

Fontenay-aux-Roses, 27 August 2018

To the Chairman of the Nuclear Safety Authority (ASN)

**Advice IRSN/2018-00232**

**Re:** Request for a study on the implementation of linear accelerators coupled with a nuclear magnetic resonance imaging system in radiotherapy (MR-linacs)  
**Ref.** Letter CODEP-DIS-2017 No. 027287 of 18/07/2017

In the letter referred to above, you asked IRSN to conduct a study on the implementation of linear accelerators coupled with a nuclear magnetic resonance imaging system in radiotherapy, referred to hereinafter as MR-linacs. The aim was to establish the state of the art for this technology and to identify any points requiring vigilance with this type of system. In particular, the study should look at the impact of the presence of a magnetic field on the operation of a radiotherapy department (other accelerators and work organisation), management of the dose delivered to the patient, including quality control of equipment, and specific issues related to patient care.

You requested that IRSN's analysis use the expertise of the French Medical Physics Society, SFPM (Société Française de Physique Médicale). A working group was set up of five medical physics experts from SFPM, appointed by the society, and one medical radiation protection expert from IRSN, leading the group.

From this analysis, I list the following main observations and the points requiring vigilance.

The specific value of an MR-linac is that it can deliver image-guided radiation therapy (IGRT) using MRI images that offer much better contrast than CT scanner images, especially for soft tissue.

On-board MRI imaging enables:

- the patient to be repositioned at the start of each session;
- the use of adaptive radiation therapy at each session, i.e. account to be taken of anatomical changes from one session to another and optimisation of the irradiation parameters before each session if necessary;
- account to be taken of target volume movement during a session (gating method).

This imaging method avoids additional exposure of the patient to ionising radiation during control imaging, which is currently done using devices that emit X-rays.

There are currently two MR-linac systems that have obtained CE marking and are on the market or about to come on the market. Both systems can currently be used to deliver treatments using the intensity-modulated radiotherapy (IMRT) technique in 'step and shoot' mode and to treat patients with small fields (of less than 1 cm x 1 cm).

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The characteristics of both MR-linac systems are as follows:

**MRIdian system (ViewRay, USA):**

- the accelerator's nominal energy is 6 MV, and it is flattening filter free (FFF), with a maximum dose of 6 Gy/minute at the isocentre (90 cm from the source);
- the MRI has a wide bore (70 cm) with a magnetic field ( $B_0$ ) of 0.345 teslas (T);
- the radiation beam is perpendicular to the magnetic field and does not cross the electromagnet;
- the system is supplied with a list of MRI-compatible (and CT-compatible) immobilization devices marketed by third parties.

**Unity system (Elekta, Sweden):**

- the accelerator's nominal energy is 7MV, and it is flattening filter free (FFF), with a maximum dose of 7 Gy/minute at the isocentre (143.5 cm from the source);
- the MRI (Philips) has a wide bore (70 cm) with a magnetic field ( $B_0$ ) of 1.5 T;
- the radiation beam is perpendicular to the magnetic field and it crosses the cryostat containing the electromagnet;
- the system has an on-board portal imaging device;
- the system is supplied with two complete sets of MRI-compatible and CT-compatible immobilization devices.

**1. Impact of the magnetic field on the operation of accelerators in neighbouring rooms**

The data available for the impact of a magnetic field on linacs is for Elekta linacs only. In the absence of any published data, the impact of the magnetic field on linacs made by other manufacturers (Varian, Accuray) cannot be analysed.

The main points requiring vigilance for both MR-linacs are as follows:

- the impact on the nearest linacs can be significant, even below the 0.05 mT line (the mean value of the Earth's magnetic field); in that case, it is necessary to adjust the settings of neighbouring linacs and to draw up procedures for handling quench situations (sudden loss of magnetic field);
- permanent magnetisation of the steel reinforcements of bunker walls is likely; the use of ferromagnetic materials in the walls is therefore to be avoided;
- measurements of magnetic leakage (fringe field) around the MR-linac should be made after installation;
- the manufacturer data for the maximum permissible magnetic field values for different equipment (linacs and other equipment) present inconsistencies between manufacturers and are incomplete; there are no data for HDR/PDR afterloaders, on-board imaging (X-ray generators), syringe pumps or infusion pumps.

## 2. Impact of MRI on dose management and quality of radiation therapy treatment

Generally, it appears that manufacturers' recommendations for equipment and measurement methods, and for quality assurance programmes, require critical analysis by users.

