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Modulated arc (mARC): principle and clinical implementation

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Introduction
The modulated arc (mARC) technique (Salter et al., 2011; Kainz et al., 2011) has recently become available for Siemens ARTISTE linear accelerators as an analogue to RapidArc and volume modulated arc therapy (VMAT) available for Varian and Elekta machines (Otto, 2008; for a recent review see Teoh et al., 2011). All techniques offer highly conformal treatment, since inversion is performed similarly to intensity-modulated radiotherapy (IMRT) for a large number of beam directions, which may create a complete or partial gantry rotation; a notable decrease in treatment time is accomplished by the continuous gantry rotation and multi-leaf collimator (MLC) movement. However, mARC differs from VMAT in underlying philosophy and practical implementation. The purpose of this work is to give a short overview on the characteristics and technical principles of mARC treatment (compare Salter et al., 2011 and Kainz et al., 2011 for more detail) and the practical application in the clinic. In addition to providing the physics background of planning and dosimetric verification, treatment planning and patient treatment for a number of clinical cases is presented.

The work was carried out on the Siemens ARTISTE at the Institute of Radiation Oncology of the Saarland University Medical Centre in Homburg/Saar (Germany). This accelerator is equipped with 160 multi-leaf collimator (MLC) and 6 MV flat and 7 MV flattening-filter-free (FFF) beam modalities with dose rates between 50 and 300 MU/min in flat and 500 to 2000 MU/min in FFF mode. Treatment planning was performed in the Prowess Panther TPS.

Background – concept of mARC treatment
In conventional arc treatment as implemented by Varian and Elekta, continuous mode delivery is applied, meaning that dose is delivered continually while the gantry and MLC move. In contrast to this, the mARC beam is only switched on while the MLC remains static, although the gantry moves along an arclet of a few degrees. This is why this mode of delivery has been called “burst mode” (Salter et al., 2011). In fact, this way of delivery approximates more closely the dose calculation as it is generally performed in treatment planning systems, since the TPS usually calculates the dose based on static fields at the control point angles. In contrast to “real” IMRT, where the dose would be delivered statically at these control points, the mARC beam is switched on in a small arclet around each control point (usually 2°-5°), which makes delivery faster since the gantry can continually rotate. The maximum width of the arclet is defined by the user; if the dose can be delivered in a shorter time than needed to rotate through the arclet, the angle will be automatically decreased by the ARTISTE firmware – if more dose must be applied, the gantry rotation is slowed down or stopped so that the maximum arclet angle is never exceeded. In this way, the gantry speed is automatically modulated so that the arclet angle is minimised.

At the same time, the firmware linearly reduces the dose rate for small-MU segments to ensure accurate linearity. It is possible to include “hybrid fields”, i.e. fields where more than one segment is irradiated from the same gantry direction; for these fields the gantry will be stopped until
the desired number of segments has been irradiated. Between one arclet and the next, the MLC is moved to the new configuration without dose delivery. This offers a free choice of MLC configuration for the treatment plan, since intermediate configurations are not irradiated, and can therefore allow for better plan optimisation than continuous-mode delivery.

**Physics concepts**

Machine data modelling and commissioning is performed in exactly the same way as usual; no further requirements for mARC facilities exist. At our institution, the mARC upgrade was carried out at an ARTISTE linac equipped with a flat 6 MV and flattening-filter-free 7 MV beam line (Multiple-X); both energies were modelled and commissioned in Prowess. The dosimetric properties of the linac can be taken from Dzierma et al. (2012).

**Figure 1:** Schematic illustration of mARC delivery (from Siemens mARC Planning Guide). Between two control points, radiation is off and the MLC leaves more into the required aperture shape for the upcoming optimisation point. In the vicinity of each optimisation point, over a small arclet (maximum gantry angle range restricted by the user and symmetrically placed around the optimisation point), the MLC remains fixed and radiation is on. Not shown here, hybrid fields can be included to irradiate several segments of different MLC configuration from the same gantry angle, equivalently to normal step-and-shoot beams.

**a. Treatment planning**

Treatment planning in the Prowess Panther TPS is performed similarly to IMRT treatment planning. For comparatively simple target volumes (e.g., brain metastases, prostate), a single arc with optimisation points spaced every 10° will give good quality plans and result in short treatment times. After the definition of the arc isocenter, collimator angle and control points, the optimisation is carried out in the same way as in IMRT planning.

It has generally been observed in arc treatment (also RapidArc and VMAT) that for complicated target volumes, one arc may not be sufficient to create an optimal dose distribution. In these cases where a single arc does not yield good quality plans, a second arclet with a different collimator orientation (and reverse gantry rotation direction) can be included; or more complicated combinations of
a number of coplanar or non-coplanar arcs can be chosen (Guckenberger et al., 2009; Vanetti et al., 2009). Alternatively, and often preferable from the point of view of both simplicity and treatment time, a number of gantry directions can be designated as hybrid fields, with a chosen number of segments (Chan et al., 2011).

b. Dosimetric verification

While treatment planning is fairly straightforward and does not prove any more complicated than for static IMRT, dosimetric verification must be more thoroughly checked before patient treatment. In this context, we shall consider two different issues: the accuracy of the dosimetric delivery by mARC as performed by the ARTISTE firmware from a purely technical view-point, and the dosimetric verification of patient treatment plans from the TPS software.

