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The influence of photon energy on dose distribution for IMRT and VMAT plans

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Purpose. Estimation of the difference between photon X-6MV and X-20MV beams for IMRT and VMAT plan's, in respect to dose-volume results and irradiation time (MU).

Materials and methods. For each of 74 selected patients four plans, two IMRT with X-6MV & X-20MV beams and two VMAT: X-6MV & X-20MV arcs, were performed. Patients were divided into two groups according to tumor localization: head & neck (H&N) and pelvis. Those localizations were chosen to highlight potential differences regarding the depth of target volume. Each plan was optimized using the same plan objectives and constraints. Plans were compared according to dose-volume results for target and Organs at Risk (OaR's) with Radiation Planning Index (RPI), and beam on time regarding the monitor units (MUs).

Results. The mean RPI factor for both technique (IMRT/VMAT) and energies (X-6MV/X-20MV) were similar for H&N region in the range of 0.2310–0.2934 and for the pelvis region the range was 0.3683–0.4007. The difference were not statistically significant ($p > 0.05$), showing the photon between 6–20 MV, doesn't influence the dose-volume results, for both localization: H&N and pelvis. The mean monitor units in IMRT plans varied from 765 MU to 1116 MU, as in VMAT plans it was from 325 MU to 492 MU. Generally, the number of MU on IMRT technique is greater than MU's in VMAT (difference statistically significant), regardless of the beam energy (X-6MV, X-20MV) and localization (H&N, pelvis). Both techniques; IMRT and VMAT plans with higher photon energy, showed shorter irradiation time (expressed in MU). But, only for pelvic region on VMAT technique, is statistically significant ($p = 0.0467$).

Conclusions. On average, photons beam, between 6–20 MV don't induce significant dose-volume difference. However, higher energy used for planning regions other than head & neck, minimizes the number of MUs and significantly reduces the time of irradiation. Furthermore, reduction of beam on time can be achieved by using VMAT plan rather than IMRT plan.

Wpływ energii wiązek fotonowych na rozkład dawek dla planów IMRT i VMAT

Cel. Ocena różnic w planach IMRT i VMAT pomiędzy wiązkami X-6MV i X-20MV w odniesieniu do uzyskanych rozkładów dawek oraz czasu napromieniania (MU).

Materiały i metody. Na potrzeby porównania wybrano 74 pacjentów, następnie dla każdego obliczono 4 plany: dwa w technice IMRT z wiązkami X-6MV i X-20MV oraz dwa w technice VMAT z łukami X-6MV i X-20MV, uzyskując rozkłady dawek. Pacjentów podzielono na dwie grupy zgodnie z obszarem napromienienia: rejon głowy/szyi oraz rejon miednicy. Lokalizacje zostały wybrane w celu uwidocznienia ewentualnych różnic wynikających z różnych głębokości na których zdefiniowano obszar tarczowy. Każdy plan był optymalizowany z wykorzystaniem z tych samych wytycznych i ograniczeń związanych z obszarami anatomicznymi. Plany zostały następnie porównane pod względem dawek dla obszarów tarczowych i organów krytycznych z użyciem współczynnika RPI (*Radiation Planning Index*). Następnie porównano czas napromieniania w ujęciu liczby jednostek monitorowych MU.

