Chapter 7

Linac Twins in Radiotherapy

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Additional information is available at the end of the chapter

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Abstract

In a radiotherapy department having more than one linear accelerator, it is rather common to match the dose output of all machines. In particular, the recently developed flattening filter free mode requires new investigations regarding the feasibility of matching and the consequences for quality assurance and workload. This refers also to the beam model of the radiotherapy treatment planning system. Our results show that matching is possible not only for flat beams but also for flattening filter free mode. Therefore, the machines can substitute each other in the case of breakdown or service without new treatment planning even in the case of complex intensity-modulated radiotherapy or volumetric-modulated arc therapy. The quality assurance is reduced to only one data set for both the linear accelerators and the radiotherapy treatment planning system.

Keywords: linac twins, matched linacs, flatness filter free, FFF, quality assurance

1. Introduction

Electron linear accelerators (linacs) are the most common treatment machines in radiotherapy. Having two (or more) equal linacs (*linac twins* or also called *matched linacs*) enables a radiotherapy department to facilitate the workflow and to reduce the amount of quality assurance. The major part of the German standards (DIN) regarding quality assurance of medical linear accelerators has been reworked or has been published for the first time in the recent years due to technical developments. Similar updates have been published in other countries, e.g., by different task groups of the American Association of Physicists in Medicine (AAPM) [1-3]. However, these updates have again been overtaken by a technical novelty: the flattening filter free (FFF) mode. In modern linacs, it allows higher dose rates than used in the standard mode with flattening filter (up to three or four times), thus reducing treatment times at the cost of a nonflattened profile. This mode requires its own procedures for acceptance and quality assurance [4, 5].

The aims of this study are to setup a commissioning procedure and a quality assurance program for linac twins and to investigate if the time required for commissioning and quality assurance can be reduced as compared to two linacs of different types. This includes also the radiotherapy treatment planning system (RTPS). Although this investigation refers to the German standards and directives, the principles are valid for all countries. Although the concept of matched linacs has been mentioned earlier [6-10], the consequences for the quality assurance and standardization have not yet been regarded. This study will only investigate photon beam qualities. Characteristics of electron beams, portal imaging systems, and cone beam CT are not included. Although the concept and first results have been part of a congress proceeding [11], this chapter presents for the first time elaborated and generalized background, results, and discussion.

2. Materials and methods

2.1. Linacs

Tenders were invited to provide two linacs of the same type to replace the old Siemens Primus machines. We asked for linacs with two photon energies (6 and 15 MV) flattened beams (FB), additional FFF option for 6 MV, capability of intensity-modulated radiotherapy (IMRT) and volumetric-modulated arc therapy (VMAT), and five to six different electron energies between 4 and 22 MeV. Our requirement was that patients should be treatable at both machines with the same treatment plan. The first of the twin machines (Figure 1), an Elekta Synergy™ with Agility head, XVI cone beam CT, and Iview GT™ portal imaging, has been installed and commissioned according to earlier experiences [12] and has been running in the clinical routine for several months, but initially not FFF. The desktop software is Integrity 3.1. For the second linac, the installation has been completed in June 2014. The manufacturer specifies a routine for acceptance testing of linear accelerators [13], which refers to matched machines only pertaining to the beam quality.

2.2. Standards and guidelines for quality assurance

Although commissioning tests, the determination of basic performance characteristics, and consistency tests for linacs according the German standards [20] have to be accomplished for each machine, they can at least be set up identically without modifications for twin machines. This is also applicable for performance characteristics and consistency testing concerning special techniques as stereotactic radiotherapy [15, 16] and IMRT [17, 18], as well as electronic portal imaging devices (EPID) [14].

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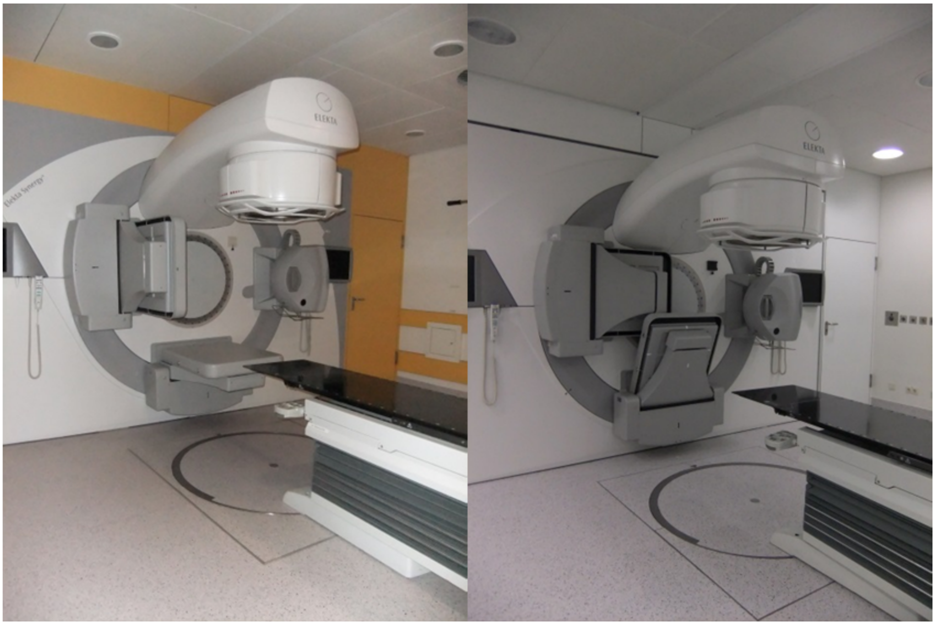

