INDEPENDENT DOSE CALCULATION FOR DYNAMIC ARC TREATMENTS DELIVERED WITH MICROMULTILEAF COLLIMATOR*

Juan Fernando Delgado[1], André Mozart Miranda Vieira[2], José Carlos Cruz[3], Laura Natal Rodrigues[4]

Abstract **OBJECTIVE: In treatment techniques such as dynamic arc, the manual verification of treatment planning system calculations is very difficult. In these cases, the use of computational tools is useful and becomes an essential component of the quality assurance program. MATERIALS AND METHODS: A worksheet-based software has been created to perform an independent dose or monitor unit calculation in treatments applying the dynamic arc technique delivered with micromultileaf collimator. The dose values calculated per arc and per complete treatment, are compared with values obtained from BrainScan v5.3 treatment planning system. The software has been tested with 229 dynamic arc fields representing 42 skull treatments. From these 229 fields, 109 have been calculated in 3D reconstruction of patients CT images, 109 in reconstruction of polymethylmetacrylate phantom images, and 21 in reconstruction of images from a water equivalent phantom. RESULTS: The mean difference of total doses found in the 42 treatments (composites of one or more dynamic arcs), between the verification software and the treatment planning system, was of +1.73% with a 0.76% standard deviation. The maximum difference was 3.32% and the minimum –0.20%. When the 229 dynamic arcs were tested one by one, the average difference found was 1.61% with a 1.04% standard deviation. Maximum and minimum differences were, respectively 4.01% and –2.04%. As a result of the test, in 80.35% the doses calculated have presented a ± 2.5% difference in relation to the doses generated by the planning system. CONCLUSION: The software presented in this study is recommended for checking point dose included in treatment plans as an integral part of the process of quality assurance in radiotherapy and stereotactic radiosurgery when the dynamic arc technique is utilized in treatment with micromultileaf collimator, where a manual calculation is very difficult or even impracticable due the technique complexity.**
Keywords: Radiotherapy; Stereotactic radiosurgery; Linac; Quality assurance in radiotherapy; Monitor unit calculation; Micromultileaf collimator.

Resumo *Cálculo independente de dose para tratamentos de arco dinâmico com colimador micromultilâminas.*
OBJETIVO: Em técnicas de tratamento como o arco dinâmico, a verificação manual dos cálculos do sistema de planejamento é muito difícil. Assim, a utilização de ferramentas computacionais é de utilidade e torna-se componente essencial do programa de controle de qualidade. MATERIAIS E MÉTODOS: Foi criado um programa computacional de tipo planilha eletrônica para realizar cálculo independente da dose, ou equivalente das unidades monitoras, nos tratamentos realizados pela técnica de arco dinâmico com micromultilâminas. Os valores de dose calculados, por arco e por tratamento completo, foram comparados aos valores obtidos do sistema de planejamento BrainScan v5.3. O programa desenvolvido foi testado com 229 campos de arco dinâmico que representam 42 tratamentos de crânio. Desses, 109 campos foram calculados em reconstrução tridimensional feita a partir das imagens de tomografia dos pacientes, 109 na reconstrução de um objeto simulador de polimetilmetacrilato e 21 na de um objeto simulador sólido equivalente à água. RESULTADOS: A diferença média de doses totais encontrada nos 42 tratamentos (compostos de um ou mais arcos dinâmicos), entre o programa de verificação e o sistema de planejamento, foi de +1,73%, com desvio-padrão de 0,76%. A diferença máxima encontrada foi de 3,32% e a mínima, de –0,20%. No caso dos 229 arcos testados um a um, a diferença média encontrada foi de 1,61%, com desvio-padrão de 1,04%. Os valores máximos e mínimos das diferenças foram de 4,01% e –2,04%, respectivamente. Em 80,35% dos arcos testados, as doses calculadas acham-se na faixa de ± 2,5% de diferença com relação às doses geradas pelo sistema de planejamento. CONCLUSÃO: O programa apresentado é recomendado para a verificação da dose pontual dos planos de tratamento, como parte do procedimento de garantia de qualidade em radioterapia e radiocirurgia estereotáxica quando se utiliza a técnica de arco dinâmico por meio de um colimador micromultilâminas, nos quais um cálculo manual é muito difícil ou inviável, pela complexidade da técnica.
Unitermos: Radioterapia; Radiocirurgia estereotáxica; Acelerador linear; Controle de qualidade em radioterapia; Cálculo de unidades monitoras; Colimador micromultilâminas.