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Wyniki. Średnie współczynniki RPI dla obydwóch technik (IMRT/VMAT) i energii wiązek/łuków (X-6MV/X-20MV) były porównywalne i zawierały się w przedziale 0,2310–0,2934 dla rejonu głowy i szyi oraz 0,3683–0,4007 dla rejonu miednicy. Różnice nie były statystycznie istotne (p > 0,05), wykazując brak wpływu wyboru energii wiązek/łuków na uzyskane rozkłady dawek dla obydwu obszarów napromieniania: głowy/szyi oraz miednicy.
Średnia liczba jednostek monitorowych zawierała się w przedziale 765 MU do 1116 MU dla planów w technice IMRT oraz 325 MU do 492 MU dla planów w technice VMAT. Liczba jednostek monitorowych w planach wykorzystujących technikę IMRT była zawsze większa od liczby jednostek w planach z techniką VMAT (potwierdzona istotnością statystyczną), niezależnie od stosowanej energii wiązek/łuków oraz napromienianego regionu głowa/szyja/miednica. Wykorzystanie wiązek/łuków o wyższej energii podczas planowania z wykorzystaniem każdej techniki (IMRT i VMAT) skutkowało zmniejszeniem czasu napromieniania (rozpatrywanego w oparciu o jednostki monitorowe), jednak tylko w przypadku techniki VMAT i obszaru miednicy jest to poparte istotnością statystyczną (p = 0,0467).
Wnioski. Zasadniczo wybór energii wiązek z przedziału 6–20 MV nie wprowadza znaczących różnic w uzyskiwanych rozkładach dawek, jednakże wykorzystanie wyższej energii w obszarach napromieniania innych niż głowa/szyja zmniejsza liczbę jednostek monitorowych i znacząco skraca czas napromieniania. Ponadto dalsze skrócenie czasu napromieniania jest możliwe z zastosowaniem techniki VMAT zamiast IMRT.

Key words: beam energy, IMRT, VMAT, RPI
Słowa kluczowe: energia wiązek, IMRT, VMAT, RPI

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Introducion

Photon beams within the range of 6–20 MV are commonly used for therapeutic purposes. In basic 3D-CRT planning, low energy beams, typically X-6MV, are effective for irradiation of lesions near the surface, because of their short build-up factor, faster increase of dose near the skin and minimizing dose below the target. While the higher energy beam up to X–20MV are more suitable for deeper located targets, like prostate tumors. Higher energy in treatment planning usually allows lowering of the global maximum dose and minimising the amount of dose deposited in healthy tissue.

Since the introduction of dynamic treatment techniques capable of moving leaves and changing dose rate, such as Intensity Modulated Radiation Therapy (IMRT) or Volumetric Modulated Arc Therapy (VMAT), the role of photon energy became negligible. IMRT improves radiation treatment by introducing a more conformal planning method, which results in higher-dose delivered to planning target volume (PTV) while decreasing the dose to normal tissue and organs at risk (OaR) [1]. Fixed-field IMRT delivers radiation from a predetermined number of fixed beams using an inverse planning algorithm and a dynamic multi leaf collimator (DMLC) delivery technique known as sliding window [1]. A novel form of IMRT is the VMAT. It is a complex technique with continuous modulation of the multileaf collimator field shape, fluence rate and gantry rotation speed [2]. It is reported that it obtains similar results to intensity-modulated radiotherapy (IMRT) with only single 360° rotation [2]. One of the benefits of VMAT is the increase in delivery efficiency [3].

Aim

The aim of this study was to compare the influence of photon energy on treatment plans. Four main questions were asked:

- whether photon energy has an influence on dose to volume results in IMRT and VMAT planning?
- whether photon energy has an influence on the amount of monitor units in IMRT and VMAT planning?
- is there a difference in dose to volume results between IMRT and VMAT, with the same photon energy?
- and is there a difference in the amount of monitor units between IMRT and VMAT, with the same photon energy?

Materials and methods

To compare the implications of the photon beam energy, treatment planning was performed retrospectively on 74 patients. The analyzed group consisted of: 39 patients with tumors located in pelvic region and 35 patients with tumors located in head and neck (H&N) region. These areas were chosen for the significant difference in 'depth' of defined therapeutic volume and to highlight any possible differences in the result. For the H&N area we can assume that target volumes are generally located at depths smaller than 10 cm, while in the pelvic area targets are generally situated at depths exceeding 10 cm.

