Clinical Evaluation of Onrad, A New Low-cost Version of TomoTherapy that Uses Only Static Beams

TARO MURAI*,**, TAKESHI TAMURA**,†, TADASHI NAKABAYASHI‡, HIROYA ITO**,
YOSHIHIKO MANABE*,‡, RUMI MURATA**, MASANARI NIWA*,**
AND YUTA SHIBAMOTO

*Department of Radiology, Nagoya City University Graduate School of Medical Sciences, Nagoya 467-8601
**Department of Radiation Oncology, JA Suzuka General Hospital, Suzuka 513-8630
†Department of Radiation Oncology, Tatebayashi Kosei Hospital, Tatebayashi 374-8533
‡Accuray Japan incorporated, Tokyo 100-0004

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Summary: Objective: This study evaluated the clinical feasibility of a new low-cost TomoTherapy system (Onrad™) and compared it with low-cost linear accelerator models (linacs).

Methods: Various aspects of treatment and cost were compared between Onrad and linacs for 3-dimensional radiotherapy (3DCRT). Dosimetric comparisons of 10 patients each with breast, stage III lung, prostate, head and neck, and cervical cancers were carried out (total 100 plans).

Results: Onrad had advantages in terms of availability of long treatment fields and a smaller mechanical footprint. For breast cancers and lung cancers, target dose homogeneity in Onrad plans was better than that in 3DCRT. In the prostate plans, Onrad plans provided superior D95, conformity and homogeneity. The rectum doses of Onrad plans were lower than those with 3DCRT. Onrad plans provided superior homogeneity and D95 in head and neck cancer. The mean dose and V10–40 Gy of the parotid glands was lower using Onrad. In the cervical cancer plans, target doses were similar with both systems. Normal tissue doses were equal.

Conclusions: Onrad is useful in the clinical setting. Onrad can achieve favorable or comparable dose distributions compared with those of 3DCRT in actual clinical treatment of breast, lung, prostate, head and neck, and cervical cancers.

Key words TomoDirect, breast cancer, cervical cancer, head and neck cancer, lung cancer, prostate cancer, Onrad

INTRODUCTION

The TomoTherapy® System (Accuray Inc., Sunnyvale, California, U.S.A.) is a high precision radiation delivery system that provides intensity-modulated radiation therapy (IMRT) and image-guided radiation therapy (IGRT) using an on-board imaging system [1]. Treatment is usually delivered via 360-degree rotation of a 6-megavolt (MV) linear accelerator (linac) gantry (TomoHelical mode), or with fixed gantries (TomoDirect mode), but the cost of the full-version TomoTherapy system is almost twice the cost of a conventional linac [2]. Recently, a new low-cost TomoTherapy system, Onrad, has been introduced. In this model, radiation delivery is only available with the TomoDirect mode, but the cost is 40–50% lower.
than that of the full-version TomoTherapy and almost equal to that of conventional linacs capable of 3-dimensional radiation therapy (3DCRT).

The availability of Onrad is regionally limited to Japan and China at present, although it may also be distributed in Western countries in the future. In Japan, radiation therapy facilities are generally not centralized due to geographical features, i.e., many isolated islands, mountainous areas and so on. Besides, there are large aging populations in these areas. It is often difficult for patients in these areas to go to a distant centralized hospital due to their comorbidities. Therefore, radiotherapy machines in these areas have long played an important role in providing radical or palliative treatments for such cancer patients. According to a recent survey, more than 840 hospitals had a total of more than 1100 radiation therapy devices [3]. The Japanese government operates a universal healthcare system that covers all citizens based on the right to life (Constitution of Japan, Article 25). Conventional 3DCRT, stereotactic radiation therapy, particle therapy and IMRT are all covered by the system everywhere in Japan, though not for all cancers, and this situation will continue until the aging population declines in these rural areas. However, rural hospitals recently face financial hurdles including an increase in the cost of linacs. The cost of a linac has almost doubled compared with that in 2000. Thus, a low-cost radiotherapy machine is needed to maintain the current healthcare system in these areas. The new low-cost version TomoTherapy system, Onrad, is expected to play such a role, but it has not yet been installed anywhere in the world as of July 2018. In this study, the feasibility of Onrad was evaluated in a clinical setting. This is the first report on Onrad.