Figure 1. First and second of the linac twins: Elekta Synergy with Agility head.

The draft of the German standard for consistency tests of RTPS DIN 6873-5 [20] requires calculations for each treatment machine. Probably part 1 of DIN 6873 for commissioning of RTPS which is in development will demand this too. A technical report of the International Atomic Energy Agency (IAEA) [21] recommends checks for each photon and electron beam used in clinical planning and therefore each beam model and treatment machine. Having only one treatment machine model reduces time and effort for quality assurance and commissioning.

2.3. RTPS and water phantom

For commissioning of the linac model in the RTPS Oncentra® 4.3 (by Nucletron an Elekta Company), a set of geometrical data, absolute, and relative dose measurements have been measured [22] using a water phantom of the type Blue Phantom^2 of IBA company. It has been operated by the software OmniPro Accept 7.4, including a module for data export for Oncentra®. The data are processed by Elekta to create a model of the treatment unit, which takes several weeks according to our experience. Once the model is delivered by the company, it has to be validated by the customer. The RTPS comprises for this purpose the Beam Data Tool, which allows not only to compare measured and calculated dose distributions but also to adapt the size of the focus and the transmission of the collimator for final optimization. One aim of the study is to investigate if this procedure can be reduced to the validation process for the second linac.

The evaluation tools of the water phantom software were used to compare the measured dose distributions of both machines. For the graphical demonstrations, smoothing with least square algorithms was performed to get rid of some noise, and the curves were renormalized to the dose maximum on the central beam. The Beam Data Tool of the RTPS was applied for comparisons of measured and calculated dose distributions. For the calculations, the collapsed cone algorithm was used. The European Society for Radiotherapy and Oncology (ESTRO) gives tolerances as confidence limits for calculated doses [23]. The specifications of the manufacturer of the RTPS Oncentra® [24] are not always comparable, e.g., the shoulder region is not defined exactly, or dose deviations refer to different points, or different units are used (Table 1). We referred to the manufacturer's specifications in our evaluations as they have to be kept by the manufacturer's beam model and used the ESTRO's—modified to a gamma evaluation of 10% and 2 mm in the sharp gradient area—only for further investigations. Distance to agreement, dose deviation, and gamma evaluation [25] are the integrated evaluation options in the Beam Data Tool. The depth dose distributions and profiles in in-plane and cross-plane direction in depths of 5, 10, and 20 cm were evaluated for square field sizes of 2, 5, 10, 15, 20, 30, and 40 cm.

From the measured depth dose curves of fields of 10×10 cm² at a source surface distance (SSD) of 100 cm, the beam quality was derived as Q = D200/D100, with D200 the dose in 20 cm depth and D100 in 10 cm.

	Specifications Oncentra®	**Recommendations ESTRO**
Central 80% of field	±3%	±3%
Shoulder region	±4%	±2 mm
Regions outside the field	±5%	±30% local dose
Regions of sharp gradient	±3 mm	±2 mm or 10%

Table 1. Accuracy of dose calculations in percent of calibration dose or mm distance deviation to correct dose value

2.4. Breakdown concept

The German directive "Strahlenschutz in der Medizin" [26], paragraph 2.3.4, requires a concept to ensure patient treatment even during machine down times (e.g., maintenance or breakdown). Linac twins allow shifting all patients from one machine to the other without calculating new treatment plans. Sjöström et al. [8] provided this as main argument for matching linacs. Depending on the tumor type and the patient state, such a transfer is also advised by the Board of Faculty of Clinical Oncology of the Royal College of Radiologists [27].

The record and verify system (Mosaiq®, version 2.50) can be configured in a manner that fields for one machine can be delivered at the other without warnings or password confirmation. Some VMAT and IMRT plans (FB and FFF) calculated with the beam model for the first machine were measured on the other to verify the exchangeability using the 2D array Matrixx Evolution phantom and software OmniPro-I'mRT, version 1.7 of IBA.

