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Evaluation of the Delta4 phantom for IMRT and VMAT verification.

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Abstract
The Delta4 diode array phantom (Scandidos, Uppsala, Sweden) was evaluated for verification of segmental intensity-modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) on an Elekta linear accelerator (Crawley UK). The device was tested for angular sensitivity by irradiating it from 36 different gantry angles, and the responses of the device to various step-and-shoot segment doses and dose rates were evaluated using an ionisation chamber as a comparison. The phantom was then compared against ionisation chamber and film results for two prostate and pelvic nodes IMRT plans, two head and neck IMRT plans and two lung VMAT plans. These plans were calculated using Pinnacle³ (Philips Radiation Oncology Systems, Madison, WI). The uniformity of angular response was better than 0.5% over the range of gantry angles, with the couch having a much larger effect of up to 4% depending on the obliquity of the beam in relation to it. The uniformity of response of the Delta4 to different segment monitor units and dose rates was better than 0.5%. The assessment of the IMRT and VMAT plans showed that the Delta4 measured a dose within 2.5% of the ionisation chamber and compared to film recorded about -2 to +7% more measurements agreeing with the planned dose to within 3% and 3 mm. The Delta4 is a complex device and requires careful benchmarking, but following the successful completion of these measurements, Delta4 has been introduced into clinical use.
1. Introduction

Complex radiotherapy treatment plans such as those involving intensity-modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) require dosimetric verification before clinical delivery (Ezzell et al 2003). The Delta4 phantom (Scandics, Uppsala, Sweden) offers a convenient means of achieving this. It consists of 1069 p-type Silicon diodes in a crossed array inside a cylindrical polymethylmethacrylate (PMMA) phantom, and associated computer software allows the user to compare the measured dose distribution for a complete treatment plan with the dose distribution predicted by the treatment planning system. The device records measured dose in relation to the individual accelerator pulses by using a trigger signal from the accelerator. Gantry angle is independently sensed by means of an inclinometer attached to the gantry or accelerator head. As this is a new device with new technology, an evaluation and benchmarking process is desirable before clinical use. Furthermore, since the device is not strictly independent of the accelerator, due to the trigger signal obtained from the accelerator, it is important to ensure that the device functions correctly for the accelerator in use. This study therefore evaluates the phantom by means of basic performance tests and by comparing its results with those produced by the more established methods of ionisation chamber and film (Bedford et al 2008b). Segmental (step and shoot) IMRT and VMAT are specifically considered, on Elekta linear accelerators.

2. Methods

2.1. Performance tests

Several basic tests were carried out to examine specific performance characteristics of the Delta4 phantom. These were not intended to be an exhaustive characterisation of the device, but rather to evaluate those features of the phantom in which greater confidence was required. The phantom was calibrated relatively and absolutely in the 6 MV beam. The November 2008 version of Delta4 software was used for all tests, and the work was carried out on an Elekta Synergy accelerator with a Beam Modulator head. This accelerator was running RTDesktop v7.01 and was fully commissioned for IMRT and VMAT (Hansen et al 1998, Bedford and Warrington 2009). The couch top was a carbon-fibre iBeam EVO type (Elekta/Medical Intelligence) and the measurements were carried out approximately 0.5m from the end of the full width section.
2.1.1 Angular sensitivity

The diodes in the phantom have an inherent angular sensitivity to radiation. This is corrected for by the Delta4 software, which compensates according to the known gantry angle of the beam being delivered. In order to check the accuracy of this correction, 36 10.4 x 9.6 cm beams with 200 MU were delivered at 10° intervals around the phantom. (10.4 x 9.6 cm on a Beam Modulator head is the equivalent of a 10 x 10 cm field on a normal head.) The response of the phantom was measured using the daily output correction facility of the Delta4. (The daily output correction measures the overall response of the Delta4 in relation to an arbitrary treatment plan, and offers the correction factor needed for agreement with that treatment plan; the reciprocal of this factor therefore gives the Delta4 response.)

2.1.2 Linearity of segment dose

An earlier version of Delta4 software was found to be inaccurate for multiple low-MU IMRT segments. The linearity of the Delta4 for delivery of segmental beams was therefore checked. A series of 10.4 x 9.6 cm beams were delivered at gantry angle 0°. The beams were for one segment with 80 MU, two segments with 40 MU each, four segments with 20 MU each, and eight segments with 10 MU each. The response of the phantom was measured using the daily output correction factor. A 0.6 cm³ Farmer ionisation chamber (Saint Gobain Crystals and Detectors, Reading, UK) was positioned under 3 cm of Solid Water (Radiation Measurements, Inc., Middleton, WI) centrally beneath the Delta4 phantom so as to correct for any true variation in accelerator output.

