Quality assurance of RapidArc in clinical practice using portal dosimetry

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Objective: Quality assurance data from five centres were analysed to assess the reliability of RapidArc radiotherapy delivery in terms of machine and dosimetric performance.

Methods: A large group of patients was treated with RapidArc radiotherapy and treatment data recorded. Machine quality assurance was performed according to Ling et al (Int J Radiat Oncol Biol Phys 2008;72:575–81). In addition, treatment to a typical clinical case was delivered biweekly as a constancy check. Pre-treatment dosimetric validation of plan delivery was performed for each patient. All measurements and computations were performed at the depth of the maximum dose in water according to the GLAaS method using electronic portal imaging device measurements. Evaluation was carried out according to a gamma agreement index (GAI, the percentage of field area passing the test); the threshold dose difference was 3% and the threshold distance to agreement was 3 mm.

Results: A total of 275 patients (395 arcs) were included in the study. Mean delivery parameters were $31.0 \pm 20.0^\circ$ (collimator angle), $4.7 \pm 0.5^\circ \text{ s}^{-1}$ (gantry speed), $343 \pm 134 \text{ MU min}^{-1}$ (dose rate) and $1.6 \pm 1.4 \text{ min}$ (beam-on time) for prescription doses ranging from 1.8 to 16.7 Gy/fraction. Mean deviations from the baseline dose rate and gantry speed ranged from -0.61% to 1.75% . Mean deviations from the baseline for leaf speed variation ranged from -0.73% to 0.41% . The mean GAI of repeated clinical fields was $99.2 \pm 0.2\%$. GAI varied from 84.7% to 100% ; the mean across all patients was $97.1 \pm 2.4\%$.

Conclusion: RapidArc can provide a reliable and accurate delivery of radiotherapy for a variety of clinical conditions.

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The RapidArc radiotherapy delivery system (Varian Medical Systems, Palo Alto, CA), a form of volumetric modulated arc therapy based on the original investigation of Otto [1], has been introduced into clinical practice at several institutions following intensive validation [2–8]. Some previous investigations have partly addressed the issue of quality assurance (QA). Methods have been developed to perform constancy tests at machine level, as described by Ling et al [9]. From a different perspective, investigations have been performed to analyse the performance and appropriateness of different detectors [10] and to expand those RapidArc QA methods developed primarily for static beam intensity-modulated radiation therapy (IMRT) [11]. Some studies have also addressed the issue of pre-treatment verification on specific treatment sites [6, 8, 12–14]. All studies confirmed a good agreement between the dose distribution computed for RapidArc and the actual delivery.

Similar investigations have been performed for other forms of volumetric modulated arc therapy [14–16] and have shown the importance of developing appropriate QA methods for new treatment techniques. A need to maintain a rigid QA for IMRT and all new related techniques is a matter of current debate. Traditional, highly frequent measurement-based QA might benefit from reinforcement or replacement with computational or less frequent simplified methods [17–19]. It is likely, especially given the conclusions of Shortt et al [17], that it is of primary importance to establish highly accurate protocols and to perform systematic machine- and patient-based tests for undetermined long periods when any new technique is introduced. Such an approach will guarantee maximum achievable protection from any unknown factor and generate sufficient data on the safety and reliability of patient treatments.

The aim of the present report is to summarise treatment characteristics and QA results from initial clinical experience. Data from the RapidArc treatment of multiple tumour types at five centres in Europe were retrospectively analysed to identify three factors: the main features

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of delivered RapidArc plans to provide evidence about the actual technical aspects of real treatments; the results of machine-orientated QA tests to provide evidence about the short- and medium-term reliability of the machine performances specific to this intensity-modulated dynamic arc method; and patient-orientated pre-treatment results aimed to demonstrate the actual level of dosimetric reliability on a large group of patients.

For machine and patient QA, all centres participating in this study adopted a dosimetric method based on electronic portal imaging, the GLAaS method (discussed in Nicolini et al [11]), which was expanded to incorporate machine tests.

Methods and materials

Five centres from Switzerland, Italy and France treating patients with the RapidArc technique participated in a retrospective analysis of treatment parameters and QA procedures. Participating centres comprised the Oncology Institute of Southern Switzerland (IOSI) in Bellinzona, the University Hospital of Zürich (USZ), the Istituto Clinico Humanitas (ICH) in Rozzano-Milano, the Istituti Ospitalieri of Cremona (IOC) and the Centre Régional de Lutte contre le Cancer Val d'Aurelle-Paul Lamarque (CRLC) in Montpellier. All centres are members of a co-operative group created to assess the GLAaS method in clinical practice following the initial phase of investigations [20–22].

The GLAaS process uses measurements performed with the amorphous silicon portal imager Portal Vision PV-aS1000 attached to the treatment machine. Employing a specific calibration and processing method, the raw data are converted into absorbed doses at the depth of the maximum dose in water (1.5 cm for 6 MV beams, 3.0 cm for 18 MV beams). Details of the GLAaS extension to RapidArc dosimetry have been reported previously [11]. For a given beam, the response of the amorphous silicon detectors is linear ($D(Gy) = m \cdot R + q$), where D is the absorbed dose, R is the detector reading, and m and q are the parameters of the linear fit, while IMRT and RapidArc fields change continuously during delivery. GLAaS accounts for such changes in time and position, using variable m and q values, and for differentiation between primary and transmitted (below the millennium multileaf collimator (MLC)) radiation on a pixel by pixel basis. The total dose d_i in the i -th pixel over the entire field delivery is given by:

$$d_i = d_{pr,i} + d_{tr,i} = \left(\sum_{s=1}^N m_{pr,s}(E_{wwF}) \cdot r_{i,s} + q_{pr,s} \right) + \left(m_{tr} \cdot \left(R_i - \sum_{s=1}^N r_{i,s} \right) + q_{tr} \right)$$

where m and q are the slope and the intercept for a field of size, respectively, E_{wwF} (equivalent window width field), r is the reading attributed to the primary radiation for the segment/control point s , and R is the total Portal Vision reading; the subscripts pr and tr refer to primary and transmitted radiation, respectively. The field is considered as a sum of N segments or control points. A characteristic

of RapidArc is delivery with variable dose. The detector response is independent of the dose rate [21].