* Study developed at Hospital Israelita Albert Einstein Department of Radiotherapy, São Paulo, SP, Brazil.

1. Physicist, Master in Applied Nuclear Technology by Instituto de Pesquisas Energéticas e Nucleares – Universidade de São Paulo. Hospital Oncológico "Solón Espinosa Ayala" SOLCA – Nucleus of Quito, Ecuador.

2. Physicist, Doctor by Instituto de Pesquisas Energéticas e Nucleares – Universidade de São Paulo.

3. Physicist, Doctor at Hospital Israelita Albert Einstein Department of Radiotherapy.

4. Physicist, Doctor at Instituto de Pesquisas Energéticas e Nucleares – Universidade de São Paulo.

Mailing address: Juan Fernando Delgado. Avenida Eloy Alfaro, s/n y Los Pinos. Hospital Oncológico SOLCA – Quito. Departamento de Radiologia. Quito, Ecuador. E-mail: juan@abfm.org.br / jdelgado@solcaquio.org.ec

Received October 16, 2005. Accepted after revision November 8, 2005.

INTRODUCTION

A program of quality control in external beam radiotherapy should check the monitor units independently from the planning system calculation. In cases where conventional treatment techniques are utilized, this verification may be manually performed in a very simple way.

With new treatment techniques like intensity-modulated radiation therapy (IMRT) and dynamic arc, the point dose calculation and the dose distribution in the treatment planning are extremely complex so the manual verification is very difficult or even unfeasible. In these cases, computational tools play an important role in the verification and, together with the absolute dose measurement, become an essential element in the program of quality control for the above mentioned techniques. Each conformational dynamic arc treatment carries a significant number of segments which should be checked, since, the planning system generates a segment at each 10º of the arc. Usually, a treatment includes several arcs.

One of the treatment techniques for stereotactic surgery is the dynamic arc modality. The principle of this technique is the target-volume conformation releasing a high dose on it, and preserving the surrounding healthy tissues. During the treatment delivery, the accelerator gantry rotates forming an arc and the field shape formed by the dynamic micromultileaf collimator (mMLC) changes continuously.

This technique presents advantages in relation to other dose conformation techniques, provided the implementation, diagnosis, planning, quality control and treatment are rigorously performed.

This study presents the results achieved by means of a worksheet-type software developed as a quality control and verification tool at Hospital Israelita Albert Einstein. The algorithm utilized in the development of the software allows the calculation of monitor units or absorbed-dose in dynamic arc treatments.

MATERIALS AND METHODS

The equipment utilized in radiotherapy treatments and radiosurgery with dynamic arc in Hospital Israelita Albert Einstein Radiotherapy Department is a Clinac 600C accelerator (Varian Medical Systems; Palo Alto, Califórnia, EUA) coupled with a mMLC system model m_3 (BrainLAB, AG; Heimstetten, Germany). The system has the capacity to produce conformed fields, intensity-modulated fields in dynamic and static modes, and dynamic rotational therapy, also known as dynamic arc treatment[1].

Brainscan v. 5.3 (BrainLAB, AG; Heimstetten, Germany) is the planning system employed to generate the treatments. The calculation is accomplished in some stages: the geometric definition of the arc projections, the optimization considering the leaves physical characteristics and, finally, the contribution of the transmission through the mMLC. The direct calculation of the dose distribution is based on the strictly collimated beam algorithm ("pencil beam")[2,3] and utilizes correction for heterogeneity.

Once the planning of the dynamic arc treatment is completed, it is reviewed and discussed between radiotherapist and physicist for approval. After approval, the treatment plan data are forwarded through the register and verification network to the linear accelerator control.

At this moment the tasks of quality control of the treatment plan selected should be developed. The planning system allows the plan to be exported to a phantom on which it is possible to perform absolute dose measurements with an ionization chamber, and dose distribution measurements with a dosimetry verification film. Then, the treatment data for each arc, such as initial and final gantry angles, table angle, isocenter points, mMLC configurations, monitor dose and units are verified. The determination of absolute dose should be based on the plan generated in the phantom, in compliance with protocols for determination of absorbed dose[4,5].

Other important stage of the quality control program, is the verification of monitor units calculated by the planning system[6–9]. A worksheet-type software has been developed to facilitate the monitor units calculation that, differently from the conventional radiotherapy techniques, cannot be performed in a direct and intuitive way. The initial idea is checking the calculation with few entry data[10].