All plans were made on Eclipse planning treatment system, version 8.6 (Varian Medical System, Palo Alto CA) on a Dell Precision T5400 workstation personal computer with an Intel Xeon CPU at 2,50 GHz and 16 GB of RAM. Optimization of IMRT plans was made by the dose-volume optimizer (DVOII, version 8.6). Respectively, the VMAT plans were made using Varian RapidArc option and were optimized with progressive resolution optimizer (PROII, version 8.6). Both optimizers used 120-leaf multi-leaf collimators (MLC). Dose calculation was performed using the anisotropic analytical algorithm (AAA, version 8.6) for both IMRT and VMAT plans. For all IMRT plans a dose rate of 300 MU/min was used and a 600 MU/min dose rate was used for all VMAT plans.

Dose calculations were made based on CT and contours that were originally prepared for patient treatment. For each of the patients four corresponding plans were used, two IMRT plans, one using photon X-6MV beams and another using photon X-20MV beams, and two VMAT plans one with only X-6MV arcs and another with X-20MV arcs.

The originally prepared plans for each patient were used, which was either IMRT or VMAT. Then the beam energy was switched, from X-6MV to X-20MV or from X-20MV to X-6MV. Two plans with the second technique were then made, with the same constraints and optimization objectives. With this approach we narrowed the analysis of the plans to only two variables: the dose-to volume result and the number of MUs needed to be delivered.

For example, when a patient had an IMRT based plan with six X-6MV beams, that plan was taken into analysis. Afterwards, without changing any geometry, described dose or dose rate, only the energy of the beams was switched to X-20MV. The optimization was run basied on original fluence maps until it reached the plateau and was then calculated. A VMAT plan was prepared using one X-6MV arc (if necessary two arcs) and the same optimization objectives, until it reached plateau and was then calculated. No additional changes during optimization were made. Finally the fourth plan was made by switching the arc energy to X-20MV. The optimization was run based on original arc fluence, this means only step 4 of the optimization, until it reached plateau and again the plan was calculated. Normalization of all four plans was based on one reference point located in one position (usually in the center of GTV/CTV).

Influence of energy (6 MV beam X-20 and X-MV) and irradiation techniques (IMRT and VMAT) to dose distribution and the number of monitor units, was evaluated in two independent groups: the area of H&N and pelvis. The resulting treatment plans were then compared with dose-to-volume results using the RPI factor computed with home made software [4].

$$RPI = \sqrt[n+m]{\prod_{i}^{m}\left\{\prod_{j}^{n}\left[\left(1-\frac{w_j\cdot\int_0^{D\max OaR} VjOAR \quad dD_{OaR}}{\int_0^{D\max OaR} VjOAR\ 100\% \quad dD_{Oar}}\right)\cdot\left(\frac{\int_0^{D\max PTV} ViPTV \quad dD_{PTV}}{\int_0^{D\max PTV} ViPTV\ 100\% \quad dD_{PTV}}\right)\cdot\left(1-SDev\cdot p_i\right)\right]\right\}}$$

The RPI index is calculated according to a complex formula. The result is determined by the dose volume histograms of critical structures (n number of OAR) and volumes treated (m number of PTV). SDev determines the standard deviation of the dose distribution in PTV, while p_i is a weight factor of the dose distribution homogeneity for the PTV_i. Each OAR is characterized by the importance factor w_j. The importance factor was introduced to rank organs sensitive to irradiation [4].

The RPI index and the number of MUs were analyzed considering beam energy and treatment technique. It was assumed that the result is statistically significant when the $p < 0.05$ (Mann-Whitney U-test, for two independent groups). All statistical calculations were performed in Statistica v10.

Results

For 74 patients, 296 plans were prepared for this study. The dose for fraction varied from 1.6 Gy to 2.5 Gy. The number of beams for IMRT plans varied between 4–9 beams. The plan summary numbers of MUs varied from 308 MU to a maximum of 2332 MU for IMRT plans, and from 175 MU to 1850 MU for VMAT (RapidArc) plans (for two arc plans). Table I shows more detailed data.

Table I. The table shows values of RPI coefficients and plan summary number of MUs for the X-6 MV and X-20 MV beams for IMRT and VMAT techniques. Basic statistical parameters are also included in the table.