### 2.1. Impact of the quality of MRI images on treatment quality

The presence of artifacts in MRI can be detrimental to image quality (geometric distortions of up to 4 mm) and can cause uncertainties with regard to dose calculation and delivery (impact on organ contouring, patient repositioning, image registration for adaptive radiotherapy and gating).

To reduce these artifacts, it is necessary to optimise the acquisition parameters, the MRI sequence type and parameters, the choice and adjustment of the radiofrequency (RF) signal reception antenna, under the real conditions of use of the MRI, taking account of the patient immobilization devices and the antenna used. Because the optimisation techniques cannot completely eliminate all artifacts, their effects on image quality need to be quantified and taken into account when defining the organ margins.

The main points requiring vigilance are as follows:

- **an MRI image quality assurance programme based on national or international recommendations must be set up by the user centre, including the acceptance and commissioning tests. This programme must take into account specific issues associated with the use of MRI imaging on an MR-linac, such as the impact of the treatment beam on the characteristics of RF transmission and reception antennas, and therefore on image quality, the influence of accelerator arm rotation on image quality, and daily checks of the alignment of the MRI isocentre with that of the accelerator;**
- **end-to-end tests must be carried out during commissioning and periodically under treatment conditions (antennas, immobilization devices, sequences) to give an overall quantitative assessment of the image quality and its influence on the doses delivered to patients;**
- **the quality assurance programme must be set up and run by an experienced physicist with a good knowledge of the physics phenomena involved in MRI.**

### 2.2 Impact of the MRI magnetic field on measurements of the accelerator beam characteristics (commissioning and quality control)

The MRI's  $B_0$  magnetic field has an impact on the electrons set in motion by photon-matter interactions, and therefore also on the response of the detectors and on the distribution of the dose which has to be measured on commissioning of the accelerator so that it can be modelled in the treatment planning system (TPS).

#### *Choice of detectors and measurement procedures*

The physicist should know the influence of the  $B_0$  field and it must be taken into account. The measuring equipment must be tested and characterised before being used clinically, in particular:

- **MRI-compatible (non-magnetic) equipment must be used;** this is now offered by the various manufacturers; the user remains responsible for determining any correction factors as well as the uncertainties as regards dose measurement (see below);
- **the sensitive volume of the ionisation chambers should not be too large to adapt to the 'bell' shape of the FFF beams and limit the impact of the magnetic field on measurements by the chamber, due to the perturbation of electron trajectories in the air cavity;**

- **shielded diodes should be avoided**, especially for measurements during commissioning;
- **measurement of output factors in small fields requires care by the user**; there does not appear to be an ideal detector for this (diodes should be avoided);
- **radiochromic films are approved for absolute and relative dose measurements (in a field of 0.35 T or 1.5 T)**, provided that particular precautions are taken regarding the length of exposure of the films to the magnetic field.

The dose distribution in the medium (patient or phantom) is modified by the presence of the  $B_0$  magnetic field (lateral shift of profiles, reduction in depth of maximum dose, off-axis maximum dose, etc.). **The procedures used to measure beam characteristics at user centres must be adapted to take account of these effects.**

The acceptance and commissioning measurements of the two MR-linacs are performed by the manufacturers, with their own equipment. **The presence of a physicist from the user centre is necessary during these phases and the centre must repeat the tests using its own equipment and procedures**, and carry out further measurements in addition to those of the manufacturer.

#### *Accelerator quality control*

The types of tests and measurements to be carried out for commissioning and quality control of the accelerator for an MR-linac are not very different from those to be carried out for a normal accelerator. However, **some special tests are necessary, such as correspondence of the MRI and linac isocentres and, specifically for the MRIdian's gating mode, testing of system latency and accuracy of dose delivery.**

#### *Absolute dose measurement (beam calibration)*

Only water phantoms are suitable for carrying out absolute dose measurements on photon beams subject to a magnetic field.

The reference dosimetry formalism must be adapted by introducing a correction factor to take into account the effect of the  $B_0$  magnetic field. This correction factor depends on the ionisation chamber model, the intensity of  $B_0$  and the chamber orientation in relation to  $B_0$ ; it can be as much as a few percent for a 0.35 T or 1.5 T field. A formalism has been proposed as part of a European project involving a group of primary laboratories, including the Laboratoire National Henri Becquerel (LNHB). In this formalism, the reference is established in a cobalt-60 beam without a magnetic field and the correction factor is determined by calorimetry in water on an MR-linac system, for a given chamber. This formalism is likely to be used in future reference protocols. It should be noted that not all the results of the European project have yet been published and that the detectors cannot yet be calibrated on an MR-linac by the French primary laboratory (LNHB), because the reference dosimetry methods still need to be adapted.