In the process of monitor units verification, the software depends on some parameters to calculate the dose estimated by the planning system in the normalization point. The following parameters are utilized:

– the files with the mMLC leaves positions for each arc, divided into segments separated by a gantry angle of 10º, transferred by the planning system;

– the mean water-equivalent depth of the normalization point for each arc;

– the monitor units (or dose) in the final report of the plan selected.

In Figure 1, there is an example of a screen displaying a text file (.txt) transferred by the planning system, including the number of segments and the leaves positions for each treatment field segment.

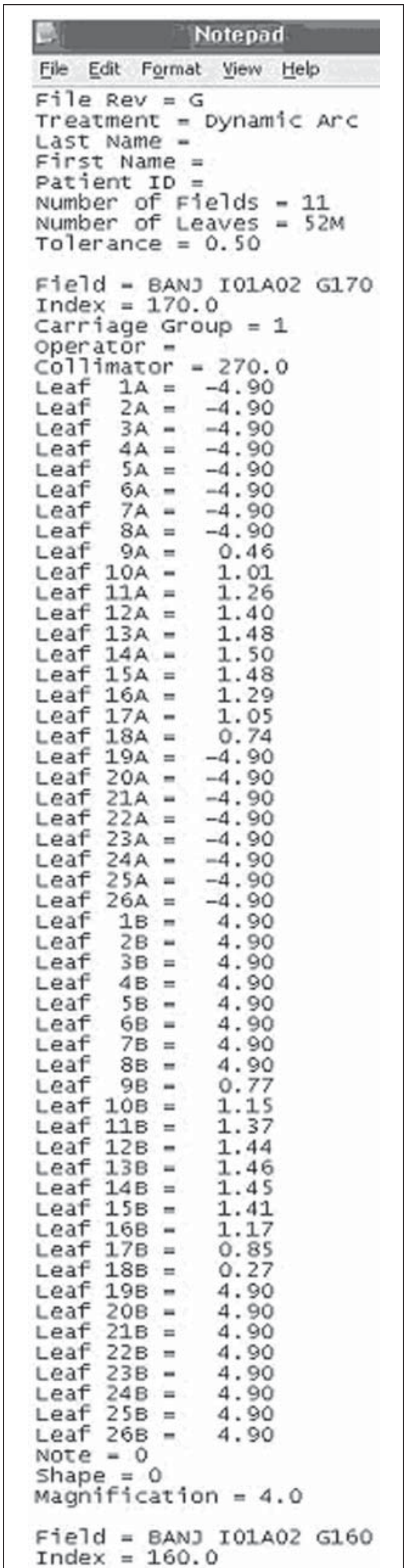
With these three data sets, the software calculates the equivalent square of each segment of the treatment arcs utilizing the Sterling ratio[11]. With the equivalent depth of each arc, the software determines the values of maximum tissue ratio, scattering factors and off-axis ratios, with basis on the values obtained in the equipment commissioning[12,13].

For the purpose of determining the off-axis ratios for each segment, the gravitational coordinates must be calculated as follows:

$$x_g = \frac{\int_{x_1}^{x_2} xy\,dx}{\int_{x_1}^{x_2} y\,dx} \quad (1)$$

$$y_g = \frac{\frac{1}{2}\int_{x_1}^{x_2} y^2\,dx}{\int_{x_1}^{x_2} y\,dx} \quad (2)$$