The parameter values computed during the configuration of GLAaS to obtain the slopes analytically come from an empirical model. Similarly, corrections for arm back-scatter and beam shoulders have been introduced and described previously [11].

GLAaS is the reference dosimetry tool in the centres participating in this study for patient-specific pre-treatment verifications. GLAaS requires no additional phantom and, for RapidArc, the detector rotates together with the gantry, thus generating a collapsed planar dose distribution. Spatial resolution of these measurements is 0.392 mm in x and y directions (aS-1000 pixel size).

GLAaS-based Epiqa software (EPIIdos, Ivanka pri Dunaji, Bratislava, Slovakia) was used by all centres for quantitative analysis of dosimetric data. The collapsed dose distributions obtained from the treatment planning system (Eclipse, versions 8.5 and 8.6; Varian Medical Systems) were used as reference against Portal Vision measurements for pre-treatment QA. The gantry position is verified by the machine control system during the RapidArc delivery every 50 ms, mutually checking the planned and actual positions of the MLC leaves and the gantry angle. During the delivery, the MLC positions are dictated by the gantry position. In the present study, no independent verification of the gantry angle has been incorporated. Interruption of the delivery by machine interlock would occur in case of major deviation. At a maximum speed of 4.8° s^{-1} , the gantry covers about 0.24° in 50 ms.

All five centres performed RapidArc treatments on Varian Clinacs iX (except USZ who used a Trilogy) equipped with an MLC with 120 leaves (spatial resolution of 5 mm at the isocentre for the central 20 cm and of 10 mm in the outer 10 cm (at both extremes); the maximum leaf speed was 2.5 cm s^{-1}). The energy used was 6 MV for all centres; CRLC also used 18 MV. For planning, leaf transmission, as determined from measurements at each institute, was set to 1.5% (IOC and USZ), 1.6% (ICH and CRLC, 6 MV) or 1.8% (IOSI and CRLC, 18 MV); the dosimetric leaf gap was set to 1.9 mm (USZ), 2.0 mm (ICH, CRLC, IOC) or 2.3 mm (IOSI). For all institutes, the PV-aS1000 was attached to the robotic Exact Arm allowing stable and precise positioning that was minimally affected by sag in the imager position with gantry rotation (as shown in [11]).

For the present comparison, all monitor unit (MU) data were converted to the same calibration at source to surface distance (SSD)=90 cm, $d=10$ cm to deliver 1 Gy in 100 MU (at isocentre).

RapidArc plans and delivery technical features

A set of technical and delivery parameters were recorded from actual delivery to assess the main features of RapidArc. These parameters included the number of arcs per plan, the dose per fraction, the MUGy^{-1} , the collimator rotation angle, the beam-on time, the gantry speed (GS), the mean dose rate (DR), the mean control point area, the mean field size area and the mean leaf aperture. The control point area (CP area) is defined as the open beam area limited by the MLC at each control point. A control point (CP) is the “elementary” beamlet resulting from optimisation. A CP is defined as the

machine status at a given instant of time and includes the shape of the MLC, the gantry angle and the dose rate information. An arc is described by 177 CPs. The mean field size area is the mean area defined by the main jaws. The mean leaf aperture is defined as the mean value (over all CPs) of the average gap between all open leaf pairs for each CP.

All parameter values are recorded as mean $\pm$ standard deviation (SD), apart from beam-on time and GS where the median value with the median absolute deviation (MAD = median ($|X_i - X'|$)), where X' is the median of the data) are recorded owing to their non-Gaussian distribution.

RapidArc-specific machine quality assurance

RapidArc introduces the need for dedicated tests to combine the three dynamic elements that continuously vary during delivery: dose rate, gantry speed and leaf speed. Three tests were performed according to the methods described by Ling et al [9]. In the first, a picket fence pattern is delivered during RapidArc and the presence of any positional error of the leaves (possibly induced by gravity) is qualitatively assessed. For comparison, patterns with intentional errors are similarly delivered, providing an eye sensitivity >0.5 mm. The second and third tests consist of quantitative evaluation of special patterns: homogeneous bands are delivered during the gantry rotation, while the dose rate and gantry speed or the MLC leaf speed are varied at pre-defined values for each band. Results are assessed in terms of the percentage deviation in each band from the measured mean reading in all bands (after performing the ratio with an open field to cancel profile horns effect). Test patterns are provided to all centres by Varian as part of the standard commissioning procedure of RapidArc and can be used for periodic checks. A dedicated module of the Epiqa package was developed to automatically perform the analysis of these tests from raw portal images. A fourth test, performed by only one centre (IOSI), consists of repeating (with biweekly frequency) the delivery of a single pre-defined typical arc to assess the reproducibility of delivery in clinical conditions over a medium-term period.

