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PHYSICS CONTRIBUTION

GEOMETRIC PARAMETER ANALYSIS TO PREDETERMINE OPTIMAL RADIOSURGERY TECHNIQUE FOR THE TREATMENT OF ARTERIOVENOUS MALFORMATION

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Purpose: To develop a method of predicting the values of dose distribution parameters of different radiosurgery techniques for treatment of arteriovenous malformation (AVM) based on internal geometric parameters.
Methods and Materials: For each of 18 previously treated AVM patients, four treatment plans were created: circular collimator arcs, dynamic conformal arcs, fixed conformal fields, and intensity-modulated radiosurgery. An algorithm was developed to characterize the target and critical structure shape complexity and the position of the critical structures with respect to the target. Multiple regression was employed to establish the correlation between the internal geometric parameters and the dose distribution for different treatment techniques. The results from the model were applied to predict the dosimetric outcomes of different radiosurgery techniques and select the optimal radiosurgery technique for a number of AVM patients.
Results: Several internal geometric parameters showing statistically significant correlation ($p < 0.05$) with the treatment planning results for each technique were identified. The target volume and the average minimum distance between the target and the critical structures were the most effective predictors for normal tissue dose distribution. The structure overlap volume with the target and the mean distance between the target and the critical structure were the most effective predictors for critical structure dose distribution. The predicted values of dose distribution parameters of different radiosurgery techniques were in close agreement with the original data.
Conclusions: A statistical model has been described that successfully predicts the values of dose distribution parameters of different radiosurgery techniques and may be used to predetermine the optimal technique on a patient-to-patient basis. © 2005 Elsevier Inc.

AVM radiosurgery, Internal geometry, Treatment technique selection, Multiple regression.

INTRODUCTION

Arteriovenous malformations (AVM) can form anywhere in the body but are of the greatest concern when they occur in the brain. Bleeding of an AVM in the brain may result in permanent disability and may also lead to death. The treatment of choice for AVM is surgery, but in the cases where they are inaccessible to surgery, they may be treated using high-energy radiation, a procedure known as radiosurgery. During radiosurgery, a large number of narrow high-energy X-ray beams are focused onto the AVM, resulting in a high dose delivered to the AVM and a minimal dose delivered to the normal surrounding tissue. The main goal of a radiosurgery treatment is to deliver a uniform prescribed dose to the target (AVM) volume, while minimizing the dose deposited to the nearby organs and surrounding healthy tissue.

There are several radiosurgery techniques presently available for treatment of AVM. One common procedure uses high-energy X-ray beams produced by a large number of ^{60}Co sources (Leksell Gamma Knife [1]). Other techniques use a modified linear accelerator (linac) to obtain high-energy beams. Linac-based techniques include the following: circular collimator arcs (2), dynamic conformal arcs (3), fixed conformal fields (4), and intensity-modulated radiosurgery (IMRS) (5). In a circular collimator arc treatment, the dose is delivered in multiple noncoplanar arcs (with single or multiple isocenters) using circular collimators to define the treatment field. Dynamic conformal arc treatments are similar to nonconformal arc treatments, except that the shape of the treatment field is constantly conformed to the beam's-eye view of the target, as the beam moves through the arcs. The treatment field is defined using a micromultileaf collimator (mMLC) at several equidistant

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angles in each arc and interpolated between them to obtain a continuously varying treatment field throughout the arc. The fixed conformal field technique uses several static fields with single isocenter to deliver the dose. The fields are conformed to the beam's-eye view of the target using the mMLC. Finally, IMRS uses static conformal fields where the beam intensity is modulated across each field using the mMLC.