METHODS

Comparison of Onrad and conventional linacs

Various aspects of Onrad and low cost basic liniac models were compared from searches of the machine catalogs and vendor homepages. Actual costs and room sizes of the machines were obtained from interviews with the vendors. Room shield data were obtained from actual data on TomoHD System (6-MV photons) (Accuray Inc, Sunnyvale, California, U.S.A) and Clinac 21 EX (6- and 10-MV photons) (Varian Medical systems, Palo Alto, California, U.S.A) from Nagoya City University Hospital. These data were calculated under the following conditions: (1) clinical use for 100 hours per 3 months as the available time, (2) 2.1 g/m$^3$ as the concrete wall density, (3) 5 m as the distance between the radiation source and wall. The dose leakage was measured using correctly calibrated ionization chamber dosimeters. The dose calculation time and irradiation time were measured by actual clinical data in the same hospital.

Patients

After anonymization, computed tomography (CT) images of cancer patients were sampled from an image database. During the fixed period from 2015 to 2016, these patients were irradiated using TomoTherapy at Suzuka General Hospital for 5 diseases: (a) breast cancer, (b) stage III lung cancer, (c) prostate cancer, (d) head and neck cancer, and (e) cervical cancer. In total, 50 adult patients’ images were analyzed. The Onrad and conventional 3DCRT plans were generated using these images. Dose distribution comparisons of these 100 plans were carried out. All cancer stages were determined according to the 7th edition of TNM staging system. This study was approved by the institutional review board (IRB No. 133).

CT Simulation and planning

To reduce breathing motion and set-up errors, patients were held in a supine position using appropriate immobilization devices (Uni-frame® thermoplastic mask, CITCO Radiotherapy, Orange City, Iowa, U.S.A. and BodyFix® system, Elekta, Stockholm, Sweden) depending on the location of the radiotherapy target. In planning CT, 2 to 3 mm sliced axial images were acquired without a contrast material to avoid radiation dose overestimation [4] using a 64-row multi-detector CT (Aquilion CX, Toshiba Medical, Otahara, Japan). Contouring of target volumes and normal structures was performed on the Pinnacle3 version 9 treatment planning system (Philips Medical System, Eindhoven, Netherlands). The contours created in the treatment planning system were exported to the TomoTherapy treatment planning system v4.0, where Onrad plans could be generated as well. In addition, 3DCRT plans were generated in Pinnacle3 using conventional linac data (Clinac 2100C®, Varian Medical systems, Palo Alto, California, U.S.A.). For breast, lung and head and neck cancers, both Onrad and 3DCRT plans were generated with 6-MV photons. The 3DCRT plans for prostate and cervical cancers used 10-MV photons.

Dose distribution parameters and statistical analyses

The prescription dose was defined as the mean dose of the planning target volume (PTV) in Onrad plans and the isocenter dose in 3DCRT plans. As the
Onrad dose-constraints, (1) D95% > 90% of the prescribed dose and (2) V90% ≥ 95% were satisfied. DX% was defined as the minimum dose delivered to X% of the PTV. VY% was defined as the percentage of the PTV receiving at least Y% of the prescribed dose. A “fine” calculation grid (1.95 mm × 1.95 mm) was used for the final calculation process.

To compare Onrad and 3DCRT plans, the dose distribution of targets and organs at risk were evaluated. A conformity index (CI) and a homogeneity index (HI) were calculated according to the following formulae [5-7].

\[
\text{Homogeneity index (HI)} = \frac{(D_{2\%} - D_{98\%})}{\text{Prescribed dose}} \quad (1)
\]

\[
\text{Conformity index (CI)} = \frac{(V_{PTV} / TV_{PTV})}{(TV_{PTV} / V_{TV})} \quad (2)
\]

These formulae used the following abbreviations: \(V_{PTV}\) = PTV (cc), \(TV_{PTV}\) = lesion volume (cc) covered by the prescribed isodose, \(V_{TV}\) = prescribed isodose volume (cc). Lower CI indicates higher conformity, and lower HI indicates better homogeneity. The V Gy value represents the percentage volume receiving the specified dose, e.g., V60 Gy is the percentage volume receiving 60 Gy.

Dose-volume parameters were compared between Onrad and 3DCRT plans using the 2-tailed paired t-test. All statistical analyses were performed in R version 3.0.0 for Windows (http://www.R-project.org.). Statistical significance was defined as \(p < 0.05\). All planning was performed by two radiation oncologists independently.