The first issue examined was the relation between photon energy and dose-to-volume results in IMRT and VMAT plans separately. For this purpose, plans were analyzed according to the calculated RPI index and grouped due to the beam energy. Figure 1 shows the plots for the relation between RPI coefficients and the energy for VMAT and IMRT plans.

Figure 1. The distribution of RPI coefficients, for H&N (upper row) and pelvic region (lower row), according to whether X-6MV or X-20MV beams were used, for IMRT technique (left column) and VMAT plans on right (with p- test U-Manna Whitneya). Where, for all figures; small square: median value; large rectangle: 25–75% values; horizontal lines: minimum and maximum values.

The results for both energies are noticeably similar. The analysis showed that no statistical significance ($p > 0.05$) between VMAT plans with X-6MV and X-20MV arcs, as well as no statistical significance ($p > 0.05$) between IMRT plans with X-6MV and X-20MV beams were found. According to these results there is no significant difference in dynamic plans with X-6MV and X-20MV beams, for both regions: head and neck and pelvis.

Secondly, the impact of the beam energy on the number of MUs in IMRT and VMAT techniques were examined. Figure 2 presents the relation between energy and number of MUs, for both VMAT and IMRT plans.

Table I. RPI coefficient and MUs number depending on beams energy for VMAT and IMRT plans

H&N region	**IMRT plans**				**VMAT plans**			
	20 MV RPI	**6 MV RPI**	**20 MV Sum of MU**	**6 MV Sum of MU**	**20 MV RPI**	**6 MV RPI**	**20 MV Sum of MU**	**6 MV Sum of MU**
Mean	0.2791	0.2934	765	825	0.2310	0.2598	325	355
Median	0.2285	0.2519	571	759	0.1837	0.2412	256	295
Standard deviation	0.2234	0.2163	369	365	0.1976	0.2044	234	242
Minimum	0.0091	0.0280	335	366	0.0145	0.0160	175	197
Maximum	0.7749	0.7157	1874	1595	0.6624	0.6981	1269	1565
Pelvis region	**IMRT plans**				**VMAT plans**			
	20 MV RPI	**6 MV RPI**	**20 MV Sum of MU**	**6 MV Sum of MU**	**20 MV RPI**	**6 MV RPI**	**20 MV Sum of MU**	**6 MV Sum of MU**
Mean	0.4007	0.3721	942	1116	0.3683	0.3574	413	492
Median	0.4049	0.3820	850	1054	0.4069	0.4000	358	436
Standard deviation	0.1990	0.1940	373	459	0.2015	0.2015	179	265
Minimum	0.0704	0.0670	470	308	0.0274	0.0294	231	226
Maximum	0.8747	0.8268	1950	2332	0.8046	0.8168	1269	1850