Pre-treatment quality assurance dosimetric measurements

To assess delivery quality and agreement between calculations and treatment, standardised pre-treatment QA dosimetric measurements were performed verifying each individual arc. Pre-treatment QA results were summarised in terms of the gamma agreement index (GAI) scoring the percentage of modulated area with $\gamma < 1$ [23] (computed with dose difference $\Delta D = 3\%$ of the maximum significant field dose [20], and distance to agreement DTA = 3 mm thresholds). GAI analysis was performed on the area defined by the jaws. Reference (treatment planning system, TPS) and test (measurement) dose maps were normalised to the maximum significant dose from the reference map. The maximum significant dose is defined [20, 21] as the maximum in the dose distribution after cutting the highest 5%. Pre-treatment dosimetry was

considered excellent if GAI exceeded 95%, acceptable if above 90% and case by case acceptance or rejection after clinical discussion was required if GAI was lower than 90%. For all clinical cases, a grid of 2.5 mm or smaller was used for dose calculation consistent with that used for actual plan calculation.

GLAaS dosimetry as independent MU verification

The GLAaS dosimetric method, comparing calculated with measured absorbed dose matrices, can also be used for independent verification of MU. To further validate the MU calculation with RapidArc, a substudy was performed using 50 clinical plans selected at random from the IOSI data set. Ion chamber (IC) measurements were performed at the isocentre, as for the electronic portal imaging device (EPID)-based measurement, with an ion chamber (0.125 cm^3 wearing a brass build-up cap for 6 MV) integrating over the entire arc and converting chamber readings into dose (scaling also for the ratio of output factors in water and in air to account for the missing scatter for in air measurements). Arcs were delivered to both the ion chamber and GLAaS measurements with the same number of MU as planned for the patients. Ion chamber and GLAaS measurement were compared mutually and against TPS calculation. Different results are expected for the GLAaS and ion chamber measurements, mainly owing to the different size and volume of the sensitive elements (e.g. for the chamber, the diameter of 5.5 mm and the length of about 8 mm are both larger than the leaf width). For this reason, comparison was performed integrating EPID and TPS data over an area around the isocentre sufficient to mimic ion chamber size. It is therefore expected that a qualitatively good average correlation can be proven between the methods. The test is intended to confirm the GLAaS method as a reliable conversion of the Portal Vision readings into absorbed dose at d_{max} .

Results

Technical features of RapidArc plans and delivery

Table 1 summarises the number of patients treated per centre, the total number of plans and arcs delivered, the number of plans delivered with more than one arc and the prescribed dose per fraction and per plan (or per patient). A total of 275 patients were included (321 plans and 395 arcs). For each centre, patients treated from the clinical introduction of RapidArc until the end of June 2009 were considered. Patients were classified according to anatomical sites. USZ and IOC had a lower number of patients owing to the relatively recent introduction of RapidArc at these centres.

The patient selection criteria for RapidArc treatment are crucial to understand the data. These reflected the local institutional code of practice and were based on two factors: computer simulation proof of potential benefit from RapidArc vs IMRT or three-dimensional conformal radiotherapy (3DCRT) for a given group of patients with similar indications (e.g. head and neck, brain, abdominal or pelvic cases) or individual selection owing to a specific clinical need or planning complexity. Our data show that

Table 1. Patient statistics

Institution	Site	No. patients	No. plans	No. arcs	No. plans with >1 arc	Dose/fraction $\pm$ SD (range) (Gy)	Total plan dose (range) (Gy)
IOSI	Prostate	63	84	84	0	2.0 $\pm$ 0.2 (1.8–3.1)	54.4 $\pm$ 20.9 (16.0–78.0)
	Anal canal plus rectum	29	31	31	0	2.0 $\pm$ 0.6 (1.8–5.0)	39.9 $\pm$ 11.8 (5.4–59.4)
	Gynaecological	10	11	12	1	1.9 $\pm$ 0.2 (1.8–2.4)	42.5 $\pm$ 10.2 (12.2–50.4)
	Other pelvic	13	16	16	0	2.0 $\pm$ 0.3 (1.8–2.5)	36.4 $\pm$ 14.7 (5.4–50.4)
	Others	15	15	25	10	2.6 $\pm$ 0.8 (1.8–5.0)	43.2 $\pm$ 12.7 (19.8–62.5)
	Total IOSI	130	157	168	11	–	–
ICH	Abdominal or liver mets	16	16	32	15	10.4 $\pm$ 4.4 (7.5–16.7)	46.6 $\pm$ 2.4 (45.0–50.0)
	Head and neck	27	29	45	16	2.1 $\pm$ 0.1 (1.8–2.2)	66.6 $\pm$ 7.4 (41.4–70.0)
	Lung	11	11	22	11	2.2 $\pm$ 0.4 (2.0–3.0)	54.4 $\pm$ 16.3 (20.0–66.0)
	Pelvis	6	6	12	6	2.0 $\pm$ 0.3 (1.8–2.6)	60.4 $\pm$ 8.7 (50.4–74.2)
	Vertebral re-irradiation	5	5	9	4	2.3 $\pm$ 0.6 (1.8–3.0)	36.6 $\pm$ 7.9 (30.6–50.0)
	Brain	3	3	5	2	2.5 $\pm$ 0.5 (2.0–3.0)	46.3 $\pm$ 17.0 (30.0–64.0)
	Total ICH	68	70	125	54	–	–
CRLC	Prostate	30	36	36	0	2.0 $\pm$ 0.0 (2.0–2.0)	79.9 $\pm$ 0.7 (76.0–80.0) ^a
	Head and neck	10	16	16	0	2.0 $\pm$ 0.0 (2.0–2.0)	68.3 $\pm$ 4.9 (56.0–70.0) ^a
	Others	6	7	7	0	1.9 $\pm$ 0.1 (1.8–2.0)	2.9 $\pm$ 13.4 (14.4–45.0) ^a
	Total CRLC	46	59	59	0	–	–
IOC	Prostate	10	10	14	4	2.2 $\pm$ 0.2 (1.8–2.3)	62.7 $\pm$ 21.4 (5.4–73.6)
	Head and neck	5	6	8	2	1.6 $\pm$ 0.5 (1.2–2.2)	32.8 $\pm$ 19.7 (10.0–50.6)
	Lung (1 stereo)	2	2	4	1	4.0 $\pm$ 2.8 (2.0–6.0)	46.0 $\pm$ 5.7 (42.0–50.0)
	Total IOC	17	18	26	7	–	–
USZ	Prostate	9	11	11	0	2.1 $\pm$ 0.3 (2.0–3.0)	58.1 $\pm$ 16.8 (24.0–74.0)
	Others	5	6	6	0	2.0 $\pm$ 0.0 (2.0–2.11)	37.0 $\pm$ 17.8 (18.0–60.0)
	Total USZ	14	17	17	0	–	–
	Grand total	275	321	395	72	–	–