**The first French centres to acquire MR-linac equipment should take inspiration from the calibration formalisms and correction factors published by pioneering centres in this technology. Eventually, the results of the work done by the primary laboratories, including those of the European project, must be taken into account.**

## 2.3 Expected performance of the TPS, commissioning and quality control

### *Taking account of the magnetic field*

The  $B_0$  magnetic field has a significant effect on patient dose mapping from 0.3 T. The differences in dose distribution are mainly at beam entry, at the interfaces of tissues of different densities and at beam exit.

The following points require vigilance when a TPS is used in combination with an MR-linac:

- **the TPS algorithm must take account of the effects of the magnetic field on the dose distribution in the medium**, including during optimisation processes with 'online' dose calculation for adaptive radiotherapy;
- **'online' calculations must be quick** (a few minutes) to avoid patient movement; suitable tools are Fast Monte-Carlo-type algorithms (used in the case of the TPSs of the two current MR-linacs) or deterministic algorithms based on solving the Boltzmann equation;
- **particular care must be taken by the user centre with the production of high precision stereotactic treatment plans (small fields)** partly because of the major impact of  $B_0$  on the dose distribution (impact on the percentage depth dose, the transverse profiles, the exit dose and influence of the differences in density of the tissues passed through), and partly because these treatments are associated with hypofractionation.

### *Taking account of elements specific to the MR-linac*

For MR-linacs, new elements must be taken into account in the TPS modelling: beam attenuation by the antennas, where relevant by the cryostat and by a table placed over the carbon table for indexing the immobilization devices. **It appears that users will need to verify using their own measurements the modelling of these elements by the TPS.**

### *Quality of image registration (deformable image registration)*

At present, MR-linac systems are not used to deliver treatments planned on the basis of MRI images alone. Dose calculations are made, as for normal linacs, on the basis of a CT image of the patient acquired before treatment. The initial CT image is registered over the MRI image acquired at the start of each treatment session, with propagation of the CT contours to the MRI. This daily registration means that the patient can be repositioned (so-called 'rigid' registration) and that adaptive radiation therapy can be given that takes account of anatomical changes from one session to another (so-called 'deformable' registration). **Daily registration appears to be an essential step in treatment using an MR-linac.**

The uncertainties associated with CT-MRI registration range from 2 mm for the cranium to 3 mm for the pelvis. The quality of registration will have an impact on patient positioning, the contouring precision of the target volumes and organs at risk, the quality of replanning and therefore the precision of dose delivery.

Regarding the TPS registration algorithms, the following points require vigilance:

- the deformable registration algorithms require parameter adjustments in order to improve their performance. **The information provided by the manufacturers of the two MR-linacs (ViewRay and Elekta) about their registration algorithms needs to be clarified and supplemented for users;**
- **the registration reports indicating the associated uncertainty are not supplied for the two MR-linacs; users must have access to these reports.**

### ***TPS commissioning and quality control***

For the two MR-linacs, the acceptance and commissioning measurements, and the modelling of data in the TPS are done by the manufacturer. It is necessary for the user to:

- **verify the data and the modelling by the TPS by doing measurements on phantoms and comparisons with calculations** following the protocols set out in the usual reference documents (not specific to the MR-linacs), and by conducting end-to-end tests under treatment conditions (antennas, immobilization devices, MRI sequences);
- **do measurements with phantoms presenting heterogeneities**, especially air cavities;
- **carry out a quantitative and qualitative evaluation of the deformable registration algorithm during commissioning**, with end-to-end tests (physical measurements with deformable phantoms or tests with computational phantoms), **and also during clinical use**, with predefined qualitative assessment criteria.

### **2.4 Quality control of the patient treatment plan**

For quality control of the patient treatment plan through measurement in a phantom (patient QC: end-to-end test), there are several MRI-compatible solutions currently on the market, about to reach the market or in development. Studies have been published on the performance and limitations, if any, of some of these. Users must take account of the results of these studies. In particular, given that MR-linacs use intensity-modulated radiotherapy (IMRT), the resolution of the detectors used must be appropriate.

### **2.5 Independent dose verification**

Quality control of the patient treatment plan through measurement in a phantom cannot be envisaged following replanning at every session (adaptive radiotherapy). Consequently, **the dose calculated by the TPS must be independently verified, either by doing an 'online' second check, or by in vivo dosimetry**. This verification must be quick to avoid patient movement.