The procedure for these plan verifications has been described in detail in earlier publications [12, 28]. The patient plans were transferred to a cuboid phantom of solid water (RW3 of the PTW company) with the Matrixx phantom in the center in a horizontal plane. The dose distribution was recalculated without modification of any parameter. When the phantom was irradiated with the original plan, the software recorded the dose. The measured dose was compared to the calculated dose by gamma evaluation [25] with a dose tolerance of 3% of the maximum dose and a distance to agreement of 3 mm. The first clinical IMRT plans with 6MV and for testing of the feasibility some single IMRT plans with 6MV FFF and VMAT plans were evaluated.

3. Results

3.1. Beam quality and measured dose distributions

The results of the beam quality evaluation of the percentage depth dose curves are given in Table 2.

	Linac 1	Linac 2
6MV	0.587	0.586
6MV FFF	0.583	0.584
15MV	0.648	0.648

Table 2. Beam quality Q = D200/D100 for both machines at the three photon beam qualities.

Although these nearly identical values have been calculated only for field size 10 × 10 cm², the depth dose curves in Figures 2, 3, and 4 show that the beam quality is comparable with other field sizes too as it is derived from depth dose parameters. Most of the curves are congruent. The presented figures show only a selection of all measured photon depth dose distributions. Due to the high congruence, the colors are often not clearly defined as in the figure texts.

Nominal field size in cm²	Linac 1	Linac 2
2 × 2	2.06	2.05
5 × 5	5.08	5.05
10 × 10	10.08	10.01
15 × 15	15.08	14.96
20 × 20	20.10	19.96

Table 3. Evaluation of the field size of 6 MV photons in cross-plane direction as given by the profiles in Figure 5.

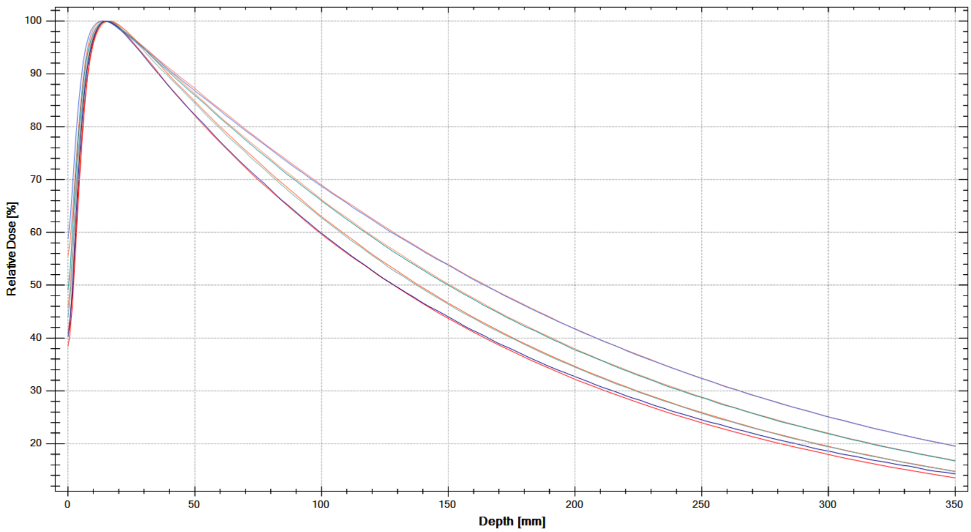

Figure 2. Depth dose curves for both machines of 6MV photons for square fields of 2, 10, 15, and 20 cm (left to right in the descending part). Red colors belong to the first, blue to the second linac.

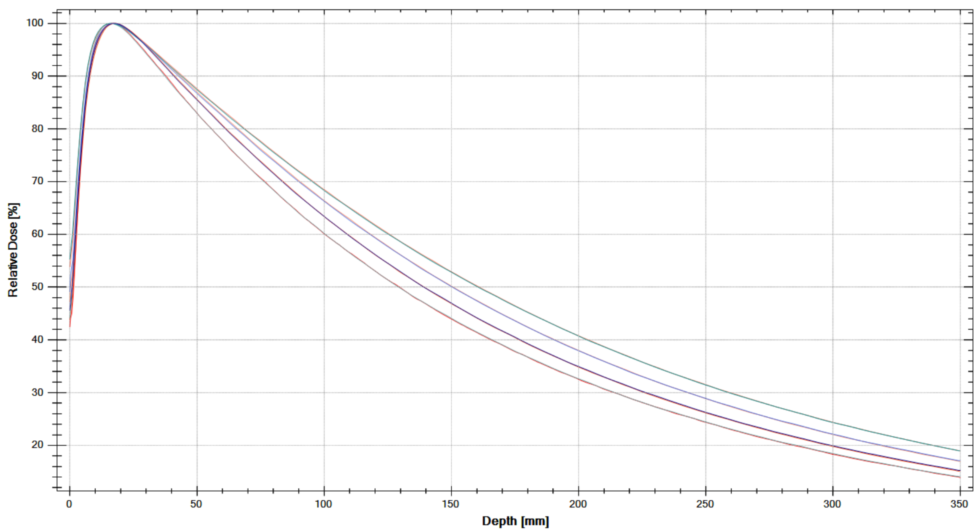

Figure 3. Depth dose curves for both machines of 6MV photons FFF for square fields of 2, 10, 15, and 20 cm (left to right in the descending part). Red colors belong to the first, blue to the second linac.

