, which sometimes, allows a repositioning in the 6 dimensional coordinates system. On the other hand, high dose rate treatments (800-2400 MU/min) are now possible, with the removal of the equalizing cone of the accelerator head, allowing delivering the treatment in a reduced time. Thus, with the development of the equipment and practices, the SRT would tend to be trivialized even though it requires the application of strict rules and an appropriate organization, to ensure the quality of the treatment and patients' safety. To start this technique, there are national and international recommendations to build on. Among the most important, at the national level, are the recent report of Working Group No. 35 of the French Society of Medical Physics (SFPM) [4], and at the international level, the report 101 of the American Association of Physicists in Medicine (AAPM) (2010) [5], the International Atomic Energy Agency (IAEA) report TRS 483 (2017) on dosimetry of small photon beams [6], and the International

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Commission on Radiation Units (ICRU) 91's report (2017) [7]. In particular, the main mission of the ICRU is to develop and implement a coherent system of quantities and units of measurement for ionizing radiation which can be accepted internationally. The ICRU 91 report is based on concepts and definitions previously introduced in ICRU Reports 50, 62 and 83 [8-10]. It is an adaptation of the ICRU 83 report on IMRT, for small fields. The ICRU 91 report sets out the fundamental principles on small field dosimetry, computational algorithms, commissioning and quality assurance of treatment devices, and emphasizes the role of imaging during treatment. In accordance with previous reports, it also makes recommendations in terms of target volumes definitions, and in terms of prescribing and dose reporting for the clinical cases eligible for SRT. This review proposes to summarize the main recommendations of the ICRU 91 in terms of radiation therapy treatment devices and to answer the question of the eligibility of the accelerators available commercially for the treatment of extra-cranial SRT.

## **2. ICRU 91's recommendations for linacs technologies**

Today's SRT treatments are delivered with megavoltage beams –either gamma rays from  $^{60}\text{Co}$  sources or X-rays from linacs. They can be split in different categories: - *SRT devices*, which means that they are only dedicated to SRS or SBRT, *gantry-based isocentric linacs* and *ring-based linacs*. Whereas, by definition, SRT dedicated devices are likely to respond to the constraints of the ICRU 91, the report outlines important features needed for other linacs to respect their constraints [7]. These are:

- High intensity photon beams (often achieved through reduced beam flattening)
- Integrated image-guidance system
- Integrated MLC with reduced leaf width or add-on conical collimators
- Improved precision of the mechanical isocenter
- Bundled motion management systems
- Bundled radiosurgery planning software
- Bundled 6D “robotic” couch tabletop

On the basis of these specifications, the technical characteristics of the main commercially available devices are going to be described and, for each technology, the question of the ability to comply with the recommendations of the ICRU 91's report will be discussed. Note that we will only focus on the devices able to perform SBRT.

### **3. Dedicated device**

There are two dedicated devices to perform SBRT, which are the CyberKnife® (Accuray, USA), and the Gamma Knife® (Elekta, Sweden), which in its last version (Icon®), can treat cervical lesions down to C3 vertebrae [11]. However, because of the limited number of indications treated by this latter device, we will only focus on the Cyberknife® technology in this part.

The CyberKnife® (Accuray, USA) consists of a 6 MV linear accelerator mounted on an industrial robotic arm [12]. The treatment is delivered using either fixed conical collimators, a variable collimator called IRIS™ (two superposed banks of six tungsten segments) or a MLC called InCise®, available in the last generation system (CyberKnife® Model M6). The robotic table (RoboCouch) enables angular corrections up to 5 degrees, and have an accuracy of 0.1 mm in the positioning. The main strength of this technology is the ability to treat patients with multiple non-coplanar beams, thus resulting in very steep dose gradients, and optimal dose conformation to the target compared to other technologies. Furthermore, this system is the first proposing real-time tracking of the tumor. The imaging guidance relies on stereoscopic planar imaging before and during treatment. Respiratory motion management is based on predictive tumor tracking through correlation of external chest wall markers and either implanted fiducial markers or direct recognition of the tumor on planar images. Thanks to the tracking modality, minimalist immobilization devices can be used which maximizes the patients' comfort. Different studies have reported a sub-millimetric global precision of the system [13]. Thus, this device clearly answers to the ICRU 91's constraints for SBRT treatments, even if some aspects could be improved. For example, soft tissue based positioning is only possible via the surgical implantation of fiducial markers. Treatment time is generally longer than with gantry-based linacs but can be considerably reduced with the use of the MLC instead of cones [14]. There is also no 3D-imaging modality for performing adaptive treatment.