#### ***Second calculation***

The MRIdian integrates a fast second calculation solution based on a Monte Carlo code taking into account the magnetic field; however, this tool uses the same beam and machine models as the TPS, which raises the question of the second calculation's independence.

The Unity does not come with second check software but Elekta says that it will rely on the solutions offered by other manufacturers. The second calculation solutions on the market today are based either on a 'convolution superposition'-type algorithm, which does not take account of the magnetic field, or on a Monte Carlo computation, but adaptation to the MR-linac systems still has to be verified.

#### ***In vivo dosimetry***

No in vivo dosimetry solutions are currently offered by the MR-linac manufacturers and no solutions are available from third party suppliers either. There are projects in existence looking at the use of a portal imaging device, particularly on the Unity, but there are major challenges to be overcome before a marketable solution will be available.

Other approaches could be envisaged, such as beam exit fluence measurements or the use of 'log files' (see Advice IRSN 2018-00146).

## 2.6 Applicability of current standards

It appears that:

- the ANSM decision of 27 July 2007 laying down the procedures for the external quality control of external radiation therapy installations is technically applicable to MR-linacs and must therefore be implemented in France;
- point 5.11 of the appendix to the ANSM decision of 27 July 2007 laying down the procedures for the internal quality control of external radiation therapy installations, on the quality control of TPSs, should be extended and adapted;
- national standards should be updated or supplemented to take account of MR-linacs, particularly the SFPM reports on quality control in MRI, on image-guided radiotherapy and on IMRT and on the commissioning and use of a TPS.

## 3. Impact of the use of an MR-linac on department organisation and human resources

### *Medical physics team*

It appears necessary that at least one physicist from the medical physics team should have solid expertise in MRI (training and experience). The medical physicist must be involved as early as possible in the equipment installation process.

### *Radiation therapists, radiotherapy technologists and dosimetrists*

Radiation therapists, radiotherapy technologists and dosimetrists are involved in the different processes connected with analysing MRI images, which require special training, such as contouring volumes, defining margins, validating registration, correcting and validating automatic contouring during an adaptive workflow, selecting gating parameters, etc. The ViewRay training programme for technologists and dosimetrists does not appear to include all of these points. Elekta has developed a training programme but details of its content are not yet available.

Training of radiation therapists by radiologists specialising in MRI is necessary and, in the specific case of image registration, the role of each member of the team must be defined.

### *Adaptive radiotherapy*

Adaptive radiotherapy requires a particular organisation to be set up, particularly for 'online' verifications and validations (registration, contouring, replanning, second calculation), raising the issue of whether a radiotherapist and a physicist should be present at each session or whether these tasks can be delegated to the technologists. These practices have not yet been settled but, in view of the prime importance of registration quality for quality of treatment mentioned in section 2.3 of this advice, **the presence of a radiotherapist would appear to be necessary at the start of each session, at least to correct and validate the contours after registration.**

*Department organisation in view of the risks due to electromagnetic fields (EMFs)*

The risks associated with the EMFs emitted by an MRI concern not only the static magnetic field but also, in the examination room, the radiofrequency pulses and the magnetic field gradients.

The organisational measures necessary to ensure the safety of personnel and patients around an MR-linac, in view of the risks associated with the EMFs produced by the MRI, are a priori the same as for a diagnostic MRI device. What is different about an MR-linac is that it is located in a radiotherapy department where personnel are not familiar with MRI risks and where there are sources of ionising radiation.

The points requiring vigilance for the safety of personnel and patients are as follows:

- the regulations require compliance with Decree No 2016-1074 on the protection of workers from the risks arising from electromagnetic fields; **in particular it is necessary to define zones where there are EMF risks, to restrict and control access, to train workers and provide them with information, and to record EMF risks in workers' job sheets;**
- the EMF risk prevention adviser must have recent professional experience in a diagnostic MRI department;
- the presence of an MRI scanner can cause some electronic dosimeters to malfunction and can cause an attraction risk due to the presence of ferromagnetic materials in (active and passive) dosimeters, which still need to be assessed;
- lastly, the restrictions and contraindications for treating patients with an MR-linac relate to:
  - **the presence of implants, shrapnel, prostheses or medical devices (active or passive) that are incompatible with MRI. Measures must be taken to prevent this risk** (questioning of patients before and during care, installation of a very sensitive metal detector at the entrance to the MR-linac room, etc.),
  - **uncontrollable claustrophobia.**

On behalf of the Director General, by delegation

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