**Planning for five types of cancer**

In the breast cancer plans (Figure 1 A, B), a clinical target volume (CTV) was contoured. The CTV was expanded by 5 mm for the PTV and 50 Gy/25 fr was prescribed. In the lung plans for stage III cancer, the prophylactic lymph node area and visible lesions were contoured as CTV1. The CTV was expanded by 5 mm plus a patient-specific internal margin for PTV1. First, 44 Gy/22 fr was prescribed to PTV1. As a second step, the visible lesions plus 5 mm margins were PTV2 and 16 Gy/8 fr was added as a boost. In total, 60 Gy in 30 fractions was prescribed. Four static ports were used in Onrad and 3DCRT plans (Figure 1 C, D). Organs at risk included the lung, skin and spinal cord. The dose constraints were: (1) lung: mean lung dose (MLD) < 20 Gy, V10 Gy < 40%, V20 Gy < 30% and (2) spinal cord + 5 mm margins: Dmax < 50 Gy.

In the prostate plans, the prostate and seminal vesicle were contoured as the clinical target volume (CTV) according to our protocol [8,9]. The CTV was expanded by 6 to 8 mm for the PTV. The prescribed dose was 74.8 Gy in 34 fractions. Five static ports (0, 75, 135, 225 and 285 degrees) were used for Onrad plans and four static ports (0, 90, 180 and 275 degrees) for 3DCRT plans (Figure 1 E, F). The dose constraints were: (1) rectum: V58.5 Gy < 18%, V38.5 Gy < 35%, maximum dose (Dmax) < 75.1 Gy and (2) bladder: V60 Gy < 20%, V40 Gy < 35%.

In head and neck cancer plans (Figure 1 G, H), prophylactic lymph node areas were contoured as the CTV according to the guideline [10]. Five static ports (0, 75, 135, 225 and 285 degrees) were used for Onrad plans. In 3DCRT plans, the half-field technique was
applied using four ports (0, 90, 180, and 275 degrees). The prescribed dose was 45 Gy/25 fr. The mean dose of the parotid glands was less than 26 Gy. The maximum spinal cord dose was less than 45 Gy.

For cervical cancers, the uterus, visible tumors and prophylactic lymph node areas were contoured as the CTV according to the guideline [11]. Five static ports (45, 105, 180, 255 and 315 degrees) were used for Onrad plans and four static ports (0, 90, 180 and 275 degrees) for 3DCRT plans. The prescribed dose was 45 Gy/25 fr (Figure 1 I, J). The rectum and bowel doses were reduced as much as possible. The maximum bowel dose was less than 50 Gy.

RESULTS

Comparison of Onrad and conventional linacs

Table 1 shows the characteristics of Onrad and conventional linacs. In Onrad, virtually all treatments are delivered as IMRT and IGRT, whereas these treatments are optional in conventional linacs. The maximum available length of treatment field is 135 cm for Onrad, while it is only 40 cm in linacs. Times required for treatment planning and delivery were somewhat longer for Onrad. Onrad has a 6-MV linac (dose rate, 8.5 Gy/minute) and a built-in counter shield, while conventional linac energy is usually 4, 6, or 10 MV (4-6 Gy/minute). As a radiation shield, a 1.5-fold thicker concrete wall is required for conventional 10-MV linacs than for Onrad. Compared to linacs, a smaller treatment footprint and less extensive shielding are required for Onrad. Both Onrad and conventional linac may be obtained at about half the price of their respective top models. The annual maintenance cost is lower in Onrad than in conventional linacs.

Planning comparison

Table 2 and Figure 2 show the dose distribution in targets and organs at risk. For breast cancers, the HI and D95 were better in the Onrad plans than those in 3DCRT plans (Table 1, breast cancer, $p < 0.0001$). The lung doses were similar in both plans (Figure 2A, $p > 0.05$). For stage III lung cancer, the Onrad plans achieved better uniformity of both targets (Table 2, stage III lung cancer, $p < 0.05$). The Onrad plans provided better conformity of PTV1 (Table 1, stage III lung cancer, 3DCRT vs. Onrad, 3.92 ± 1.46 vs. 2.60 ± 0.5, $p < 0.05$) and favorable target coverage (D95) of PTV2 (Table 1, stage III lung cancer, 56.1 ± 2.0 Gy vs. 58.0 ± 1.1 Gy, $p < 0.05$). The maximum doses to
TABLE 1. Characteristics of Onrad and conventional linac