From the technical side, accuracy of mARC is evaluated in comparison with step-and-shoot IMRT plans. For this reason, we programmed a conversion program from IMRT plans exported in RTP file format into mARC plans (Dzierma et al., submitted to Medical Physics). Both the original step-and-shoot and the converted mARC plans were then irradiated and compared; irradiation times were reduced by about half for the mARC converted plans. This dosimetric test is independent of the quality of the TPS calculation and commissioning and only detects any deviation in dose that arise from the mARC treatment controlled by the ARTISTE firmware. Apart from the “smearing” of the dose delivery across the arclet angle (set to 4°), no difference should exist between both plans if the technical delivery is accurate. It is recommended to limit arclet widths to 5° maximum to keep dose-smearing effects small. Absolute dosimetric verification of both the
step-and-shoot and mARC plans by point dose measurements with a PTW semiflex ionization chamber (type 31010) showed deviations below 3% local dose, which is within the specifications allowed at our institution for IMRT verification. The absolute dosimetric verification of mARC plans deviated from step-and-shoot plans by no more than 1%.

Planar dose distributions of both plan varieties (step-and-shoot vs. mARC) were measured in an acrylic phantom using GafChromic film. The agreement between both treatment modalities is excellent, with over 95% of points within 3% deviation in dose and 3 mm distance to agreement; an example is shown in Figures 3-4 for a hybrid prostate PTV plan.

In principle, validation of the treatment planning system need not explicitly be performed from the technical perspective, since dosimetric verification for IMRT plans was already checked in the commissioning phase (Dzierma et al., 2012), and since the deviation of the mARC plans from the step-and-shoot plans is negligible. However, we perform these measurements for completeness using the PTW Octavius phantom with 729 2D-Array. Furthermore, for original mARC plans (not created by conversion from step-and-shoot plans), dosimetric verification before treatment should be carried out for each patient, just as it is done for IMRT treatments. For all plans tested at our institution, over 80% of the points passed the criteria of 3% local dose deviation and 3 mm distance to agreement (example shown in Figure 5), which provided an independent verification of the dose distribution of the mARC plan. Deviations mainly arose in the low-dose area (below 20% maximum dose), while the agreement within the high-dose region is much better.
Clinical cases
Within the nine months experience at our clinic, most cases treated have been prostate patients. Both PTV and shrinking field can be planned with a single arc and optimisation points spaced every 10° (see Figure 6 for an example plan treated with 6 MV). For brain tumours, a single arc stereotactic treatment can equally well be planned, as shown by the example plan (Figure 7) for an acoustic neuroma patient treated with FFF 7 MV. Complicated target volumes, e.g., head-and-neck cases with integrated boost, require more planning effort. In these cases, a second arc or the inclusion of a number of hybrid fields may be required to achieve a clinically acceptable dose distribution.

Clinical application of the mARC has hitherto been straightforward, with no problems of treatment delivery. A large advantage of the mARC as compared with VMAT and RapidArc is that the treatment can be easily interrupted and resumed, with a known delivered dose at each instant – a case we have admittedly not experienced yet since no interruption occurred and all treatments were delivered as planned. Treatment times were measured for all patients and range between 2 and 5 minutes for a single arc, depending on the use of flat vs. FFF beams and whether or not hybrid fields are included.

Summary
The mARC presents an alternative to VMAT and RapidArc treatments. Due to the burst mode dose delivery, which interrupts the beam for MLC movement, the delivery time is still slightly longer than for VMAT and RapidArc; at the same time, this technique provides a further degree of freedom for the MLC configuration. The burst delivery technique is also of advantage in case of treatment...
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interruption, as the delivered dose is precisely known at each instant. As long as the arclet angles do not exceed 5°, the delivered dose is calculated very accurately, with good agreement between step-and-shoot and mARC delivery. Verification of the measured mARC plan (Octavius with 2D-Array) against the TPS calculation is straightforward, and of comparable quality as IMRT verification. From the technical point of view, performance is excellent, with no malfunctions or irradiation problems so far.

The mARC offers the possibility to save significant amounts of time, with single-arc treatments of only a few minutes achieving comparable dose distribution to IMRT plans taking up to twice as long. We are currently implementing mARC treatment into clinical routine step-by-step for different tumour locations, starting with prostate patients.

References


Y. Dzierma, N. Licht, F. Nuesken, Ch. Ruebe, "A novel implementation of mARC planning with automated gantry angle optimization for hybrid fields", Rad. Onc., under review


Figure 7: Example plan of an acoustic neuroma patient, treated with a single arc of energy 7 MV (FFF). Optimisation points were spaced every 10°, with no hybrid fields.