#### **4. Gantry-based isocentric linear accelerators**

Typical examples of dedicated gantry-based linacs mentioned in the ICRU 91 report are the Varian Novalis® TX (with ExacTrac®, Brainlab), Varian TrueBeam STX® and EDGE®, Elekta Axesse® and Versa HD® [15-16]. All the linacs deliver either filtered or flattening-filter free (FFF) beams (allowing to achieve dose rates up to 2400 MU/min), except for older linacs such as the Novalis TX, which do not have FFF beams. They are all equipped with MLCs having leaves width  $\leq 5$ mm, leaf transmission  $< 2\%$  and leaf leakage  $< 3\%$ . Leaf inter-digitation is also possible, which is an advantage for treating multiple targets in the same treatment session. Another important feature is the positioning accuracy of the leaves ( $< 1$ mm). Besides portal imaging, to answer to the ICRU 91's constraints, all gantry based dedicated linacs must be at least equipped with on-board cone-beam CT (CBCT) imaging.

Furthermore, 2D-kV stereoscopic planar imaging (ExacTrac®) is now available with all these devices and has two main advantages:

- to control intra-fraction motion, based on bone-registration, thus offering the possibility to treat patients with less rigid or non-personalized immobilization devices;
- to control the positioning of patients in case of non-coplanar irradiation at all tables angles.

In the case of SBRT, even if for now tracking is not available, linacs have an undeniable contribution to the management of mobile lesions, with the possibility of 4D imaging. The CBCT enables checking anatomical changes, and verify that the internal target volume encompasses all the positions of the macroscopic tumor during a respiratory cycle. Stereoscopic imaging, while useful, can either be replaced by rigid immobilization devices for controlling intra-fraction motion, different gating strategies, or surface imaging if non-coplanar beams are used, which is mandatory for SRS treatment, but not appears essential for SBRT. Finally end-to-end accuracy is sub-millimetric for all the above described devices, which is mandatory for performing SBRT. However, to ensure the long term accuracy and avoid drifts, these linacs require a specific quality assurance with strict tolerances, which are described elsewhere [4-5].

#### **5. Ring-based linacs**



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Different ring-based linacs are available: the TomoTherapy Hi-Art® system (Accuray), the current version being the Radixact™ system [17], the Halcyon® (Varian) [18], and two MRI-linacs: MRIdian (ViewRay, USA) [19] and Unity (Elekta) [20]. Another ring-based linac mentioned in the ICRU 91's report is the Vero system (Brainlab, Germany) which was discontinued in 2015. This latter system was manufactured to fulfill all the requirements for SBRT treatments. The MLC leaves-width is 5mm at the isocenter (maximum field size 15\*15 cm<sup>2</sup>). The couch can rotate ±60° for non-coplanar treatments or what is referred to as "dynamic wave" treatments where couch and gantry move synchronously to produce a unique non-coplanar beam path [21]. The couch can provide pitch and tilt corrections while rotational corrections are possible through the main linac ring. In addition to performing treatment ballistic, the system responds to all the criteria in terms of imaging equipment since it has two coplanar flat panels imagers able to perform stereoscopy, fluoroscopy and CBCT images.

Contrary to all other ring-based systems, the Tomotherapy employs a synchronously rotating gantry and a translating couch [22]. The MLC is composed of 64 interspersed leaves measuring 6.25mm wide in the transverse direction. During treatment small beamlets are delivered through a binary MLC (leaves' position "open" or "closed"). In the superior-inferior direction, the beam is collimated by a jaw which aperture is fixed during treatment. Field defined by jaws can be set to 1, 2.5 or 5 cm during treatment. In the superior-inferior direction, the total treatment length can be up to 135 cm, with no beam junction. The modulation degree of the beam can also be controlled by adjusting the pitch of the table. Although highly conformal plans can be obtained, the Tomotherapy version HD® or HDA® suffers from a lack of imaging equipment to completely respond to the ICRU 91's constraints. Pretreatment positioning is performed with MVCT imaging using a reduced energy beam from the therapy linac. The poor image's contrast does not enable soft-tissue based positioning without the use of fiducial markers. Then, because the table does not allow correction of rotations, only the translations and the roll of the patient (with the gantry angle position adjustment) can be corrected. Because of the helical mode, the delivery of high doses per fraction takes more time than with other dedicated linacs, with no possibility to control intra-fraction motion. Finally, only coplanar beams can be performed.