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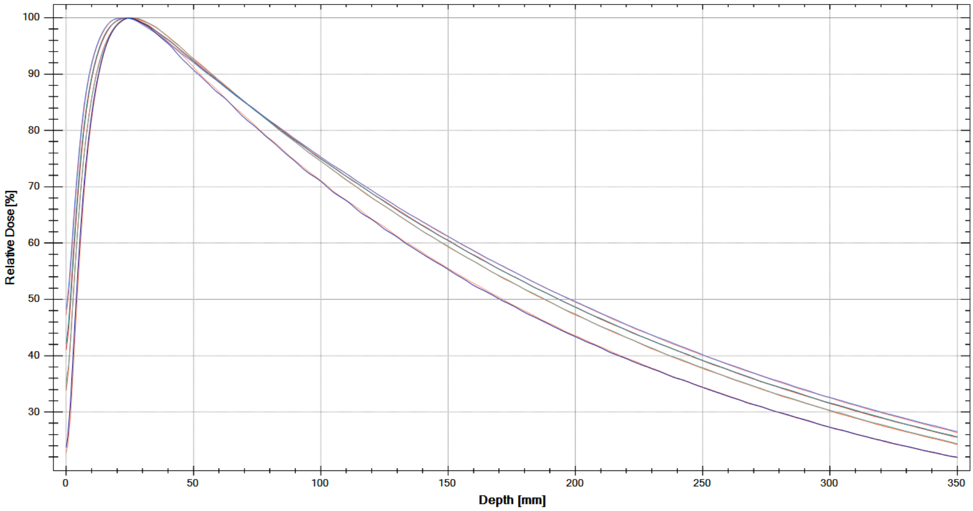

Figure 4. Depth dose curves for both machines of 15MV photons for square fields of 2, 10, 15, and 20 cm (left to right in the descending part). Red colors belong to the first, blue to the second linac.

The second group of figures shows profiles in the cross-plane direction in a depth of 10 cm. Others with further field sizes, in different depths, and in in-plane direction have been measured with similar results. The difference between the flattened and the flatness filter free mode is obvious; as the angular distribution of the bremsstrahlung is not compensated, the maximum dose is always on the central beam. The high congruence of the corresponding curves makes often only one of them visible, sometimes in a mixed color. Numerical values of the field size evaluation are given in Table 3.

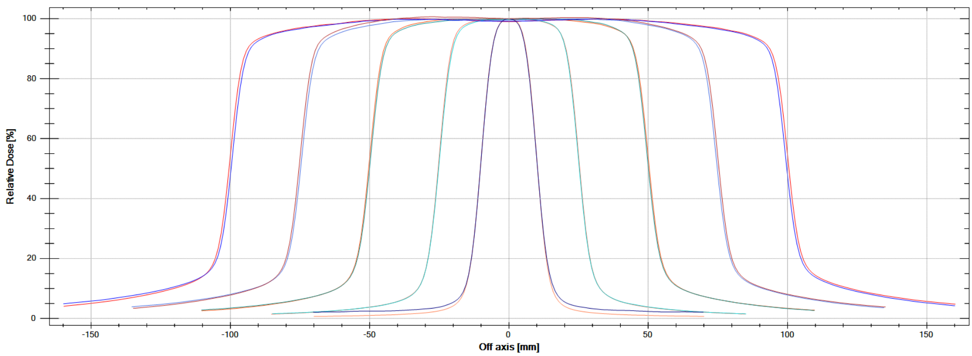

Figure 5. Profiles for both machines of 6MV photons for square fields of 2, 5, 10, 15, and 20 cm. Red colors belong to the first, blue to the second linac.

