MR-guided Radiotherapy: through the magnet

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Introduction
MRI caused a revolution in diagnostics. Its excellent soft tissue contrast makes MRI extremely well suited for oncology, both to define the geometry of the tumour process and characterize its functional information. The increasing magnetic field strengths, combined with better gradients, multi-channel RF technology and the continuously improving sequence design, makes MRI the standard for stationary locations as the brain. Present developments in special image sequences using breath hold and cardiac gating and the use of ultra fast sequences, make MRI also the standard for those body locations dominated by breathing, cardiac, bowel and bladder related motions. This diagnostic revolution must now be expanded towards on-line and real-time therapy guidance in oncology.

Vision
In recent years, cone beam CT has been integrated in radiotherapy linear accelerator systems. This use of cone beam CT on the linac provides good treatment guidance based on bony structures and implanted fiducial markers and some guidance based on soft tissues (lung, head&neck). With these cone beam CT-linac systems great success has already been realized in the minimal invasive treatment of prostate tumours, stereotactic ablative body radiotherapy (SABR) of lung tumours and stereotactic treatment of tumours of the brain. For these tumours, there is already a clear trend visible towards less fractionation, better targeting with less normal tissue involvement and thus less toxicity and surgery. This therapy must now also be implemented for all remaining tumour locations like radiotherapy of tumours of the rectum, oesophagus, pancreas, kidney, lymph nodes, etc. This may provide a breakthrough in the application of radiotherapy and redefine the relation radiotherapy and surgery.

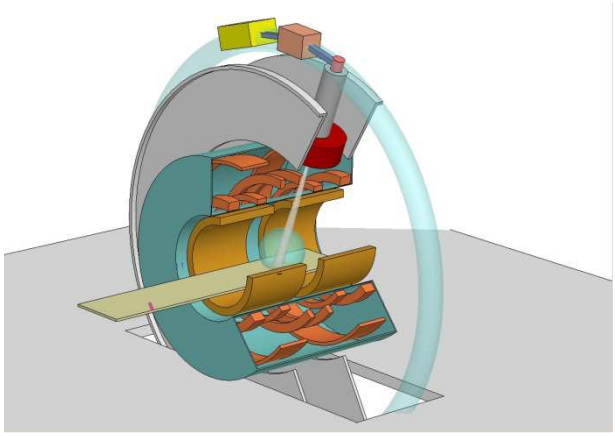

Figure: MRI linac, schematic impression (grey linac gantry and linac, red linac head, green: 1.5 T MRI, light blue toroid with zero magnetic field)

Design MRL
The design of the MRL has been described in Lagendijk et al. [4, 5]. To assure the diagnostic image quality of the system the prototype system has been constructed on the design of a close bore 1.5 T Philips Achieva system. The active shielding coils of the superconducting magnet of this system were modified such that the sensitive gun section of the accelerator is positioned at a toroid area without a magnetic field present, effectively decoupling the two systems. The positioning of the linac at the central plane of the MRI implies that the beam has to pass the MRI. We modified the magnet such that a transparent and homogeneous window is created in the cryostat to let the beam pass. All coils and system heterogeneities are moved out of the central plane creating a gap with a 24 cm projection in the isocentre. Also the gradient coils are split to allow undisturbed beam passage. The total mass in this window is minimised to reduce the beam absorption and the photon scatter towards the patient. The remaining total thickness of the present system is equivalent to about 10 cm of aluminium. In the final clinical system, based on a wide bore Philips Ingenia, this will be reduced to less than 5 cm of homogeneous aluminium. Also due to the geometry chosen the isocentre target distance is about 1.4 meters, requiring a special high output linac and dedicated MLC.

Dosimetry and treatment planning
The photon beam in the MRL isn't affected by the magnetic field. However, secondary electrons, released by the photon beam are experiencing the Lorentz force and this causes an altered dose distribution [6]. The build-up distance of the beam is slightly reduced while the whole beam experienced a 0.6 mm off set in the direction of the Lorentz force [6]. The difference in dose distributions is most prominent at tissue air-interfaces. Without magnetic field the electrons scatter away from the tissue, with a magnetic field, the electrons are forced back into the tissue by the Lorentz force resulting in an increased dose at the exit side of the beam [7], the Electron Return Effect (ERE). The ERE effect is dependent of the electron energies and the strength of the magnetic field making the effect also dependent on the width of the radiation field [9,3].
The impact of the magnetic field on the dose distribution can be well described by using Monte Carlo dose computations. The impact of the magnetic field is compensated in first order by choosing opposing beams or multiple beam angles [8]. It was shown that by using a multi beam set-up in combination with inverse optimisation resulted in the same dose distributions as for the case without magnetic field. The ERE effect requires Monte Carlo dose calculation for the actual anatomy. The MRI accelerator facilitates continuous patient anatomy updates regarding translations, rotations and deformations of targets and organs at risk. Accounting for this, demands high speed, online intensity-modulated radiotherapy (IMRT) re-optimization. We developed a fast IMRT optimization system which combines a GPU-based Monte Carlo dose calculation engine for online beamlet generation and a fast inverse dose optimization algorithm. This Virtual Couch Shift (VCS) system can recalculate the required IMRT settings within seconds [1]. The MRI must supply real-time information about the actual position of the tumour and organs at risk. Dedicated sequences and correction protocols are being developed to guarantee fast and geometrically correct imaging. Pencil-beam navigators are good options where the main mode of the motion is a translation along a single axis. Demonstrations of gated as well as tracked delivery on the basis of feed-back from pencil-beam navigators have been performed [2]. For 2 and 3D acquisition, the flexible and fast bSSFP sequences in combination with speed-up strategies like parallel imaging, under-sampled radial acquisition, etc. are being tested. New T2-FFE MRI methods have been developed which provide excellent tools for direct lymph node localization.

Status:
MRI guidance will start a paradigm shift in radiotherapy: the central position becomes MR imaging and guidance not fractionation and/or radiobiology. As a consequence, radiotherapy becomes more an interventional radiology process. Close collaboration is needed between the radiation oncologist, radiologist, pathologist, medical physicist and surgeon. Such a multi-disciplinary team will guided the care of those oncology patients with local disease.

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