2.1.3 Dose rate dependence

The output of the Delta4 was examined as a function of dose rate. A series of 10.4 x 9.6 cm beams were delivered at gantry angle 0°. The dose rate of the beam was set to 600 MU/min, 300 MU/min, 150 MU/min, 75 MU/min and 37 MU/min. The output of the Delta4 was measured using the daily output correction factor. A Farmer chamber was also used to simultaneously correct for the accelerator output as in 2.1.2 above. Ion recombination within the ionisation chamber was measured at 600 MU/min and 37 MU/min and found to be around 0.5% in both cases, which was expected, as the dose per pulse of the Elekta accelerator is constant at all dose rates. As ion recombination was clearly a constant factor in the measurements of dose rate dependence, it was subsequently neglected.
2.2. Comparison studies

Having established that the basic performance of the Delta4 was satisfactory, the device was compared with the more traditional IMRT plan verification methods using ionisation chamber and film in a water-equivalent phantom. Six treatment plans were considered: two prostate and pelvic nodes IMRT plans, two head and neck IMRT plans and two lung VMAT plans. The prostate and pelvic nodes plans consisted of five segmental (step and shoot) beams, with approximately 10 segments per beam (Adams et al 2004), while the head and neck plans consisted of seven beams with approximately 10 segments per beam. The VMAT plans each consisted of a single gantry arc (Bedford et al 2008a). The IMRT plans were computed on the Pinnacle³ treatment planning system (Philips Radiation Oncology Systems, Madison, WI), and the VMAT plans were generated using an in-house program AutoBeam and a final dose calculation was made within Pinnacle³. The Pinnacle³ treatment planning system had previously been fully commissioned for IMRT (Bedford et al 2003, 2004). As the use of the planning system with the Delta4 involved calculating dose in PMMA, some additional measurements were made to ensure that Pinnacle³ was performing this correctly.

The six treatment plans were verified using an ionisation chamber and film, prior to patient treatment. The plans were delivered using an Elekta Synergy accelerator with standard multileaf collimator head and RTDesktop v7.01, and daily output of the accelerator was corrected for in all cases. The ionisation chamber measurements were made with a 0.6 cm³ Farmer chamber in a rectangular stack of Solid Water in a region of homogeneous dose. The film measurements were made using EDR2 (Eastman Kodak, Rochester, NY) and Gafchromic EBT (International Specialty Products, NJ) film. The film was located coronally in the same Solid Water stack as the ionisation chamber. The films were analysed using OmniPro I'mRT (Wellhöfer-Scanditronix, Schwarzenbruck, Germany) and normalised to a region of homogeneous dose. Ionisation chamber readings were required to be within 3% of TPS dose, and 90% of each film was required to satisfy a gamma criterion of 3% and 3 mm (Low et al 1998). For the Delta4 evaluation, the plans were delivered to the Delta4 phantom and the response compared with the ionisation chamber and film measurements. The absolute dose was assessed using the daily output correction factor, and the overall response was measured by recording the percentage of the measurements agreeing with the plan to within 3% and 3 mm.
3. Results

3.1. Performance tests

3.1.1. Angular response

The angular response of the Delta4 at a range of gantry angles is shown in Figure 1. The variation of the response from 270° through 0° to 90° shows that the variation in response is less than 0.5%. The effect of couch attenuation is included in the plot to show that this is much larger than the inherent Delta4 sensitivity to gantry angle.

3.1.2. Linearity of segment dose

The response of the ionisation chamber and Delta4 as a function of IMRT segment dose and number is shown in Figure 2. The response of the ionisation chamber is taken to represent the output of the accelerator. Compared to the ionisation chamber, it is clear that the Delta4 responds linearly to within 0.5% to the different IMRT segmentations.

3.1.3. Dose rate dependence

The response of the ionisation chamber and Delta4 as a function of accelerator dose rate is shown in Figure 3. Again, the ionisation chamber is taken to represent the accelerator output. The Delta4 responds to all dose rates similarly, to within 0.5% of the ionisation chamber.