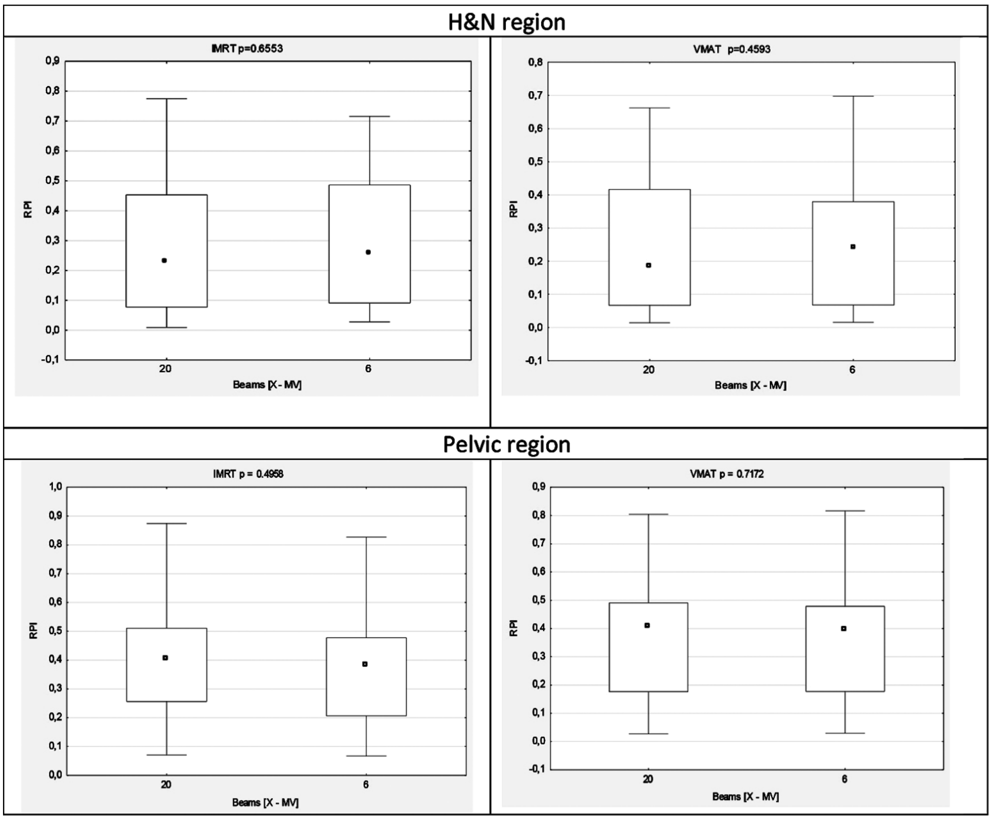

Figure 1. RPI coefficient depending on beams energy for VMAT and IMRT plans

Figure 2. The distribiution of number of MUs for each plan according to the X-6MV or X-20MV beams, for VMAT plans on left and IMRT plans, for H&N and pelvic region. For IMRT technique (left column) and VMAT plans on right and H&N — upper row; pelvic region — loweer row, with p- test U-Manna Whitneya. Where, for all figures; small square: median value; large rectangle: 25–75% values; horizontal lines: minimum and maximum values.

Calculations indicate (table I and figure 2) that for higher energy to obtain comparable dose distributions, requires