The total number of monitor units for each dynamic arc is equally distributed among the arc segments. The contribution of each arc segment (con_i), on the prescribed dose at the normalization point (on the central axis) is defined according to the degree of the normalization point coverage by the leaves. If the distance from the normalization point to the edge nearest the leaves is > 0.5 cm, the uncovered field contribution is maximum (con_i = 1.0). For the



```
Notepad
File Edit Format View Help
File Rev = G
Treatment = Dynamic Arc
Last Name =
First Name =
Patient ID =
Number of Fields = 11
Number of Leaves = 52M
Tolerance = 0.50

Field = BANJ I01A02 G170
Index = 170.0
Carriage Group = 1
Operator =
Collimator = 270.0
Leaf  1A = -4.90
Leaf  2A = -4.90
Leaf  3A = -4.90
Leaf  4A = -4.90
Leaf  5A = -4.90
Leaf  6A = -4.90
Leaf  7A = -4.90
Leaf  8A = -4.90
Leaf  9A =  0.46
Leaf 10A =  1.01
Leaf 11A =  1.26
Leaf 12A =  1.40
Leaf 13A =  1.48
Leaf 14A =  1.50
Leaf 15A =  1.48
Leaf 16A =  1.29
Leaf 17A =  1.05
Leaf 18A =  0.74
Leaf 19A = -4.90
Leaf 20A = -4.90
Leaf 21A = -4.90
Leaf 22A = -4.90
Leaf 23A = -4.90
Leaf 24A = -4.90
Leaf 25A = -4.90
Leaf 26A = -4.90
Leaf  1B =  4.90
Leaf  2B =  4.90
Leaf  3B =  4.90
Leaf  4B =  4.90
Leaf  5B =  4.90
Leaf  6B =  4.90
Leaf  7B =  4.90
Leaf  8B =  4.90
Leaf  9B =  0.77
Leaf 10B =  1.15
Leaf 11B =  1.37
Leaf 12B =  1.44
Leaf 13B =  1.46
Leaf 14B =  1.45
Leaf 15B =  1.41
Leaf 16B =  1.17
Leaf 17B =  0.85
Leaf 18B =  0.27
Leaf 19B =  4.90
Leaf 20B =  4.90
Leaf 21B =  4.90
Leaf 22B =  4.90
Leaf 23B =  4.90
Leaf 24B =  4.90
Leaf 25B =  4.90
Leaf 26B =  4.90
Note = 0
Shape = 0
Magnification = 4.0

Field = BANJ I01A02 G160
Index = 160.0
```

Figure 1. Screen displaying a text file exported by the planning system including the positions of leaves for an arc segment.

points covered by the leaves in at least 0.5 cm, the contribution is that determined by the multileaf system transmission resulted from the system commissioning[13]. When the normalization point is between the points previously described, localized at 0.5 from the leaves edges and covered up to 0.5 cm, the algorithm determines the contribution by linear interpolation, depending on the normalization point position in relation to the leaves.

So, the monitor units of each segment are determined as follows:

$$UM_i = UM_{SP} \times w_i \times con_i \qquad (3)$$

where UM_{SP} are monitor units calculated by the planning system and UM_i are monitor units of each segment.

The dose whereby each segment contributes to the normalization point is calculated as follows:

$$D_i = UM_i \times TMR_i \times S_{cp,i} \times OAR_i \qquad (4)$$

where D_i is the dose of each segment; UM_i are monitor units of each segment; TMR_i is the maximum tissue ratio at the equivalent depth for each segment;, $S_{cp,i}$ is the total scattering factor for the equivalent field of the segment being calculated.. OAR_i is the off-axis ratio from the position of the segment gravitation point.

The total arc dose is obtained by the sum of segments contributions:

$$D_{AD-VER} = \sum_i D_i \qquad (5)$$

The doses calculated by the software (D_{AD-VER}) have been compared with the doses calculated by the planning system (D_{AD-SP}):

$$\%dif = \frac{D_{AD-VER} - D_{AD-SP}}{D_{AD-SP}} \times 100 \qquad (6)$$

Also, results were compared with basis on the total doses in different treatments. In these cases, the differences between the treatment dose generated by the verification ($D_{TOTAL-VER}$) and the total dose calculated by the planning system ($D_{TOTAL-SP}$) have been found as follows:

$$\%dif = \frac{D_{TOTAL-VER} - D_{TOTAL-SP}}{D_{TOTAL-SP}} \times 100 \qquad (7)$$

All of the fields tested have been compared with the respective planning system calculations. In some cases, the calculations have been based on patients CT images ($D_{AD-VER-PAC}$), in other, the calculations have been based on CT images of a solid water-equivalent phantom (Solid Water® – SW), the doses being calculated by the system ($D_{AD-VER-SW}$) and, finally, the cases where a polymethylmetacrylate (PMMA) phantom ($D_{AD-VER-PMMA}$), the latest being developed just to test dynamic arc and intensity-modulated fields, simulating a skull. In all the cases included in the present study, the material-density correction factor inherent in the planning system has been utilized.

As already described, each treatment arc presents a certain number of segments, depending on the arc amplitude. In the present study, the highest number of segments per arc utilized in calculations was 13, and the lowest was seven segments, corresponding respectively to 120º and 60º arcs.