Stratification is done according to general anatomical sites with at least three patients treated in the group.

IOSI, Oncology Institute of Southern Switzerland; ICH, Istituto Clinico Humanitas; CRLC, Centre Régional de Lutte contre le Cancer Val d'Aurelle–Paul Lamarque; IOC, Istituti Ospitalieri of Cremona; USZ, University Hospital of Zürich; SD, standard deviation.

^aTotal patient dose.

Table 2. Plan and delivery parameter statistics^a

Institution	Site	No. arcs	Collimation (°)	MU Gy ⁻¹	Beam-on time (min) ^b	Mean GS (° s ⁻¹) ^b	Mean DR (MU min ⁻¹)	Mean CP area (cm ²)	Mean field size area (cm ²)	Mean leaf aperture (cm)
IOSI	Prostate	84	24 ± 8	229 ± 50	1.25 ± 0.00	4.79 ± 0.00	371 ± 85	49.4 ± 38.6	177 ± 98	3.6 ± 1.6
	Anal canal or rectum	31	24 ± 9	147 ± 26	1.24 ± 0.00	4.80 ± 0.00	235 ± 61	145.4 ± 43.9	373 ± 106	7.4 ± 1.5
	Gynaecological	12	20 ± 7	179 ± 38	1.24 ± 0.00	4.80 ± 0.00	253 ± 71	124.4 ± 49.5	440 ± 218	5.3 ± 1.6
	Other pelvic	16	23 ± 3	204 ± 50	1.24 ± 0.0	4.80 ± 0.00	307 ± 78	77.2 ± 54.1	298 ± 197	4.3 ± 1.4
	Others	25	19 ± 9	192 ± 94	2.26 ± 0.10	4.80 ± 0.00	264 ± 136	96.8 ± 65.4	394 ± 279	4.3 ± 1.8
	Mean IOSI		27 ± 17 (10–45)	204 ± 67 (105–576)	1.24 ± 0.00 (0.6–2.5)	4.79 ± 0.00 (4.3–4.8)	319 ± 103 (105–596)	81.0 ± 59.4 (16.1, 267.7)	267 ± 117 (62–1023)	4.6 ± 2.1 (1.0–9.4)
ICH	Abdominal or liver metastasis	32	45 ± 0	163 ± 25	2.83 ± 0.03	3.68 ± 0.15	591 ± 14	19.3 ± 9.1	61 ± 28	2.6 ± 0.7
	Head and neck	45	22 ± 6	170 ± 39	2.27 ± 0.11	4.80 ± 0.00	241 ± 85	42.6 ± 18.4	217 ± 104	3.0 ± 0.9
	Lung	22	24 ± 7	166 ± 45	1.77 ± 0.10	4.80 ± 0.00	281 ± 119	75.0 ± 45.7	293 ± 143	4.2 ± 2.0
	Pelvis	12	21 ± 8	167 ± 34	2.15 ± 0.07	4.80 ± 0.00	214 ± 139	91.3 ± 31.9	351 ± 150	4.8 ± 1.1
	Vertebrae re-irradiation	9	77 ± 3	201 ± 29	1.89 ± 0.24	4.77 ± 0.01	333 ± 121	25.4 ± 10.2	89 ± 26	2.5 ± 0.9
	Brain	5	29 ± 11	207 ± 74	1.68 ± 0.57	4.80 ± 0.00	278 ± 44	14.8 ± 4.4	38 ± 0	2.4 ± 0.6
	Mean ICH		33 ± 16 (15–80)	171 ± 39 (112–312)	2.19 ± 0.13 (0.8–7.3)	4.57 ± 0.03 (2.3–4.8)	346 ± 174 (113–600)	44.5 ± 34.2 (7.7–164.3)	187 ± 140 (16–620)	3.2 ± 1.3 (1.2–7.7)
CRLC	Prostate	36	45 ± 0	218 ± 26	1.26 ± 0.00	4.78 ± 0.00	403 ± 55	25.3 ± 8.5	147 ± 41	2.3 ± 0.5
	Head and neck	16	31 ± 5	207 ± 23	1.25 ± 0.00	4.80 ± 0.00	376 ± 45	59.1 ± 24.3	359 ± 112	2.9 ± 0.9
	Others	7	43 ± 11	175 ± 13	1.25 ± 0.00	4.79 ± 0.00	337 ± 63	53.8 ± 38.5	308 ± 214	3.1 ± 1.3
	Mean CRLC		42 ± 7 (25–60)	215 ± 30 (142–244)	1.25 ± 0.00 (1.2–1.3)	4.78 ± 0.00 (4.7–4.8)	388 ± 58 (259–509)	36.4 ± 23.9 (14.9–123.5)	214 ± 133 (86–707)	2.5 ± 0.8 (1.1–4.8)
IOC	Prostate	14	42 ± 19	208 ± 53	1.40 ± 0.35	4.53 ± 0.15	344 ± 124	52.3 ± 28.3	245 ± 136	3.4 ± 1.2
	Head and neck	8	40 ± 37	207 ± 66	1.20 ± 0.08	4.80 ± 0.00	213 ± 68	54.0 ± 31.1	272 ± 175	3.4 ± 1.2
	Lung (1 stereo)	4	45 ± 0	138 ± 31	2.26 ± 1.11	4.52 ± 0.00	439 ± 228	50.2 ± 30.0	166 ± 133	4.1 ± 1.2
	Mean IOC		42 ± 25 (8–80)	200 ± 58 (115–295)	1.31 ± 0.22 (1.0–3.4)	4.69 ± 0.10 (2.3–4.8)	311 ± 136 (147–600)	52.6 ± 27.6 (17.3–104.3)	245 ± 145 (63–575)	3.5 ± 1.1 (1.8–5.6)
USZ	Prostate	11	37 ± 12	250 ± 24	1.29 ± 0.01	4.62 ± 0.04	508 ± 56	23.4 ± 5.2	131 ± 59	2.2 ± 0.5
	Others	6	36 ± 17	211 ± 64	1.06 ± 0.10	4.64 ± 0.04	442 ± 80	47.8 ± 25.4	220 ± 107	3.1 ± 1.3
	Mean USZ		36 ± 14 (10–50)	236 ± 49 (111–304)	1.24 ± 0.03 (0.6–1.7)	4.66 ± 0.02 (3.8–4.8)	486 ± 70 (361–576)	31.5 ± 18.5 (11.8–84.5)	161 ± 86 (82–336)	2.5 ± 0.9 (1.3–4.8)
	Global mean		31 ± 20 (8–80)	195 ± 14 (105–576)	1.24 ± 0.01 (0.6–7.3)	4.79 ± 0.01 (2.3–4.8)	343 ± 134 (105–600)	59.6 ± 49.5 (7.7–267.7)	228 ± 160 (16–1023)	3.7 ± 1.9 (1.0–9.4)