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However, some improvements are expected in the latest commercial version called Radixact™. First, the dose rate is higher than for the Tomotherapy HD® (1000 vs 850 cGy/min), thus possibly reducing the treatment time [23]. Then, it is also equipped with a 1 dimension kV X-ray (mounted 90° offset from the MV treatment beam), and an optical camera system is mounted above the foot of the couch. This experimental system tracks target motion by acquiring an x-ray image every few seconds during gantry rotation. These improvements would enable managing respiratory (periodic) motion as well as other intra-fraction motion. In particular, respiratory motion correction would be performed by continuously updating jaw positions and MLC leaf patterns to reshape (effectively re-pointing) the treatment beam to follow the 3D target motion [17]. Hence, the new system would comply with ICRU 91's recommendations for SBRT, except for the corrections of rotations and for non-coplanar irradiations, but the implementation of a kV-CBCT imaging device would inevitably bring additional value to the system.

Another ring-based linac recently made available on the market is the Halcyon (Varian). Similarly to the Tomotherapy system, it consists of a 6 MV FFF linac mounted on an O-ring gantry [14]. The system has no backup jaws, only a MLC which is composed of two staggered layers of 28 leaf pairs, with a projected leaf width of 10 mm. Because of this alignment, the theoretical modulation resolution is comparable to a 5mm leaf width MLC. Two imaging modalities were available on the first commercialized version of the Halcyon: orthogonal anterior-posterior/lateral pairs (MV-MV) and MV-CBCT. However, in the last version, they have added a kV-CBCT device, and an integrated couch-mounted camera, to control the patient's movements in the ring. Originally this system was built to increase the time-efficiency of volumetric modulated arc therapy compared to gantry based linacs, thanks to the fast rotating O-ring, without decreasing the plan quality. With this system, the image acquisition and plan delivery time are effectively reduced compared to conventional linacs. Hence, the system responds to all the criteria of the ICRU 91 for SBRT treatments, except for the corrections of rotations and for non-coplanar irradiations.

The last O-ring technology is the MR-linac. The first commercially available magnetic resonance imaging (MRI)-guided radiation therapy (RT) device was the ViewRay® system (ViewRay Inc., USA). It

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consisted of a 0.35-Tesla split-bore design MRI scanner with three Cobalt-60 sources separated by 120 degrees mounted on a ring gantry, each head equipped with independent doubly focused multileaf collimators, with 1.05 cm leaf thickness [19]. The real-time MRI capabilities of the system allowed for soft tissue imaging throughout radiation therapy delivery. The treatment was performed using “step-and-shoot” intensity modulated radiation therapy (IMRT) technique. An on-couch adaptive RT treatment-planning system allowed for rapid adaptive planning and beam delivery control based on the visualization of soft tissues. Because of the poor characteristics of the Co-60 source beams and the large MLC leaf width, this system has been recently replaced by the MRIdian Linac (ViewRay Inc.). This device can generate 6 MV FFF beams with higher penetrability and smaller penumbræ than those of the ViewRay® system. Similarly to the ViewRay system, the MRIdian Linac system is equipped with a 0.35 Tesla MRI scanner thus enabling acquiring 3D volumetric and 2D planar MR images. The treatment beam is perpendicular to the magnetic field and never crosses the electromagnet, the latter being divided in 2 parts, on both sides of the linac [24]. In addition, it is equipped with a double-stacked and double-focused MLC that can project field sizes of 0.2 cm × 0.4 cm to 27.4 cm × 24.1 cm at the isocenter located 90 cm from the source. Treatments are still delivered using IMRT “step-and-shot” technique.

Its competitor on the market is the Elekta Unity® MRI linac. This device delivers 7 MV FFF beams and has a source-axis distance of 143.5cm. It is combined with a 1.5 Tesla MRI (Philips, The Netherlands). Contrarily to the MRIdian system, a ring gap has been created within the magnet so that radiation beam passes in between [20]. The MLC has 160 leaves, with a projected leaf width of 7mm at 143.5 cm. The maximum beam width is 22cm x 57.1cm<sup>2</sup>. This system is also equipped with on-board portal imaging. Similarly to the MRIdian system, Unity has an integrated workflow for performing online adaptive radiotherapy, and real-time MRI imaging can be done. In addition, treatments are also delivered using IMRT “step-and-shot” technique. Regarding the ability to respond the ICRU 91’s constraints for performing SBRT, at first sight, there are some technological limitations which are:

- The table of both systems only support longitudinal motion for patient setup. Thus, there is no ability to adjust a patient position for an existing treatment plan. Hence, online

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adaptation of the treatment plan is necessary. There is also no possibility of performing non coplanar irradiations.