Figure 2 shows a screen displaying the results of the worksheet with an example of a nine-segment arc calculation.

RESULTS

The software has been tested with 229 dynamic arc beams with the above mentioned algorithm. These 229 beams correspond to 42 skull treatments. Of these 229 fields, 109 have been calculated in the planning system on patients CT images, 109 in polymethylmetacrylate (PMMA) phantom images, and 21 in a solid water-equivalent (SW) phantom.

The difference found in total doses of the 42 dynamic arc treatments between the verification software and the planning system was +1, 73%, with 0.76% standard deviation. The maximum difference found was 3.32% and the minimum,–020%. The results are shown in Figure 3.

For the 229 arcs, the mean difference found was 1.61%, with a 1.04% standard deviation. These results are shown in Figure 4. The maximum and minimum differences were respectively 4.01% and –2.04%.

The 229 arcs have been analyzed according to the medium where the planning system calculations were performed (patients CT images, PMMA phantom or SW phantom). Results are shown in Figures 5, 6 and 7, and Table 1.

	1	2	3	4	5	6	7	8
PERIMETRO	7.7	7.12	6.7	6.26	6.14	6.08	6.7	7.02
AREA [CM2]	4.944	4.485	4.134	3.78	3.729	3.87	4.158	4.923
A/P	0.64207792	0.629916	0.617015	0.603833866	0.607329	0.636513	0.620597	0.701282
LADO EQ	2.56831169	2.519663	2.46806	2.415335463	2.429316	2.546053	2.482388	2.805128
TMR	0.9114	0.911	0.910396	0.909847151	0.909993	0.911207	0.910545	0.913902
Scp	0.900607	0.899442	0.898206	0.896942412	0.897277	0.900074	0.898549	0.906281
prof [cm]	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.06
Xg segmento	-0.16671723	-0.17111	-0.14497	-0.079761905	-0.14138	-0.14614	-0.18802	-0.2202
Yg segmento	0.15837379	0.191338	0.224238	0.206190476	0.274296	0.218605	0.221645	0.171572
radial fact off	0.22994976 2.299498	0.256891 2.568906	0.267019 2.670192	0.221080243 2.2108024	0.308588 3.08588	0.262954 2.629539	0.290648 2.906484	0.279154 2
X normaliz	0	0	0	0	0	0	0	0
Y plano	0	0	0	0	0	0	0	0
dist radial mi	0.55798407	0.549181	0.566039	0.540832691	0.524309	0.583095	0.609016	0.697782
OAR	**1.00075458**	**1.000871**	**1.000916**	**1.00071591**	**1.001097**	**1.000898**	**1.001019**	**1.000969**
wi	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
con 1	1	1	1	1	1	1	1	1
NU	121	121	121	121	121	121	121	121
NUi	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1
Di	9.93975871	9.922539	9.903507	9.881643339	9.890683	9.932777	9.909934	10.03156

Figure 2. Screen displaying results of calculations for eight segments forming a treatment field.

From the total of cases, 80.35% of beams were in the range of ± 2.5% difference related to the doses calculated by the planning system. The values found in the present study are similar to those found in studies published in the literature by Linthout[(14)] and Linthout *et al*.[(15)].

DISCUSSION

A reason for deviations found in the present study is the utilization of a single mean depth (called "equivalent depth" by the planning system) for all the segments of a same arc, generating an approximate result. For a more accurate calculation, the depth of each segment should be utilized rather than the mean segments depth. However, this data is utilized because it is supplied by the treatment report and can be easily included in the worksheet for the respective calculation. On the other hand, when this method is utilized for independent verification of IMRT fields, this depth is the same for all the segments forming a field.

Another reason for differences is that the verification software algorithm considers the calculation medium as a homogeneous medium, without heterogeneities (bones, air cavities, etc.), notwithstanding resolving the problem with the utilization of the equivalent depth.