IOSI, Oncology Institute of Southern Switzerland; ICH, Istituto Clinico Humanitas; CRLC, Centre Régional de Lutte contre le Cancer Val d'Aurelle–Paul Lamarque; IOC, Istituti Ospitalieri of Cremona; USZ, University Hospital of Zürich. CP, control point; DR, dose rate; GS, gantry speed; MU, monitor units.

^aRange is given in brackets. ^bValues expressed as median ± median absolute deviation (MAD); all other values are expressed as mean ± standard deviation (SD).

multiple arc treatments represented 22% of RapidArc cases, and that they were used in about 50% of cases to deliver long volumes (IOSI) or hypofractionated treatments; in the remaining 50% of cases, multiple arc treatments were used to improve plan quality (e.g. brain, head and neck or lung cases). Fractionation was found to be conventional or moderately hypofractionated (up to 3 Gy fraction⁻¹), with the exception of the stereotactic treatments of abdominal metastasis at ICH [24]. A few cases were treated with 5 Gy fraction⁻¹ at IOSI (pre-operative rectum or palliative metastasis) and one stereotactical lung treatment was performed with 6 Gy fraction⁻¹ at IOC.

Table 2 summarises some technical features of the treatments. The collimator angle, which was manually selected by planners, ranged from 8 to 80° covering almost all the possible angles within this range. The average angle was 31°, which differs from the original 45° suggested by Otto [1]. The wide range was due partly to clinical reasons: elongated target volumes tend to be better optimised when using smaller collimator angles; more spherical targets can be satisfactorily optimised with the collimator angle in the range of 45°; and particularly complex cases with highly irregular shapes can benefit from collimator angles proximal to 70–90°. Collimator angle reflected individual planner preferences and

experience and was not constrained by planning protocol in any of the participant institutes. The average number of MU Gy⁻¹ was always smaller than 250, confirming a significant increase in delivery efficiency when using RapidArc with respect to conventional IMRT (the reduction might be a factor of 2–3 [2, 3, 7] depending on dose prescription, number of fields and smoothing level). The mean DR varied from 311 to 486 MU min⁻¹ (range 105–600), showing that in the cases considered the entire dynamic range of RapidArc was used. In most cases the GS was kept at a maximum speed (4.8° s⁻¹), indicating that this component tends to be used only in conjunction with a significant hypofractionation (e.g. the ICH abdominal metastases cases with mean DR of 591 MU min⁻¹ and a median GS of 3.68° s⁻¹). CP area, leaf aperture and field area scaled with the size (length and width) of the targets were as expected. Mean leaf aperture ranged from 2.5 to 4.6 cm; this aperture was significantly wider than the standard aperture observed with sliding window IMRT [25], where the mean leaf is normally <2.5 cm. The average ratio between CP area and field area defined by the jaws ranged from 0.17 to 0.30; this value was strongly correlated with the average leaf aperture in cm ($r^2=0.89$). Altogether, these relatively large geometrical dimensions directly contribute to keep the MU Gy⁻¹ low.

Figure 1. Examples of machine quality assurance tests for RapidArc. First row: acquired images and region-of-interest analysis. Second row: visual and quantitative analysis performed with the Epiqa software.