3.2. Comparison studies

An example of the Delta4 output for one of the head and neck cases is shown in Figure 4, and the comparison of Delta4 with ionisation chamber and film for all of the clinical cases is shown in Table 1. There is no particular trend in the differences between doses recorded by ionisation chamber and Delta4, but the agreement is to within ±2.5%. On average, the Delta4 records a higher percentage of points agreeing with the planned dose to within 3% and 3 mm than film, with the range, relative to film, being from -2% to +7%.
4. Discussion

The Delta4 at first appears to be a straightforward device for measuring dose. However, because of the connection to the accelerator trigger output, which means that it is not necessarily completely independent of the accelerator, and because of the various software corrections made to the basic diode response after measurement, the device is complex and careful quality assurance and benchmarking before use is therefore recommended. In particular, the treatment plan to be verified must be recalculated on an artificial CT scan of the Delta4 phantom, which has a higher density than water. This density is less than optimal for most treatment planning systems. In the case of Pinnacle\textsuperscript{3} used in this study, it is known that the dose is subject to some uncertainty at high tissue density (Bedford \textit{et al} 2003). Further measurements carried out specifically in PMMA (results not shown) have shown that the dose calculated by Pinnacle\textsuperscript{3} for simple fields on PMMA is accurate to around ±2%.

The performance tests carried out in this study show that the basic Delta4 behaviour is accurate. The angular response is uniform over the complete range of gantry angles, with the couch attenuation being a much larger factor. For a VMAT plan, where roughly one third of the arc is through the couch, the iBeam EVO couch attenuation causes a drop in overall central dose of around 1%. The response of the Delta4 for segmental IMRT beams is accurate to within 0.5%, and the device handles the variable dose rate required for VMAT properly.

For the plan comparisons, the Delta4 absolute response is within about 2.5% of the ionisation chamber measurements. However, as the ionisation chamber measurement is over a much smaller volume than the Delta4 measurement, perfect agreement is not expected. Couch attenuation is present on both the ionisation chamber and Delta4 measurements. The gamma measurements are in reasonable correlation, with the cylindrical Delta4 showing slightly better agreement between measured and calculated dose than the film in the cuboid phantom.

Several general features cause that the results of the Delta4 should not necessarily be tested against the same criteria as the results of film and ionisation chamber. In particular, Delta4 uses a three-dimensional gamma calculation, which is more challenging than the two-dimensional one used for film. Moreover, Delta4 measurements are absolute, as opposed to measurements with film, which are relative. Consequently, an absolute dose difference manifests itself in the Delta4 gamma, whereas such a difference is typically removed in the film gamma by normalisation. On the other hand, the Delta4 is not susceptible to errors in
calibration and processing like film. Based on the results of these tests, it seems reasonable to maintain a
tolerance of 90% of the gamma map achieving 3% and 3mm agreement, or perhaps tighten the tolerance
slightly to 95% of the gamma map achieving 3% and 3mm.

Following these successful comparative measurements, the Delta4 has been introduced into clinical
use for IMRT and VMAT verification.

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Figure 3

Figure 4
Figure captions

Figure 1. Delta4 response as a function of gantry angle. The circumferential axis shows gantry angle in degrees, and the radial axis shows the percentage Delta4 response, normalised to the response at gantry angle 0°. The attenuation due to the couch is included in the response.

Figure 2. Variation of Delta4 response, as a function of number of segments and segment monitor units. Solid line: Delta4 response; dashed line: ionisation chamber response, representing accelerator output. Normalised to 1 x 80 MU response.

Figure 3. Variation of Delta4 response as a function of accelerator dose rate. Solid line: Delta4 dose; dashed line: ionisation chamber dose, representing accelerator output. Normalised to 600 MU/min.

Figure 4. Delta4 output for one of the head and neck cases. The two main panels show the planned dose distribution in greyscale and the measured dose in colour over the two detector planes. The histograms show (from left to right) dose deviation, distance to agreement and gamma (3% and 3 mm) of the measurements in relation to the treatment planning system.
Table 1. Comparison of ionisation chamber, film and Delta4. The ionisation chamber difference is the percentage difference of the measured dose in relation to the dose calculated by the treatment planning system. Delta4 difference is the response indicated by the daily correction factor. Gamma results are the percentage of points passing the gamma criterion of 3%/3mm.

<table>
<thead>
<tr>
<th>Case</th>
<th>Ion chamber diff (%)</th>
<th>Film ( \Gamma ) (%)</th>
<th>Delta4 diff (%)</th>
<th>Delta4 ( \Gamma ) (%)</th>
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</thead>
<tbody>
<tr>
<td>IMRT prostate/pelvic nodes</td>
<td>-0.4</td>
<td>89.2</td>
<td>-2.3</td>
<td>96.1</td>
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<tr>
<td>IMRT prostate/pelvic nodes</td>
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<td>98.7</td>
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<td>91.5</td>
<td>1.2</td>
<td>97.7</td>
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<tr>
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<td>93.2</td>
<td>0.2</td>
<td>96.5</td>
</tr>
<tr>
<td>VMAT lung</td>
<td>-1.1</td>
<td>97.6</td>
<td>-2.2</td>
<td>95.7</td>
</tr>
<tr>
<td>VMAT lung</td>
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<td>0.1</td>
<td>98.8</td>
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