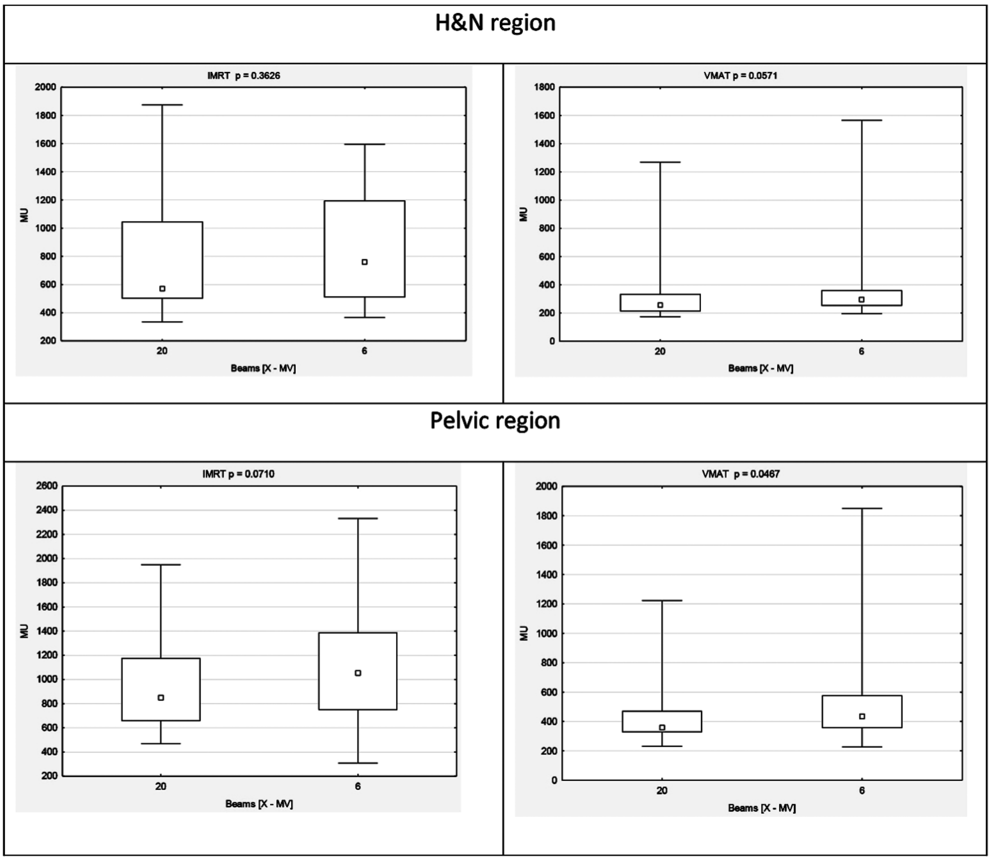

Figure 2. Number of MUs depending on beams energy for VMAT and IMRT plans

a smaller number of monitor units, regardless of the technique (IMRT/VMAT) and location (H&N/pelvis). However, only in the case of VMAT techniques in pelvic region, differences between energy is statistically significant ($p < 0.05$). In this case, it is reasonable to use higher energy. Reduction of MUs was respectively: 7.3% for IMRT in H&N region, 15.6% for IMRT in pelvis region, 8.5% for VMAT in H&N region and 16.1% for VMAT in pelvis region.

The third phase of the study was the comparison of the dose-to-volume results between IMRT and VMAT plans with the same beam energy. The results were compared due to RPI index. The resulted plots are showed in figure 3.

Figure 3. The distribiution of RPI coefficients according to the treatment technique, for X-6MV beams/arcs on left and X-20MV beams/arcs on right, end the region H&N — up, pelvic — below.

There is no statistical significance ($p > 0.05$) between RPI index values for IMRT and VMAT plans with neither X-6MV nor X-20MV beams/arcs. Therefore, these techniques can be alternatively used and are equally useful in dynamic plans.

The last question was whether the summary number of MUs varies for IMRT and VMAT plans, in regard to the beam energy. The results are illustrated in figure 4.

Figure 4. The distribution of summary number of MUs according to the used technique, for 6 MV beams/arcs on left and 20 MV beams/arcs on right.

For both beams (energy) X-6MV X-20MV and irrespective of the region, of the head and neck and pelvis, there is a statistically significant difference between the number of monitor units for both techniques: IMRT vs VMAT. VMAT technique requires fewer monitor units than IMRT. The difference it is almost double. Reduction of MUs was respectively: 57.0% for X-6MV and 57.5% for X-20MV in H&N region also 56.0% for X-6MV and 56.1% for X-20MV in the pelvis region.

For H&N and potentially other localizations with target volumes at small depth, the IMRT plan requires the usage of mean total/summary 825 MU for X-6MV beams and 765 MU for X-20MV beams. This difference is not found to be statistically significant (U-Mann Whitney test $p = 0.3626$). For the VMAT plans, the required mean total/summary MUs are 355 MU for X-6MV arcs and 325 MU for X-20MV arcs. This dependence is on the edge of statistical significance ($p = 0.0571$).

For the pelvis region, which corresponds to deeper localization of target volume, the mean total/ summary number of MUs in IMRT plans are 1116 MU for X-6MV beams and 942 MU for X-20MV beams. This analysis is not statistically significant ($p = 0.0710$). But, for VMAT plans applied to the pelvic region, the mean total/summary MUs are 492 MU and 413 MU for X-6MV and X-20MV arcs, respectively. This difference is statistically significant ($p = 0.0467$).