- From a ballistic point of view, the treatment plan using step-and-shoot IMRT is likely to be of lowest quality in terms of dose distribution than VMAT plan.
- The leaf width, over 5mm, may also be a handicap for treating very small targets.

However, the strengths of both technologies rely on imaging. Current image guided radiotherapy techniques using on-board CBCT are already very effective, but are limited due to the reduced soft-tissue contrast. Very often, it is difficult to discriminate tumor from soft tissues, with the consequence that dose escalation strategies are difficult to implement. Such treatment, if implemented using low contrast imaging during treatment, would require the use of important treatment margins. Hence, the difference in plan quality between VMAT and IMRT would be counterbalanced by the margin reduction capability, using MR imaging. Both devices provides direct visualization of the tumor and its surrounding tissue anatomy and real-time imaging, which constitute a real advantage for performing SBRT treatments, in particular, for the treatment of specific organs affected by motions [25].

Finally, only respiratory gating techniques are used on commercially available linacs to manage tumor motion, but further works are in progress to implement MLC-tracking [26]. Hence, there is a large potential to increase further the accuracy in the targeting of tumor, and reducing dose to the organs at risk with these systems.

## **6. Discussion**

We have reviewed, in this article, the main technologies available on the market for performing SRT. As mentioned in the ICRU91's report, the concept of SRT started with the need to deliver a high dose in a single fraction to intracranial targets. This was both biologically and clinically feasible because of the limited treated volumes and lack of organ motion. The technique was subsequently used for extracranial treatments, thus covering larger volumes and moving targets and opening the door to the use of non-dedicated linacs, to perform such treatments. Dose delivery has also evolved since SRS was originally performed with multiple non-coplanar and/or non isocentric small beams, and

now, IMRT and VMAT techniques are widely used. Initially, VMAT and IMRT techniques were designed to produce dose homogeneity similarly to conventional radiotherapy within the tumor but superior conformity, as recommended in the ICRU83's report (ICRU 2010). With the principle of "inverse treatment planning", different pattern of doses delivery in the tumor can be achieved, including heterogeneous dose profiles, similar to those obtained with dedicated SRT devices or with three-dimensional conformal radiotherapy. To respond to the ICRU 91's constraints for SBRT treatments, high degree of conformation of the prescribed dose to the target volume, with steep dose gradients must be achieved, which is difficult with three-dimensional conformal radiotherapy. Hence, all gantry or O-ring based linacs respond, in part, to the ICRU 91's constraints for SBRT treatment, as long as IMRT or VMAT is available. The availability of these techniques is mandatory but insufficient to fill all the constraints, as the performances of the MLC (leaf width, positioning accuracy, leaf leakage, leaf speed) and the geometric accuracy of the linac have to be considered. In addition, all the above described systems have an inframillimetric global accuracy in dose delivery. Having the possibility to treat using high dose rate photon beams has also been highlighted in the report. All above mentioned linacs have FFF beams, either by default or in option. Which makes the difference between devices is the type of integrated image-guidance system. Linacs having only 2D-MV or 3D-MVCT imaging such as the Tomotherapy system, do not respond to the ICRU's constraints in their current version for performing SBRT in moving targets. Other limitations of these devices are due to the couch design which does not enable correcting the patient' shifts in the 6 directions of the space. This is also a limitation of the MRI-linac, but this is compensated by real-time imaging and adaptive planning. Lastly, most of O-ring linacs do not enable non-coplanar irradiations which is clearly a handicap for performing SRS, but is not fundamental for SBRT treatments.

## **7. Conclusion**

In conclusion, most of the contemporary linacs fulfill the recommendations of the ICRU 91 for SBRT treatment. For others, significant improvements are expected in the short term, to compensate the weaknesses of the current models, which mainly rely on the imaging equipment and ability to manage intrafraction motion. Modern planning system combined with modern gantry-based linac

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can lead to SBRT treatment quality close to the “gold standard” SBRT delivered with the Cyberknife.

Commercially available ring-based linacs provide high treatment plan quality, but offer only coplanar treatments, and couch movements are limited to translations. In SBRT, non-coplanar irradiations are not mandatory, contrarily to SRS treatments. Furthermore, patients' rotations can be corrected thanks to real-time adaptive radiotherapy, available on MRI-linacs. Finally, the treatment device is only one part of the workflow. A high quality SBRT treatment requires a specific quality assurance program, a performing treatment planning system, with accurate dose algorithm in presence of heterogeneities, and a consistent methodology for the prescribing, reporting, and recording of the dose volume metrics for SBRT.

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**Conflicts of interest:** None

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