Table 3. Machine quality assurance for RapidArc: test 2 (dose rate and gantry speed)

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7	Mean
DR (MU min ⁻¹)	~105	~210	~315	~415	~520	~590	600	
IOSI 6 months	1.47 ± 0.13	0.30 ± 0.08	-0.33 ± 0.11	-0.51 ± 0.10	-0.61 ± 0.08	-0.48 ± 0.07	0.17 ± 0.13	0.00 ± 0.74 (-0.78 to 1.69)
IOSI 10 repetition	1.96 ± 0.12	0.50 ± 0.04	-0.10 ± 0.06	-0.44 ± 0.09	-0.61 ± 0.03	-0.62 ± 0.03	-0.70 ± 0.08	0.00 ± 0.96 (-0.82 to 2.08)
ICH 10 repetition	1.39 ± 0.35	0.61 ± 0.53	0.39 ± 0.17	-0.66 ± 0.17	-0.53 ± 0.13	-0.60 ± 0.06	-0.77 ± 0.18	0.00 ± 0.85 (-1.02 to 1.73)
USZ 10 repetition	2.15 ± 0.17	0.57 ± 0.10	-0.16 ± 0.10	-0.56 ± 0.09	-0.69 ± 0.08	-0.69 ± 0.08	-0.63 ± 0.20	0.00 ± 1.05 (-0.90 to 2.42)
Mean	1.75 ± 0.37 (1.29–2.42)	0.54 ± 0.20 (0.19–0.87)	-0.05 ± 0.31 (-0.56 to 0.68)	-0.54 ± 0.10 (-0.92 to -0.30)	-0.61 ± 0.06 (-0.84 to -0.37)	-0.60 ± 0.08 (-0.84 to 0.45)	-0.48 ± 0.43 (-1.02 to 0.32)	

Results are presented as the percentage deviation in each band with respect to the mean in all bands; tolerance was set to 2%.
IOSI, Oncology Institute of Southern Switzerland; ICH, Istituto Clinico Humanitas; USZ, University Hospital of Zürich; DR, dose rate.

Table 4. Machine quality assurance for RapidArc: test 2 (leaf speed)

	Band 1	Band 2	Band 3	Band 4	Mean
Leaf speed (cm s ⁻¹)	1.6	0.8	0.4	2.4	
IOSI 6 months	-0.08 ± 0.77	0.49 ± 0.50	0.60 ± 0.34	-1.01 ± 0.65	0.00 ± 0.65 (-1.72–1.26)
IOSI 10 repetition	-0.43 ± 0.36	-0.19 ± 0.91	0.98 ± 0.46	-0.36 ± 0.52	0.00 ± 0.66 (-1.53–1.55)
ICH 10 repetition	-0.41 ± 0.60	1.06 ± 0.96	0.00 ± 0.45	-0.65 ± 0.44	0.00 ± 0.76 (-1.40–2.45)
USZ 10 repetition	0.69 ± 0.45	0.33 ± 0.37	0.01 ± 0.28	-1.03 ± 0.18	0.00 ± 0.74 (-1.36–1.57)
Mean	-0.04 ± 0.52 (-1.43 to 1.57)	0.36 ± 0.52 (-1.53 to 2.45)	0.41 ± 0.49 (-0.83 to 1.55)	-0.73 ± 0.29 (-1.72 to 0.44)	

Results are presented as the percentage deviation in each band with respect to the mean in all bands; tolerance was set to 2%.
IOSI, Oncology Institute of Southern Switzerland; ICH, Istituto Clinico Humanitas; USZ, University Hospital of Zürich.

Figure 2. Three repeated measurements of a typical clinical RapidArc pattern performed at 3 month intervals to assess reproducibility: (a) 25/11/08; (b) 17/2/09; and (c) 14/5/09. The plot in the bottom right shows the gamma agreement index (GAI) values.

RapidArc machine quality assurance

Figure 1 shows an example of the three tests performed to assess machine performance as analysed by the Epiqa tool. The top row shows for tests 1, 2 and 3 the data acquired with the Portal Vision aS-1000 and re-elaborated by the software (also showing the regions of interest where numerical analysis is performed). The second row shows for each test the profiles along the solid line, which in this example corresponded to leaf 30.

All institutes passed test 1 at both acceptance and repeated instances without detecting any visible deviation in the picket fence pattern. Tables 3 and 4 summarise the quantitative findings for tests 2 and 3 repeated in the short term (10 consecutive repetitions within 1 h at IOSI, USZ and ICH) and in the long term (12 repetitions on a biweekly basis over a period of 6 months at IOSI). Results reported in the table are averages and ranges of the percentage deviation in each band with respect to the average in all bands. Evaluation was performed on readings inside rectangles centered in each band (as depicted in Figure 1). Rectangle analysis covers one-third of the band width and one-half of its length. In general, excellent results were achieved in bands 2–7 (test 2) and 2–4 (test 3), whereas in both cases larger deviations were observed in the first band. However, average deviations were within the 2% tolerance suggested by the manufacturer. Only in 2 out of 42 cases (<5% of tests of band 1 and <1% of all tests) was the deviation in band 1 of test 2 >2%. This could be due to either initial inertia in the gantry movement or initial instability of the low dose rate. All data from test 3 were within tolerance levels.

Figure 2 shows the results of three repeated measurements and the corresponding γ map (computed against reference) of the clinical pattern at 3 month intervals (the test is performed biweekly); the graph of the GAI trend over time is also depicted. Table 5 summarises the γ analysis performed on these tests and illustrates the high reproducibility of RapidArc in a clinical case where all dynamic variables are simultaneously changed.

As per comparison, data from IOSI on repeated clinical patterns for IMRT fields (65 repetitions over a period of 3 years for 4 fields) showed an average $\text{GAI} = 99.4 \pm 0.5\%$ (range 97.2–100.0%), consistent with the observed results for RapidArc.