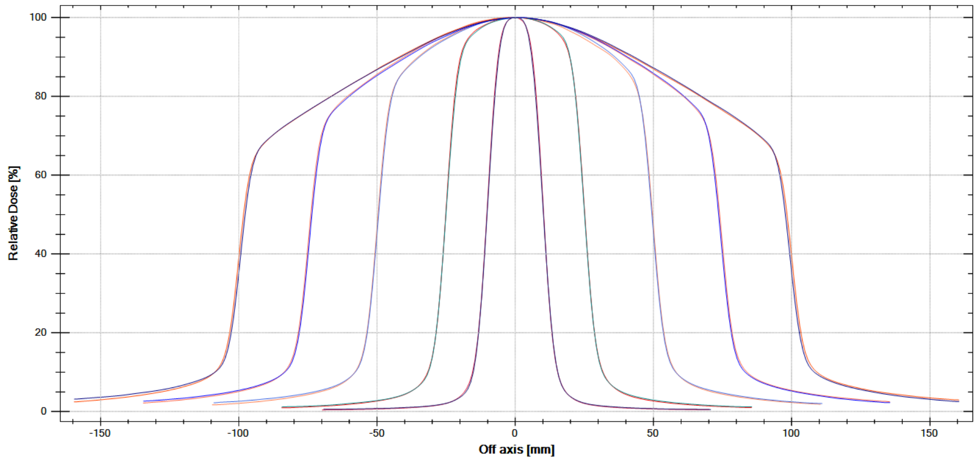

Figure 6. Profiles for both machines of 6MV FFF photons for square fields of 2, 5, 10, 15, and 20 cm. Red colors belong to the first, blue to the second linac.

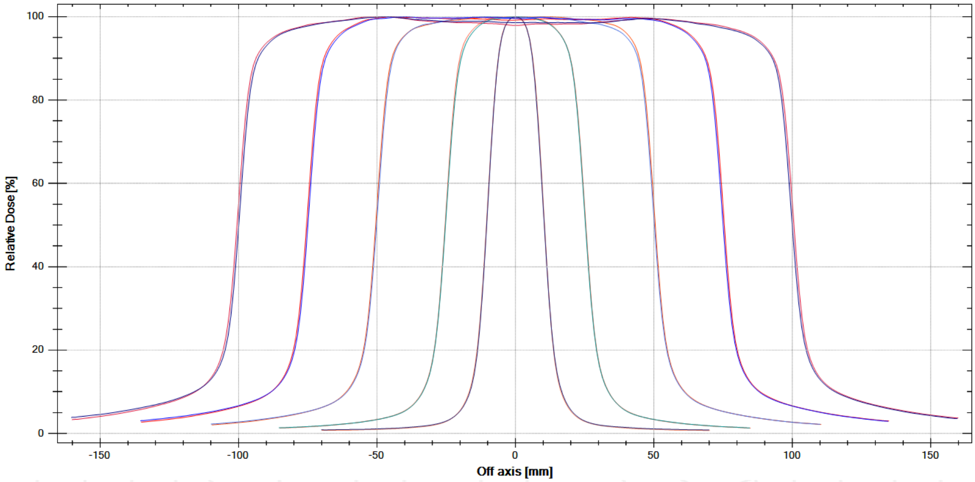

Figure 7. Profiles for both machines of 15MV photons for square fields of 2, 5, 10, 15, and 20 cm. Red colors belong to the first, blue to the second linac.

3.2. RTPS commissioning

As described above, no model for the second linac has been created in the RTPS, but all calculations were done with the first linac model and compared to the measurements of the second. Figure 8 shows the results of such a validation at an example of FFF profiles. The left ordinate refers to the measured and calculated profiles (green and orange), the right to the validation criterion. In the first step, both curves are compared using the dose deviation of the calculated dose from the measured dose. The horizontal orange lines show the limits of ±3%. They are not valid in the region of the field borders (high gradient). Therefore, the evaluation was repeated plotting the distance to the next point with the same dose with a distance to agreement of 3 mm in the second step. Here all points in this region are within the limits.