Dynamic conformal arcs and IMRS may be superior compared to circular arcs and fixed conformal field techniques in terms of their ability to conform the dose distribution to the target volume. The extra degree of freedom provided by motion through the arc in dynamic conformal arcs and intensity modulating across the fields in IMRS offers the potential for sparing of sensitive organs and increasing the target dose conformity, especially for cases where organs at risk are in close proximity to the irregularly shaped targets. However, the increased complexity of these plans results in various shortcomings, such as longer treatment times and complicated treatment accuracy verifications. Furthermore, IMRS beam profiles are generally complex and susceptible to noise and numeric artifacts (sharp peaks and valleys). Delivering such beam profiles results in certain practical difficulties: They generally require a larger number of segments and monitor units, which makes the overall treatment delivery less efficient; high gradients in the intensity profiles may result in plans that are sensitive to treatment uncertainties such as target movement and patient setup. Also, the prolonged treatment time results in increased contribution of indirect radiation to the total delivered dose. As a result, more of the surrounding normal tissue may be exposed to the significant levels of radiation. Therefore, even though we recognize that dynamic conformal arcs and IMRS are superior compared to circular arcs and fixed conformal field techniques in terms of their ability to conform the dose distribution to the target, there might be cases where the simpler method of dose delivery proves to be more beneficial. For instance, fixed conformal field technique might be suitable for cases where the target is relatively distant from the critical structures, and circular arcs may still be optimal for very small ($<\sim 2$ cm in maximum dimension) and nearly spherical lesions (6).

There are various studies in the literature that compare different radiosurgery techniques (6–10). The treatment plan results are generally evaluated by comparing the isodose distributions and dose–volume histograms (DVHs) produced by the competing techniques. The quality of the plan is usually determined based on the conformity of the dose to the target volume and dose homogeneity throughout the target volume. An ideal treatment plan would deliver perfectly homogeneous dose (equal to the prescribed dose) to the target volume and deliver no dose to the surrounding normal tissue. For evaluation of radiosurgery plans, dose conformity to the target volume is an important characterization parameter, whereas the dose homogeneity throughout the target volume is of slightly less concern and importance. Once the treatment plans are evaluated, the plan that most closely approximates these ideal conditions is considered to be superior to the other plans. However, these findings are often limited to the particular case (patient or phantom) considered in the study. It would be useful to generalize this result and conclude that a particular treatment technique will always be superior to the other techniques for that particular type of treatment. However, the situation is frequently complex, because there are many variables affecting the dose distribution from patient to patient and treatment site to treatment site, making it difficult to predict the treatment results for different patients. These variables include size, shape complexity of the target, proximity of the critical structures to the target, overlap of the critical structures with the target, etc. Thus, even though one treatment technique might prove to be better in a particular patient, another technique might be more effective for the next patient. The situation gets more complicated and unpredictable as the number of competing plans and the number of variables between patients increase. Therefore, to successfully predict the treatment results of different treatment techniques on a patient-to-patient basis, a systematic approach is required.

In this article, we present the first comparative quantitative analysis of four radiosurgery techniques applied to a group of patients with a range of target locations, shapes, and sizes. We have developed a statistical method that may be used to predict the values of dose distribution parameters of different radiosurgery techniques for treatment of AVM based on internal geometric parameters. Eighteen previously treated AVM patients were used as a sample group in this study. The multiple regression model is employed to establish the correlation between the internal geometric parameters and the dose distribution for different treatment techniques. The results of this study may be used to predetermine the optimal radiosurgery technique for treatment of AVM on a patient-to-patient basis.

METHODS AND MATERIALS

For each of the 18 AVM patients, four different treatment plans were created using the following techniques: circular collimator arcs, dynamic conformal arcs, fixed conformal fields, and IMRS. All the plans were created with BrainSCAN (BrainLAB AG, Heimstetten, Germany) by a single experienced physicist to ensure the consistency between the treatment plans and common dosimetric criteria, i.e., target coverage (the details of the planning procedures will be reported separately). The original plans used for treatment were not used in this study. The circular collimator arc plans were normalized to the maximum dose and the doses prescribed to 80% and 50% of the maximum dose for single and multiple isocenter treatments, respectively. The dynamic conformal arc, conformal field, and IMRS plans were normalized to 100% at the isocenter, and the dose was prescribed to 80% of the isocenter dose. Prescribed doses ranged from 16 to 25 Gy and were delivered in a single fraction (stereotactic radiosurgery). All of these 72 plans were analyzed and evaluated based on the DVHs for target, normal tissue, and critical structures. To evaluate the dose conformity to the target volume and the dose homogeneity in the