<table>
<thead>
<tr>
<th>Onrad</th>
<th>Conventional linac (3DCRT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMRT*</td>
<td>Standard Option</td>
</tr>
<tr>
<td>IGRT†</td>
<td>Standard Dependent on version</td>
</tr>
<tr>
<td>Treatment field (length, cm)</td>
<td>135</td>
</tr>
<tr>
<td>Dose calculation time (minutes)</td>
<td>4 - 10</td>
</tr>
<tr>
<td>Actual irradiation time (minutes)</td>
<td>3 - 8</td>
</tr>
<tr>
<td>Radiation energy (mega-volt)</td>
<td>6</td>
</tr>
<tr>
<td>Dose rate (Gy/ minute)</td>
<td>8.5</td>
</tr>
<tr>
<td>Room size (meter square)</td>
<td>40</td>
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<tr>
<td>Room concrete wall shield (cm)</td>
<td>159</td>
</tr>
<tr>
<td>Shield against neutrons</td>
<td>Not required</td>
</tr>
<tr>
<td>Installation cost (%§)</td>
<td>40 - 50%</td>
</tr>
<tr>
<td>Annual maintenance cost (%§)</td>
<td>30 - 40%</td>
</tr>
</tbody>
</table>

* intensity-modulated radiation therapy, † image-guided radiation therapy, ‡ 3-dimensional radiotherapy, § % of flagship model.

TABLE 2. Target coverage in Onrad and 3-dimensional radiotherapy plans

<table>
<thead>
<tr>
<th></th>
<th>3DCRT‡</th>
<th>Onrad (Mean ± SD†)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breast cancer</td>
<td>PTV* CI‡</td>
<td>3.01 ± 0.98</td>
<td>2.25 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>HI‡</td>
<td>0.70 ± 0.06</td>
<td>0.15 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>D95 (Gy)</td>
<td>26.6 ± 3.7</td>
<td>45.6 ± 0.5</td>
</tr>
<tr>
<td>Stage III lung cancer</td>
<td>PTV1 CI</td>
<td>3.92 ± 1.46</td>
<td>2.60 ± 0.50</td>
</tr>
<tr>
<td></td>
<td>HI</td>
<td>0.44 ± 0.08</td>
<td>0.35 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>D95 (Gy)</td>
<td>42.5 ± 2.1</td>
<td>44.2 ± 1.3</td>
</tr>
<tr>
<td></td>
<td>PTV2 CI</td>
<td>6.3 ± 3.3</td>
<td>5.0 ± 2.1</td>
</tr>
<tr>
<td></td>
<td>HI</td>
<td>0.2 ± 0.0</td>
<td>0.1 ± 0.0</td>
</tr>
<tr>
<td></td>
<td>D95 (Gy)</td>
<td>56.1 ± 2.0</td>
<td>58.0 ± 1.1</td>
</tr>
<tr>
<td>Prostate cancer</td>
<td>PTV CI</td>
<td>5.79 ± 3.72</td>
<td>2.27 ± 0.31</td>
</tr>
<tr>
<td></td>
<td>HI</td>
<td>0.16 ± 0.03</td>
<td>0.12 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>D95 (Gy)</td>
<td>67.4 ± 1.0</td>
<td>70.9 ± 1.3</td>
</tr>
<tr>
<td>Head and neck cancer</td>
<td>PTV CI</td>
<td>2.33 ± 0.72</td>
<td>2.95 ± 0.39</td>
</tr>
<tr>
<td></td>
<td>HI</td>
<td>0.38 ± 0.28</td>
<td>0.13 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>D95 (Gy)</td>
<td>37.2 ± 10.2</td>
<td>43.1 ± 0.8</td>
</tr>
<tr>
<td>Cervical cancer plan</td>
<td>PTV CI</td>
<td>2.10 ± 0.50</td>
<td>2.38 ± 0.40</td>
</tr>
<tr>
<td></td>
<td>HI</td>
<td>0.12 ± 0.04</td>
<td>0.10 ± 0.05</td>
</tr>
</tbody>
</table>

* Planning target volume, † standard deviation, ‡ conformity index, †† homogeneity index, ‡ 3-dimensional radiotherapy
the spinal cord decreased in the Onrad plans (48.4 ± 4.3 Gy vs. 43.7 ± 3.0 Gy, p = 0.02). The lung doses of Onrad plans were similar to those of 3DCRT (Figure 2B, p > 0.05).