Pre-treatment quality assurance dosimetric measurements

Figure 3 reports pre-treatment verifications for two examples. Calculated and measured dose maps are shown together with the corresponding γ map, dose

Table 5. RapidArc biweekly reproducibility tests over a period of 8 months at IOSI

Parameter	mean $\pm$ SD
No. of tests	16
Average γ	0.26 ± 0.01
SD γ	0.20 ± 0.01
GAI	
$\gamma < 1$ (range) (%)	99.2 ± 0.2 (98.4–99.4)
$1 < \gamma < 1.5$ (%)	0.7 ± 0.1
$\gamma > 1.5$ (%)	0.1 ± 0.0

GAI, gamma agreement index; IOSI, Oncology Institute of Southern Switzerland; SD, standard deviation.

Figure 3. Examples of pre-treatment dosimetric verification. Two-dimensional dose maps calculated by the planning system (left), two-dimensional dose maps converted into dose with GLAAs (right) and two-dimensional γ maps (centre). Profiles for the measured and calculated data along two orthogonal axes are shown below together with a histogram of the γ distribution.

Figure 4. Histogram of the gamma agreement index (GAI) of the cohort of 395 arcs.

profiles along orthogonal directions and a histogram of the γ distribution inside the modulated area. Figure 4 shows the histogram of the GAI distribution over the 395 arcs. Some 13% of the arcs showed $90\% < \text{GAI} < 95\%$ and only 2% (8 arcs) resulted in a $\text{GAI} < 90\%$. A more detailed analysis of these eight arcs highlighted three factors: the arcs corresponded to arcs planned for 18 MV photons, where lower GAI values are expected [11, 21]; a careful analysis of violation patterns showed that these were not connected to generate clusters located inside the field; and a profile analysis showed that deviations were mostly located between adjacent leaves from either tongue and groove or interleave leakage. These eight arcs were accepted by clinicians for treatment.

Table 6 summarises the results of the γ analysis. The results showed considerable coherence between the different sites; an average $\text{GAI} > 97\%$ confirmed the clinical reliability of the RapidArc delivery. As a comparison, the IMRT data from IOSI show that over a sample of 585 dynamic sliding-window fields (verified with the GLAaS method and using the same thresholds for γ analysis from plans calculated with the same version of Eclipse employed in this study) $\text{GAI} = 98.9 \pm 1.0\%$ (range 90.5–100.0%), $\text{GAI} < 95\%$ in approximately 1% of cases (5/585) and an average $\gamma = 0.26 \pm 0.06$.

GLAaS dosimetry as independent MU verification

Figure 5 shows a histogram of the difference between ion chamber (IC)- and GLAaS-measured doses at the isocentre when delivering the same arc using the MU

computed for the patient treatment. The average observed difference between IC and GLAaS was $0.6 \pm 1.4\%$ (range -3.7 to 3.5%). As reference, the mean difference between IC and Eclipse was $-0.2 \pm 1.6\%$ (range -3.4 to 3.7%), whereas the difference between GLAaS and Eclipse was $-0.9 \pm 1.1\%$ (range -4.1 to 2.2%).

Discussion

A retrospective investigation on technical and QA data from the treatment of 275 patients (395 arcs) from 5 departments was performed to provide evidence about RapidArc delivery features, accuracy and machine performance.

The analysis of technical and delivery parameters of RapidArc, with a variety of clinical indications and dose prescriptions, highlighted several factors. Firstly, treatments were mostly administered with single arcs (doubling the number mainly for long volumes or hypofractionated treatments). Secondly, beam-on time was typically < 2 min. Thirdly, the average dose rate was lower than the maximum allowed, suggesting significant potential for further modulation if needed and highlighting the possibility of increasing the dose/fraction within the same short delivery time. Fourthly, MU Gy^{-1} values were on average < 250 , lower than conventional IMRT or even 3DCRT. This observation suggests interesting perspectives from the radiation protection point of view (e.g. for long-term survivors or paediatric patients). Finally, the average size of CP and of the leaf aperture is relatively large, suggesting an intrinsic higher MU efficiency of the RapidArc algorithm compared with sliding-window IMRT.

The results from the machine-related QA procedures confirmed both short- and long-term stability and reproducibility of the dynamic elements of RapidArc delivery. Namely, tests performed according to the recommendations of Ling et al [9] demonstrated a reproducibility of GS, DR and MLC speed variations within 2% tolerance. This was also demonstrated by repeated measurements of clinical patterns. All the tests performed during rotation with integrated acquisitions do not permit identification of potential errors owing to gravity effects. These can nevertheless be identified and estimated, for example, by comparing picket fence tests during arc rotation with the same tests performed using the gantry fixed at different angles. Typically, angle

Table 6. Pre-treatment quality assurance with portal dosimetry (GLAaS method)^a

Institution	IOSI	ICH	CRLC	IOC	USZ	Total
No. of arcs	168	125	59	26	17	395
Average γ	0.31 ± 0.05	0.33 ± 0.05	0.38 ± 0.08	0.44 ± 0.07	0.31 ± 0.05	0.33 ± 0.06
SD γ	0.26 ± 0.08	0.25 ± 0.07	0.39 ± 0.11	0.40 ± 0.22	0.33 ± 0.10	0.39 ± 0.64
GAI ($\gamma < 1$)	97.6 ± 1.5	97.7 ± 1.6	94.2 ± 3.4	95.2 ± 2.4	96.8 ± 1.9	97.1 ± 2.4
(range) (%)	(91.4–99.9)	(93.2–100.0)	(84.7–98.9)	(90.1–98.5)	(93.1–99.0)	(84.7–100.0)
$1 < \gamma < 1.5$ (%)	1.8 ± 1.1	1.5 ± 1.0	3.0 ± 1.8	3.3 ± 1.7	1.8 ± 1.1	1.9 ± 1.3
$\gamma > 1.5$ (%)	0.6 ± 0.6	0.8 ± 0.7	2.8 ± 1.8	1.5 ± 1.2	1.3 ± 0.9	1.2 ± 1.4

^aDistance to agreement = 3 mm and dose difference (ΔD) = 3% were used to compute the gamma agreement index (GAI). The dose grid used for pre-treatment verification in all cases is the same as that used for patients (i.e. 2.5 mm or smaller).