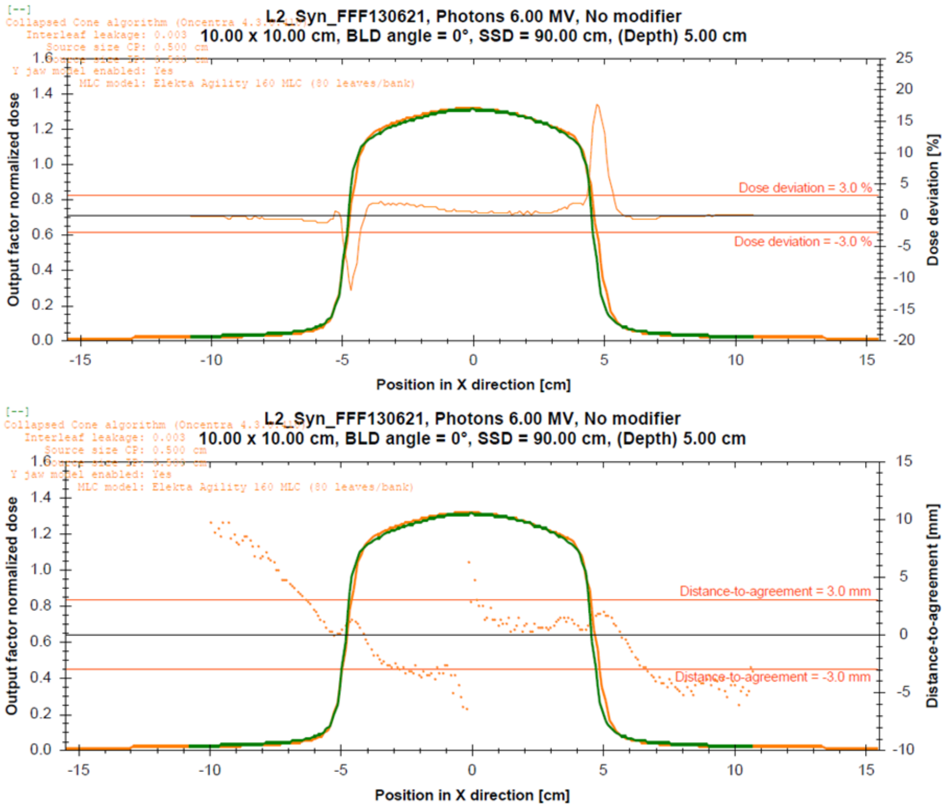

Figure 8. Profiles 6MV FFF as examples of the validation of the first linac model (calculated profiles in orange) in the RTPS for the second linac (measurements in green). In the upper part, a dose evaluation is shown (also in orange) referring to the right ordinate, in the lower part a distance to agreement evaluation.

All depth doses for 6MV, 15MV, and 6MV FFF were within the tolerances given by the specifications of the manufacturer. One example is shown in Figure 9. For a total amount of 42 analyzed profiles per energy, the specifications were met in the central region in every case. They were only excessed in single points in the gradient region of 6 MV for the smallest field size (2 cm square). The ESTRO recommendations were failed in single points of the two largest field sizes for the sharp gradient regions.

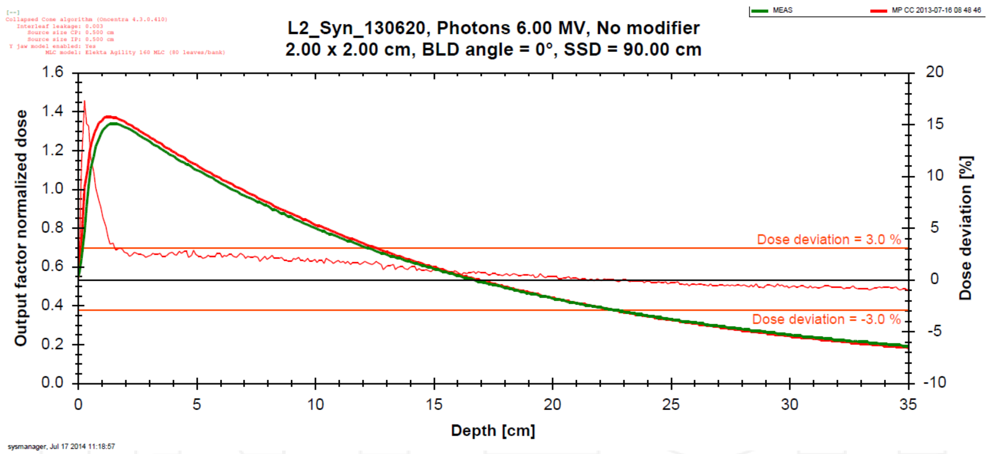

Figure 9. Depth dose curves of 6MV photons (calculation in red, measurement in green) for a field size of 2 cm square. The dose difference curve (also in red) refers to the right ordinate.

3.3. IMRT and VMAT plan verifications

Figures 10 and 11 show the evaluations of a VMAT plan with 6 MV and of an IMRT plan with 6MV FFF as it is presented on the screen of the OmniPro-I'mRT software. The upper left corner demonstrates the calculated dose distribution in the measurement plane, below the measured dose distribution can be seen. The upper-right corner presents profiles in both planes (calculated in red, measured in green). The position and the direction of these profiles are variable. The lower-right corner shows the gamma evaluation. Pixels in blue and white passed the evaluation. The number of pixels representing a specified value is given in the histogram below. Plans with a passing rate of 95% or more are accepted.

4. Discussion

The conformity of the depth dose distributions for the linac twins could be shown in the beam quality and the depth dose curves. The differences are in the order of repeated measurements at the same device. The quite unchanged beam quality of 6MV and 6MV FFF shows that not only the linacs are matched but also the FFF mode is matched to the flattened mode [29]. This is not self-evident; the beam hardening of the flattening filter must be compensated by the energy selection [30] that has been performed by the manufacturer.

The slight difference in the field size for the larger fields is within the specifications of the manufacturer [13]. However, this could be adjusted by the service engineer. From a practical point of view, the measured dose distributions are equivalent.