The HI, D95 and CI of Onrad plans for prostate cancers were better than those of 3DCRT plans (Table 1, prostate cancer, p < 0.0001). The maximum dose and V20, 30, 40, 50 and 60 Gy of the rectum of Onrad plans (Figure 2C, black lines with squares) were lower than those of 3DCRT plans (Figure 2C, red lines with squares, p < 0.05). In contrast, V10Gy of the bladder was lower in the 3DCRT plans than in the Onrad plans (Figure 2C, 3DCRT vs. Onrad, 51.8 ± 19.9% vs. 74.4 ± 18.8%, p = 0.02), while V40Gy, V50Gy, V60Gy and V70Gy of the bladder in the Onrad plans were higher than those in the 3DCRT plans (Figure 2C, p < 0.05). The maximum doses of the bladder and rectum in 3DCRT plans were lower than those in Onrad plans (bladder, 75.4 ± 0.4 Gy vs. 79.4 ± 1.5 Gy, p < 0.0001) (rectum, 74.4 ± 0.8 Gy vs. 76.1 ± 0.8 Gy, p < 0.0001).

In head and neck cancer, Onrad plans were better as regards HI and D95 (Table 2, head and neck cancer, p < 0.01). The mean dose and V10, 20, 30 and 40 Gy of both parotid glands were lower in Onrad plans (Figure 2D, p < 0.001). The spinal cord dose was also significantly reduced (3DCRT vs. Onrad, 46.6 ± 1.2 Gy vs. 42.7 ± 1.9 Gy, p = 0.001). Conversely, the conformity was inferior to 3DCRT due to dose spillage (Table 2, head and neck cancer, 2.33 ± 0.72 vs. 2.95 ± 0.39 Gy, p = 0.02).

CI, HI and D95 did not differ between the two plans in cervical cancer (Table 2, cervical cancer, p > 0.3). V40Gy of the bladder in Onrad plans were lower than those in 3DCRT plans (Figure 2E, triangles, 3DCRT vs. Onrad, 90.0 ± 5.8% vs. 79.0 ± 7.9%, p = 0.005), while 3DCRT plans reduced V10Gy of the bowel (Figure 2E, squares, 85.0 ± 8.5% vs. 92.1 ± 3.0%, p = 0.03) and V10Gy and V20Gy of the rectum (Figure 2E, circles, p < 0.05).

DISCUSSION

When Onrad and conventional linacs are compared, IMRT and IGRT are routinely delivered with Onrad, while they are optional and installation of additional hardware and software for IMRT and IGRT represents an extra cost with conventional linacs. One of the greatest advantages of Onrad (and TomoTherapy) is the availability of long treatment fields (up to 135 cm); long targets can be treated without gaps. Onrad can optionally be upgraded to the TomoHDA system. Dose distribution of the Onrad (and TomoDirect) plans is intermediate between 3DCRT and TomoHelical plans. However, dosimetric comparison between 3DCRT and TomoDirect plans for targets other than the breast has not been carried out yet [12,13].

According to the Japanese Radiation Oncology Database (JROD) (http://www.jastro.or.jp/aboutus/JROD2015.pdf), the five cancers investigated in the present study are the most frequently treated with radiotherapy in Japan. Breast conservative therapy is widely accepted in Japan, even in rural areas. Recently, IMRT has been clinically applied to breast conservative therapy in some institutions [12,15]. Concurrent chemoradiotherapy is the standard treatment for stage III lung cancer [16,17]. The TomoHelical mode is generally preferred to the TomoDirect mode in TomoTherapy treatment for head and neck cancer, prostate cancer, and cervical cancer. In the 2000s and earlier, these patients were treated with 3DCRT, but recent studies suggest that IMRT should be the first-line treatment for these cancers [20-22]. Thus, they should be treated with IMRT at every institution.

In the current analysis of prostate cancer, the rectum doses were lowered and target coverage and conformity improved in the Onrad plans. In addition, the parotid gland doses were reduced in Onrad plans for head and neck cancers. While the conformity was inferior to 3DCRT as regards dose spillage, the homogeneity and dose coverage in Onrad plans were favorable. These results suggest that Onrad plans can provide a favorable dose distribution, better target coverage, and sparing of organs at risk in clinical settings.

Onrad breast plans in the current study provided better target coverage and more homogeneous dose distribution than 3DCRT. The results are consistent with previous reports in which TomoDirect plans and 3DCRT plans were compared [12-14]. Nagai et al. [12] reported the clinical outcomes of 152 patients receiving TomoDirect treatment for breast cancers. The three-year local control rate was 99%. Grade 2 or higher acute radiation dermatitis was observed in 15.8% of the patients and grade 2 radiation pneumonitis in 2.7%. Similar clinical results were reported by Lee et al. [15] These clinical data indicate the feasibility of the TomoDirect mode. The dose distribution for breast cancer in Onrad plans is equal to that in TomoDirect. Although electron beams cannot be used in Onrad, decreases in the skin dose can be avoided by using a bolus. Boost irradiation to the breast tumor bed can also be delivered using Onrad. Therefore, Onrad for breast cancer would provide at least acceptable clinical outcomes.