Values given are mean $\pm$ SD. SD, standard deviation; GAI, gamma agreement index; IOSI, Oncology Institute of Southern Switzerland; ICH, Instituto Clinico Humanitas; CRLC, Centre Régional de Lutte contre le Cancer Val d'Aurelle–Paul Lamarque; IOC, Istituti Ospitalieri of Cremona; USZ, University Hospital of Sweden.

Figure 5. Histogram of the difference between the absorbed dose measured at the isocentre with an ion chamber (IC) and with GLAaS for 50 arcs.

selections of 0° , 90° , 270° and 180° might be sufficient to identify the presence of gravity effects; however, in the institutes participating in this study no such effects were observed.

Concerning the third aim of the study, the results shown in Table 6 for the pre-treatment verification of RapidArc are consistent with expected performances of the GLAaS method applied to IMRT, as derived from previous investigations [20, 21] and from the mono-institutional IMRT data set presented as a comparative sample. In addition, the present results are comparable with the summaries provided by other groups using different and independent dosimetric tools [12–14]. This observation proves that the machine delivers what it is instructed.

The possibility of using GLAaS as an independent verification of MU, inherent to the GLAaS method that generates absorbed dose matrices from acquired portal images, was confirmed in this study for RapidArc. Differences between IC measurements and GLAaS, at the isocentre, were on average $<1\%$, consistent with the same deviations obtained comparing IC data with TPS calculations for GLAaS *vs* TPS.

An important feature of the GLAaS-based verification of RapidArc is that the detector, the Portal Vision PV-aS1000, has a spatial resolution of $0.392 \text{ mm pixel}^{-1}$ [11]; this is the lowest value among all electronic dosimetric systems currently available commercially and is potentially bettered only by films (conventional or Gafchromic). The fine spatial resolution associated with GLAaS dosimetry is particularly important for two reasons. Firstly, Eclipse enables computation of dose maps with a grid ranging from 1 to 5 mm. Typically, grid sizes of 2.5 mm are used for clinical cases and this introduces in the “expected” dose map a certain degree of smoothing not present at delivery level (the MLC moves with a precision of 0.1 mm or more). The relevance of such smoothing cannot be detected by coarser detectors with spatial resolutions of 5–10 mm between measuring centres (*i.e.* the typical resolution of two-dimensional arrays) but can be assessed and investigated with EPID (and GLAaS). The second point of interest is linked to the interleaf leakage (IL) and tongue and groove (TG) detection. RapidArc optimisation and anisotropic analytical algorithm (AAA) calculation include an algorithm

designed to minimise the TG effect accounting for the leaf shape and, owing to delivery with collimator angles different from zero, the potential residual contribution from TG (and IL) is “smeared out” in the patient. Nevertheless, with GLAaS dosimetry being performed with the detector rotating together with the gantry and measuring the dose in a plane orthogonal to the beam for each gantry position, residual TG and IL accumulate on the same lines, allowing an estimate of their maximum impact and of their localisation (*e.g.* the small stripes in the γ maps of Figure 3). Note that for the eight cases with GAI $<90\%$, residual TG (and higher IL) played a significant role that was most evident at higher energy. This is mostly due to insufficient modelling in AAA (*e.g.* IL is not modelled) and the effect is enhanced at higher energy where the physical effects are more pronounced.

Concerning the GAI results, it is interesting to note that the group with the lowest GAI has similarly low mean leaf aperture and a low ratio between CP and field areas. These facts, owing to the clinical indications treated and from planning strategies (not addressed here) are consistent with similar findings for IMRT [25]. In IMRT studies, attempts were made to assess the importance of smoothing optimal fluence to improve agreement between calculation and delivery; here, it was shown how the mean leaf aperture directly correlated with the modulation index and, finally, to the level of GAI.

Although the γ analysis was performed on a collapsed dose matrix (*i.e.* generating a dose pattern quite different from that achievable from other methods), it is a valid instrument to verify the accuracy of calculation *vs* measurements. In fact, the loss of gantry angle information is a feature common to most systems (with detectors fixed on the treatment couch) in use for pre-treatment verification of modulated arcs. Time-resolved dosimetry systems are clearly desirable but, at the current stage of development, not commonly available.

Conclusion

A retrospective multicentre investigation of RapidArc technical characteristics and QA results established three factors: this new technique is reliably and accurately deliverable to patients; machine performances are reproducible and within tolerances in the short- and medium-term; and GLAaS-based dosimetry can be used routinely as a standard approach for rotational modulated therapy. The promising results reported here do not imply that patient-based pre-treatment verification can be relaxed at present. It is likely that even more advanced tests might detect subtle inadequacies of plans by further enhancing the sensitivity of QA procedures. Nevertheless, the methods applied in the present investigation—with the high spatial resolution of the detector and the usage of a collapsed reference dose map—are comparable with other phantom-based procedures.

Conflict of interest

L Cozzi acts as Scientific Advisor to Varian Medical Systems and is Head of Research and Technological Development at the Oncology Institute of Southern

Switzerland (IOSI), Bellinzona. The entire team from IOSI participated in the development of GLAaS and provide scientific support to EPIDos in their implementation of the GLAaS methods in the EPIQA package.

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