Therefore, the results allowed to continue with the validation of the model of the first machine in the RTPS for the employment at the second one. Deviations from the calculated dose above

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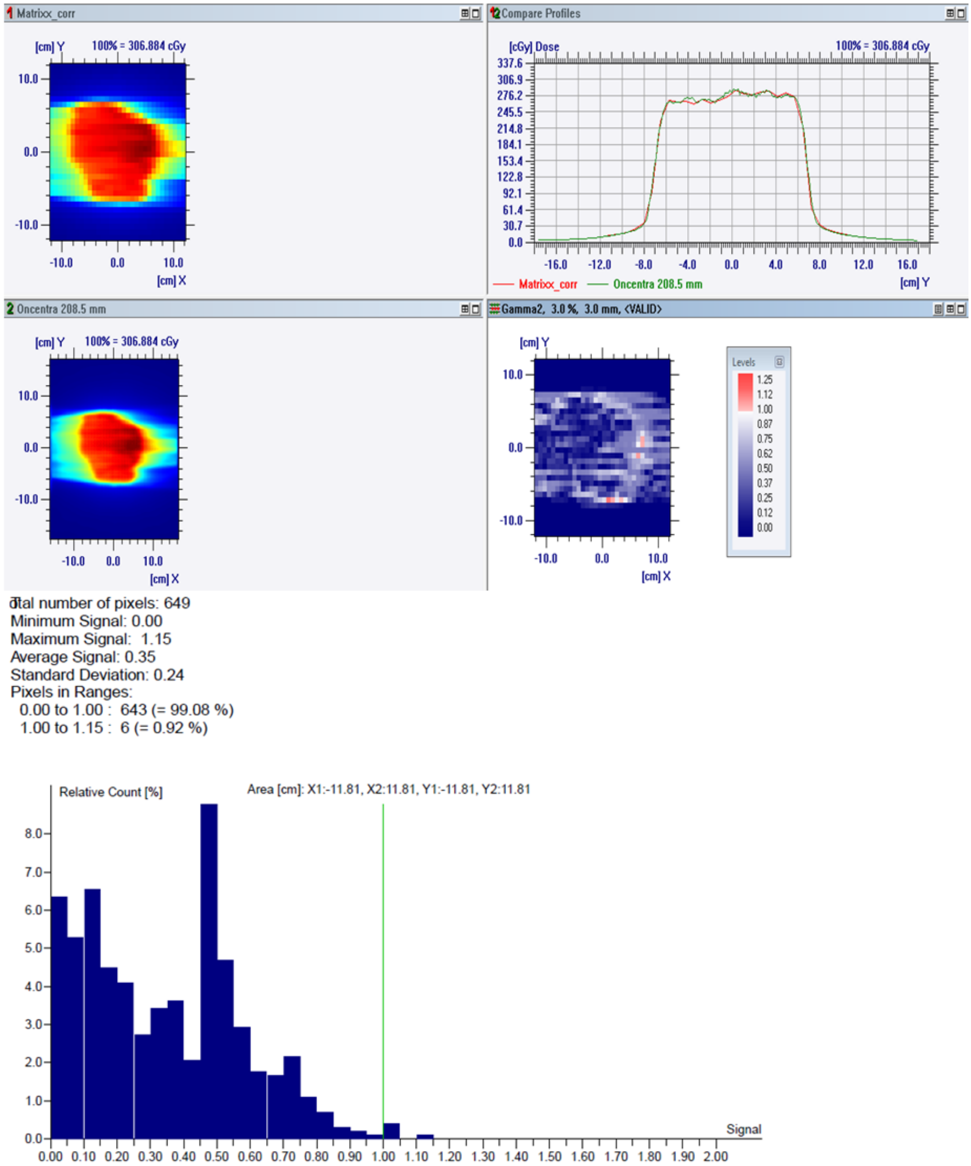

Figure 10. Plan verification of a VMAT plan with 6MV calculated for one machine and treated at the other. The gamma image was evaluated with 3% and 3 mm and showed a passing rate of 99%, which is indicated in the histogram below.

the specifications are exceptions in single points and have been assessed clinically to be acceptable. For example, exceeding the gamma criterion of 10% and 2 mm for the largest field size in the sharp gradient area can be traced back to the slightly different field size calibration