For stage III lung cancer, the present study showed...
that Onrad plans achieved better uniformity and coverage of the targets than 3DCRT plans. Previous studies suggested that TomoDirect plans were more favorable in dose distribution than TomoHelical plans for lung cancer [2,18,19]. Murai et al. [2] reported that, in lung cancer treatment, V5Gy of the lung in the TomoDirect mode was lower than in the TomoHelical mode. Low dose irradiation to the lung often induces severe toxicity in concurrent chemoradiotherapy. Thus, Onrad treatment may reduce lung toxicity in stage III lung cancer treatment. In terms of dose distribution, Onrad is possibly the best option for lung cancer.

In contrast, the Onrad plans for cervical cancer appeared to have both advantages and disadvantages compared with 3DCRT. In contrast to the other 4 cancers, the dose distributions in Onrad and 3DCRT plans for cervical cancer were comparable or equivalent. Hashimoto et al. [23] reported a planning study for cervical cancer, in which 7-field IMRT provided better target coverage and risk-organ sparing, compared with 3DCRT plans. The difference between our results and those of Hashimoto et al. may be due to the use of fewer ports in our Onrad plans. In cervical cancer, the target is surrounded in all directions by organs at risks like the bowel, rectum and bladder, compared with prostate and head and neck cancers. Seven or more ports might improve the dose distribution, while the irradiation time would reach 10 minutes or longer. The total treatment time including set-up and pretreatment image-acquisition would exceed 30 or more minutes. Thus, considering clinical feasibility for frail patients, it may be difficult to realize the advantages of Onrad in cervical cancer plans. This may be the reason why Onrad and 3DCRT treatments for cervical cancer are almost equivalent.

This study has the following limitations so the results should be interpreted carefully. First, differences between planning doses and actual doses were not verified. Therefore, physics quality assurance must be carried out for each treatment plan. Second, we evaluated dosimetric aspects of Onrad plans using the radiotherapy planning system. Dose build-up by the couch effect might not be fully calculated on the system. Therefore, we must caution that the risks of radiation-induced dermatitis may be underestimated in lung, pelvis or head and neck plans. Finally, with regard to clinical aspects, treatment and planning times of Onrad are generally longer than those of 3DCRT. At least 1 or 2 days is needed for preparation. Furthermore, patients with bone metastases often move during treatment due to the pain. An opioid or a nonsteroidal anti-inflammatory drug should be administered, and irradiation should be delivered thereafter [24]. In Onrad treatment, these patients may be treated with 2-opposed ports to reduce planning and treatment times.

On the other hand, although the cost of Onrad is similar to that of conventional linacs, the treatment equipment has a smaller footprint and less extensive shielding is required because the beam energy is 6 MV and non-coplanar beams are not used. Thus, additional expansion of radiation shields is not necessary for the installation. Thus, Onrad seems to have various advantages over conventional linacs when small and middle-sized hospitals replace old machines, where not so many patients are treated.

CONCLUSIONS

Onrad has various advantages over conventional linacs. Onrad can achieve more favorable dose distributions than 3DCRT in the treatment of breast, lung, prostate, head and neck cervical cancers. The introduction of Onrad should provide opportunities for patients to receive the current standard treatment in facilities where 3DCRT has been used.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE: This study was reviewed and approved by the institutional review board (No. 133). Patients were given a chance to opt-out of this study.

COMPETING INTERESTS: Dr. Shibamoto received a research fund from Accuray Japan, Inc., in 2015. Dr. Nakabayashi is an employee of Accuray Japan, Inc.

AVAILABILITY OF DATA AND MATERIALS: The presented data are summarized in this paper. The complete datasets can be obtained from the authors upon formal request.

AUTHORS’ CONTRIBUTIONS: Each author participated sufficiently in the work to take public responsibility for appropriate portions of the content. TM and YS designed the study. TN provided technical support for the TomoTherapy planning system. TM, TT, TN, MN, RM and HI collected the data. TM, YM and YS interpreted the data and made some figures. The manuscript was written by TM and YS; all other authors helped. All authors read and approved the final manuscript.

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