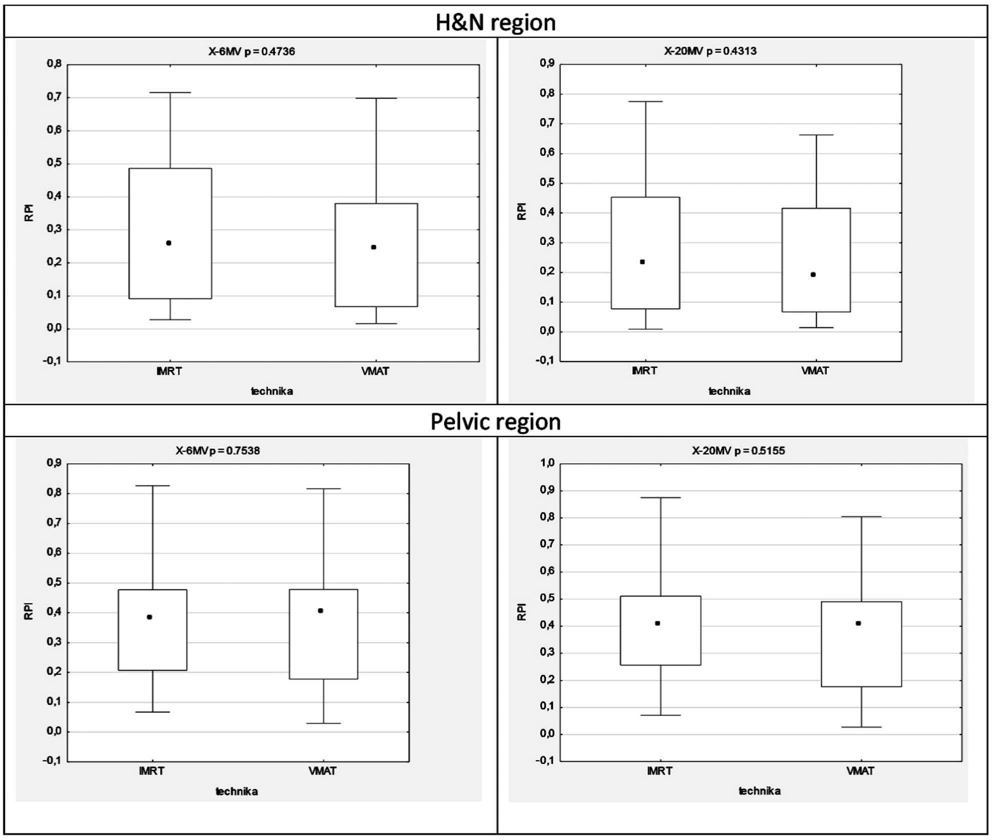

Figure 3. RPI coefficient depending on the treatment technique for 6 MV and 20 MV beams