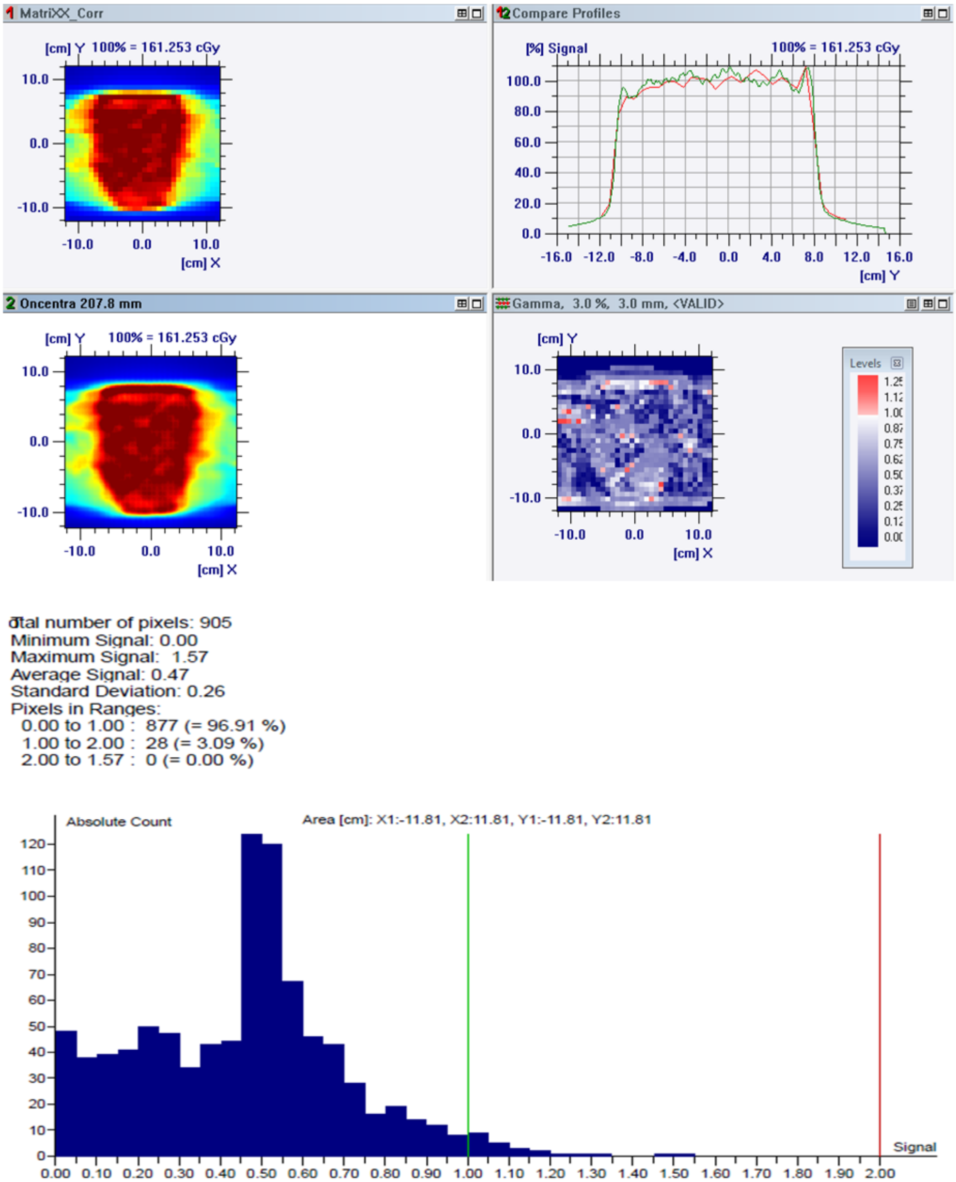

Figure 11. Plan verification of an IMRT plan with 6MV FFF, calculated for one machine and treated at the other. The gamma image was evaluated with 3% and 3 mm and showed a passing rate of 97% which is indicated in the histogram below.

of both machines, which has also be seen in the comparison of the measure data. Nevertheless, the specification of the manufacturer with a distance to agreement of 3 mm was met.

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Thus, the compatibility of the linac twins has been proven for the depth dose distributions and profiles on both main axes in different depths and for the full range of collimator apertures. The acceptance test of the manufacturer for matched linacs, which only refers to the beam quality, is only a first step and runs too short as it has also been reported for the matching process of another manufacturer [8].

The evaluations of different IMRT and VMAT plans, which had been calculated for the first machine and irradiated at the second one, showed very good results. The passing rates were in the same range as they had been seen for verifications at the "original" machine. The beam model in the RTPS of the first machine has been demonstrated sufficient for the second machine even for plans of very high complexity as IMRT with 6MV FFF or VMAT. This means that the second linac can substitute the first one in cases of breakdown. Chang et al. [10] had similar satisfying results for three matched Varian linacs. However, they first measured the data of all three linacs and combined them by averaging to get composite beam data. Having a time interval of several months or more between the installation of different linacs, as it is given in the case of replacement of old machines, this procedure is not applicable.

5. Conclusion

It has been shown that the dose distributions for all photon energies and modes could be adjusted equivalent. The new FFF mode presents no exceptions. Plan verifications of complex IMRT and VMAT plans demonstrate the exchangeability of the linacs also for the FFF mode, allowing continued therapy during downtimes, e.g., service works. Our results confirm that the time and effort for commissioning and quality assurance can be reduced for linac twins:

- There will be only one set of quality checklists, including the tolerance values.
- One beam model for both machines is sufficient in the RTPS.

Nomenclature

DIN; Deutsches Institut für Normung (German Institute for Standards)

ESTRO; European Society for Radiotherapy and Oncology

FFF; Flattening filter free

IMRT ; Intensity-modulated radiotherapy

Linac; Linear accelerator

RTPS; Radiotherapy planning system

VMAT; Volumetric-modulated arc therapy

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