The algorithm utilized permits the method to be extrapolated to IMRT fields, since the calculation of these fields in the planning system is performed by means of the strictly collimated beam algorithm[(16)]. For this purpose, it should be taken into

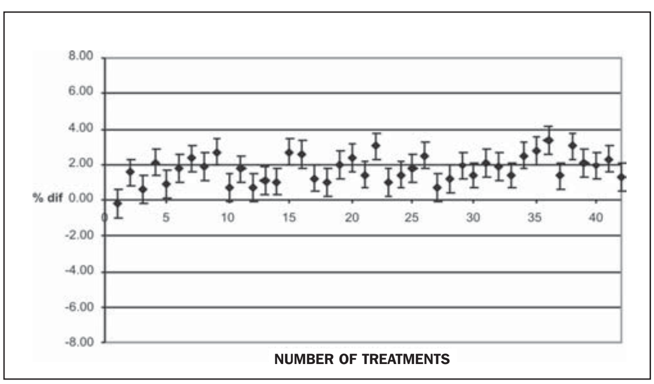


Figure 3. Comparison between total dose values calculated by the verification software and the values calculated by the planning system for the 42 skull treatments.

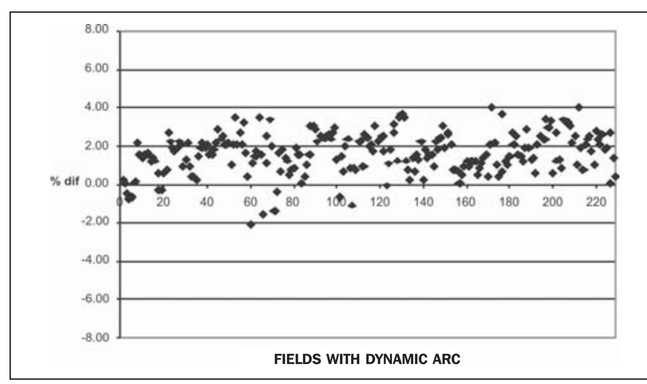


Figure 4. Comparison between the doses calculated by the verification software and by the planning system for the 229 tested arcs.

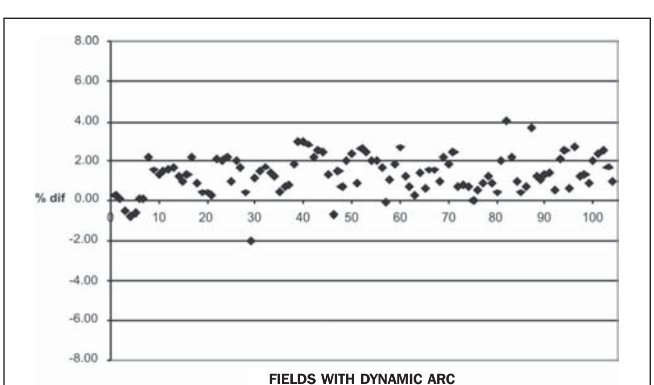


Figure 5. Comparison between doses calculated and those planned on patients CT images.

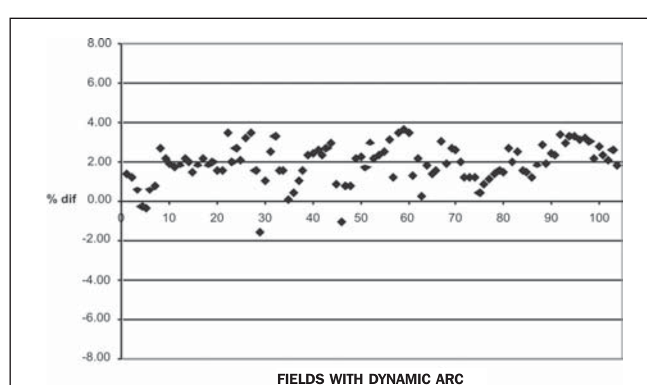


Figure 6. Comparison between doses calculates and those planned on the PMMA phantom.

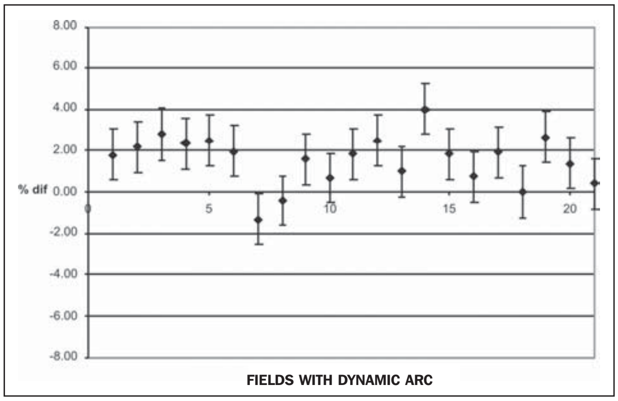


Figure 7. Comparison between doses calculated and those planned on the SW phantom.