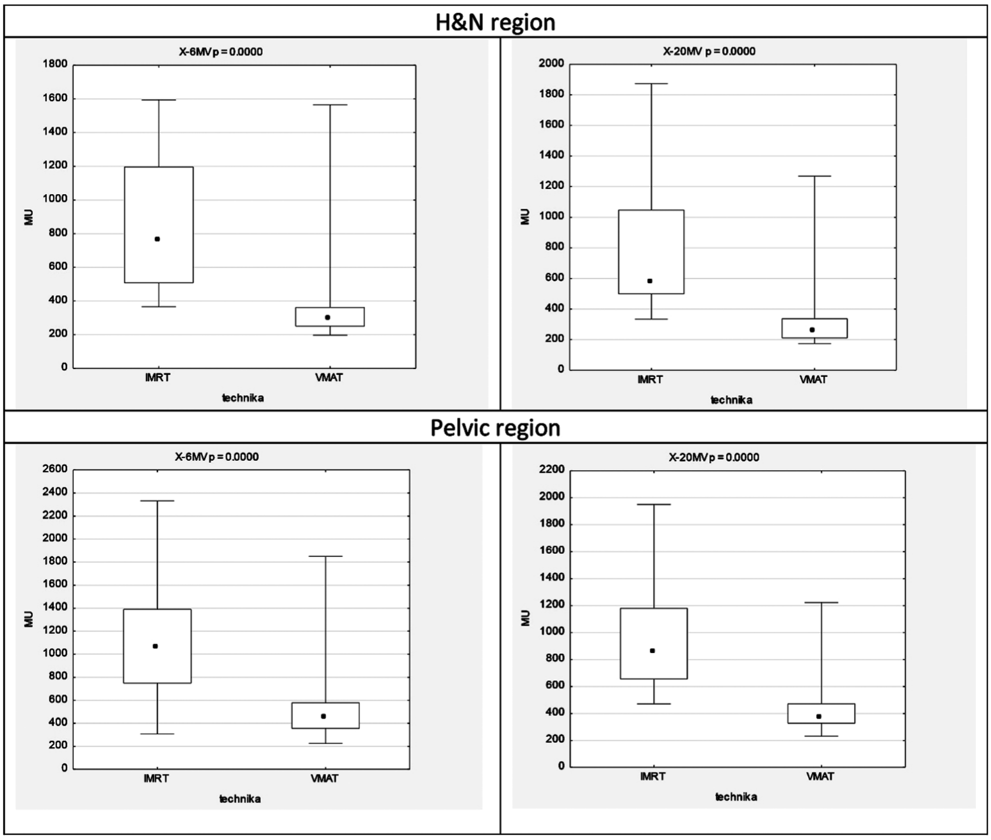

Figure 4. Number of MUs depending on treatment technique for 6 MV and 20 MV beams

Discussion

In summary, in both IMRT and VMAT plans, similar dose-to-volume results can be reached with a lower number of MUs, when using higher energy beams. In this particular study it is shown that 7.3–16.1% less MUs is needed for VMAT and IMRT plans, respectively.

For irradiation of the head and neck region, the choice between beams of X-6MV and X-20MV energy, is not relevant in reaching comparable dose-to-volume results. However, when regarding the time of irradiation expressed by the number of MUs, the plans with lower energy require more MUs. This relationship applies to both IMRT and VMAT plans. Also the deeper the tumor is located the higher the number of MUs required. This means that the irradiation of the chest, abdomen or pelvis takes longer time than the irradiation of the head & neck region. The irradiation time (MUs) for VMAT in relation to IMRT is shorter being 56–57.5% for both energy levels. Smaller values of the RPI coefficient for lower depth (H&N region) are associated with a higher number of OaRs included in dose calculations compared to the pelvic region [4]. However, it is essential that there is no statistically significant difference between the techniques and energies.

These results correspond with the results of Elisabeth Weiss et al, who analyzed the implication of using 6 MV and 18 MV beam IMRT plans on lung cancer treatment plans [5]. The authors also came to the conclusion, that chosen beam energy doesn't influence the dose conformity, homogeneity and does not improve normal tissue sparing [5, 6]. Their results for the required MU per one fraction, has no sign of statistical significance for both energies, indicating only clinically irrelevant elongations of treatment time with 6 MV compared to the total IMRT treatment time [5]. In only a limited number of publications, regarding the analysis between different energy beams used for planning, authors take beams with higher energy than 18 MV into comparison. Usually authors concentrate on beams up to 10 MV, which makes further discussion and confrontation difficult [7–10].

Our additional analysis of the impact of localization, suggests that for tumors located deeper in the patient body, it is recommended that beams and arcs of higher photon energy are used. Although the dose-to-volume results are similar for different energy beams, the gain of shortening the time of irradiation is useful for minimizing the error caused by patient motion.

In our study we didn't investigate any additional secondary neutron dose. Neutron creation when using photon beams of energy > 10 MV in radiotherapy is a well known topic. Because it is difficult to measure and calculate secondary neutron dose, it should be taken under a separate examination. Secondly our study relies on the data gathered from a planning platform that doesn't include the extra dose from neutron creation [11].

Conclusion

Comparing Intensity Modulated Radiation Therapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT) we can say that dose-to-volume results are comparable when using the same energy beams and arcs. Additionally the overall number of MUs is always lower for Volumetric Modulated Arc Therapy, which is desirable to reduce the time of irradiation.

When planning regions where target volumes are at a quite small depth, the impact of used energy is negligible. Contrarily, in cases of planning target volumes located at bigger depth, the usage of higher energy beams and arcs can introduce a desirable reduction in irradiation time. This could potentially result in a reduction of treatment error due to patient motion.

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