Table 1 Comparison between results of the calculations performed by the verification software and by the planning system in different mediums.

Medium	Mean difference	Standard deviation	Maximum percentage	Minimum percentage	Number of fields tested
Paciente	1.32	0.97	4.00	–2.04	104
PMMA	1.92	1.00	3.71	–1.59	104
SW	1.55	1.22	4.01	–1.32	21

PMMA, polymethylmetacrylate; SW, solid-water.

consideration that in IMRT fields, the number of segments per treatment field is higher, and that many of these segments will contribute to the total dose due only to the leaves transmission.

CONCLUSIONS

The verification software developed is an useful tool in dynamic arc treatment quality control programs utilizing the BrainLab system and with fields shaping by BrainScan strictly collimated beam algorithm.

The use of the software described in the present study is recommended for radiotherapy services which utilize this type of equipment/technique, since it adds a method for checking data resulting from the planning system calculations for dynamic arc treatments. In 80.35% of tested arcs the doses calculated were in the range of ± 2.5% difference related to the doses calculated by the planning system.

This algorithm can be implemented in services of Radiotherapy which utilize the mMLC system BrainLab m_3, provided the dosimetry data of the equipment are entered together with the values of beam penumbra and leaf transmission obtained in the equipment commissioning.

REFERENCES

1. Informações técnicas e especificações do micro colimador multi-lâminas m_3 BrainLab. Disponível em: <http:\\www.brainlab.com>. Acessado em: 8/4/2005.
2. Mohan R, Chui C, Lidofsky L. Differential pencil beam dose computation model for photons. Med Phys 1986;13:64–73.
3. Mohan R, Chui C, Lidofsky L. Energy and angular distributions of photons from medical linear accelerators. Med Phys 1985;12:592–597.
4. Almond PR, Biggs PJ, Coursey BM, *et al*. AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams. Med Phys 1999;26:1847–1870.
5. International Atomic Energy Agency. Absorbed dose determination in external beam radiotherapy: an international code of practice for dosimetry based on standards of absorbed dose to water. Technical Reports Series No. 398. Vienna: IAEA, 2002.
6. Kutcher GJ, Loia L, Gillin M, *et al*. Comprehensive QA for radiation oncology: Report of AAPM Radiation Therapy Committee Task Group 40. Med Phys 1994;21:518–618.
7. Fraass B, Doppke K, Hunt M, *et al*. American Association of Physicists in Medicine Radiation Therapy Committee Task Group 53: Quality assurance for clinical radiotherapy treatment planning. Med Phys 1998;25:1773–1829.
8. International Atomic Energy Agency. Aspectos físicos de la garantía de calidad en radioterapia: Protocolo de control de calidad. Technical Document No. 1151. Vienna: IAEA, 2000.
9. International Atomic Energy Agency. Commissioning and quality assurance of computerized planning systems for radiation treatment of cancer. Technical Reports Series No. 430. Vienna: IAEA, 2004.
10. Boyer A, Xing L, Ma CM, *et al*. Theoretical considerations of monitor unit calculations for intensity modulated beam treatment planning. Med Phys 1999;26:187–195.
11. Khan FM. The physics of radiation therapy. 2nd ed. Maryland: Williams & Wilkins, 1994.
12. Cosgrove VP, Jahn U, Pfaender M, Bauer S, Budach V, Wurm RE. Commissioning of a micro multi-leaf collimator and planning system for stereotactic radiosurgery. Radiother Oncol 1999;50: 325–336.
13. Delgado JF, Cruz JC, Cecilio PJ, Caprioglio L, Vieira AM. Testes de aceitação, comissionamento e controle da qualidade com colimador micro multilâminas. Rev Imagem 2005;27(Supl nº 1): 62–63.
14. Linthout N. Evaluation of conformal radiation therapy techniques using various multileaf collimators. (Tese de Doutorado). Brussels: Vrije Universiteit Brussels, Faculteit Geneeskunde en Farmacie, 2003.
15. Linthout N, Verellen D, Van Acker S, Storme G. A simple theoretical verification of monitor unit calculation for intensity modulated beams using dynamic mini-multileaf collimation. Radiother Oncol 2004;71:235–241.
16. Software Guide BrainScan. Version 5.3. Art. No. 60900-90 EN. Heimstetten, Germany: BrainLAB AG.