Report Number: WUCS-93-13

1993-01-01

Objective Evaluation of Radiation Treatment Plans

Nilesh L. Jain and Michael G. Kahn

The evaluation of radiation treatment plans involves making trade-offs among doses delivered to the tumor volumes and nearby normal tissues. Evaluating state-of-the-art three-dimensional (3D) plans is a difficult task because of the huge amount of planning data that needs to be deciphered. Multiattribute utility theory provides a methodology for specifying trade-offs and selecting the optimal plan from many competing lans. Using multiattribute utility theory, we are developing a clinically meaningful objective plan-evaluation model for 3D radiation treatment plans. Our model incorporates three of the factors involved in radiation treatment evaluation - treatment preferences of the radiation oncologist, clinical condition... Read complete abstract on page 2.

Objective Evaluation of Radiation Treatment Plans

Nilesh L. Jain and Michael G. Kahn

Complete Abstract:

The evaluation of radiation treatment plans involves making trade-offs among doses delivered to the tumor volumes and nearby normal tissues. Evaluating state-of-the-art three-dimensional (3D) plans is a difficult task because of the huge amount of planning data that needs to be deciphered. Multiattribute utility theory provides a methodology for specifying trade-offs and selecting the optimal plan from many competing lans. Using multiattribute utility theory, we are developing a clinically meaningful objective plan-evaluation model for 3D radiation treatment plans. Our model incorporates three of the factors involved in radiation treatment evaluation - treatment preferences of the radiation oncologist, clinical condition of the patient, and complexity of the treatment plan.

Objective Evaluation of Radiation Treatment Plans

Nilesh L. Jain and Michael G. Kahn

WUCS-93-13

April 9, 1993

Division of Medical Informatics
Campus Box 8005
660 S. Euclid Ave
Washington University School of Medicine
St. Louis MO 63110

Submitted to the Seventeenth Annual Symposium on Computer Applications in Medical Care to be held in Washington DC from October 31, 1993 to November 3, 1993

Objective Evaluation of Radiation Treatment Plans

Nilesh L. Jain, M.S. and Michael G. Kahn, M.D., Ph.D.
Division of Medical Informatics, Department of Internal Medicine; Department of Computer Science; Washington University School of Medicine, St. Louis MO 63110

The evaluation of radiation treatment plans involves making trade-offs among doses delivered to the tumor volumes and nearby normal tissues. Evaluating state-of-the-art three-dimensional (3D) plans is a difficult task because of the huge amount of planning data that needs to be deciphered. Multiattribute utility theory provides a methodology for specifying trade-offs and selecting the optimal plan from many competing plans. Using multiattribute utility theory, we are developing a clinically meaningful objective plan-evaluation model for 3D radiation treatment plans. Our model incorporates three of the factors involved in radiation treatment evaluation — treatment preferences of the radiation oncologist, clinical condition of the patient, and complexity of the treatment plan.

INTRODUCTION

The goal of radiation treatment is to irradiate uniformly all tumor volumes to their prescribed doses, and at the same time, to minimize radiation to the nearby normal tissues [1]. Each potential plan must make trade-offs in the doses delivered to tumor volumes and normal tissues. The evaluation of 3D radiation treatment plans is difficult because it requires the radiation oncologist to decipher a huge amount of planning data. Making an unambiguous conclusion about the merits of one plan over another is a difficult task, and thus far objective plan-evaluation methodologies that reflect actual clinical practice have been non-existent.

Most real-life decisions involve choosing among available alternative plans in order to fulfill conflicting multiple objectives. In radiation treatment, two conflicting treatment objectives have to be satisfied simultaneously: delivering the prescribed dose to the tumor, and minimizing the dose to nearby normal tissues. *Multiattribute utility theory* provides a methodology for specifying the trade-offs involved and for selecting the optimal plan [2, 3]. The outcome of the plan is divided into a number of meaningful component attributes which contribute to the overall utility of the outcome. The utility of each attribute is assessed over all possible outcomes; weights signifying the trade-offs among the attributes are acquired. The overall utility for each plan is obtained by combining the utilities and weights of all the attributes. Normative decision theory states that the alternative with the maximum overall utility is the one that should be chosen.

We are using multiattribute utility theory to develop objective plan-evaluation models for ranking competing radiation treatment plans. This paper describes a preliminary model and some of its shortcomings, and then describes a new model which we propose to investigate.

PRELIMINARY MODEL

The plan-ranking problem was formulated as a multiattribute decision problem [4, 5]. Each attribute represented a specific clinical issue that may appear in a treatment plan. Typical attributes (clinical issues) were non-eradication of tumor and radiation-induced damage to normal tissues. For each issue, its *utility* was computed as a number from 0 to 1. *Utility* of 0 for an issue meant the plan addresses that issue in an undesirable manner, and 1 meant the plan addresses that issue in a desirable manner. A multiplicative combining function was used to obtain the overall utility or *figure of merit (FOM)* of the plan. Thus:

$$FOM = \prod_{i}^{issues} utility_i \qquad (1)$$

Not all issues had the same clinical relevance in the evaluation of the treatment plans. To obtain *utility* of an issue, the probability of the occurrence of that issue was combined with the clinical relevance of the issue in the plan. For issue i:

$$utility_i = 1 - probability_i * weight_i \qquad (2)$$

In Eq. 2, *probability* was the likelihood of occurrence of the issue. *Weight* indicated the clinical relevance of an issue. *Weight* of 0 meant the issue was irrelevant, and 1 meant it was important. Thus, *FOM* was computed as:

$$FOM = \prod_{i}^{issues} (1 - probability_i * weight_i) \qquad (3)$$

The plans were ranked based on their *FOM*. *Utility* value was used to determine which issue should be improved to increase *FOM* of the plan.

One shortcoming in this model is that the utility of an attribute depended on its trade-off weight, whereas multiattribute utility theory recommends that utility should be independent of weight. The probability values for normal tissues rarely exceeded 0.03. This meant that *utility* was at least 0.97 and all trade-off decisions were being made in the narrow interval from 0.97 to 1.00. Similarly, for some of the patients, the best achievable tumor eradication probability was less than 0.75. This meant that *utility* for the tumor volume could not exceed 0.75, whereas most of the other issues would have higher *utility*. This affected the ability of the model to select issues for improvement as the tumor volume had already been optimized to the best achievable dose.

NEW DECISION THEORETIC MODEL

Any objective plan-evaluation model should incorporate the preferences of the decision maker, and also fine tune these preferences based on the conditions or abilities of the other people involved in the process. Hence, we seek to model the treatment preferences of the radiation oncologist. These preferences can be affected by both the clinical condition of the patient, and the ability of the technician to administer a very complex treatment plan. But no objective radiation treatment plan-evaluation models in the literature incorporate these factors. Thus, the evaluation of radiation treatment plans should involve the radiation oncologist prescribing the treatment, the patient receiving the treatment, and the technician administering the treatment.

The plan-ranking problem is again formulated as a multiattribute decision problem, having the same attributes (issues) and *utility* for each issue. *Utility* will be a function of the dose distribution in the tissue represented by that issue. The objective of the issue depends on the type of tissue represented by it. In the case of a tumor volume, the objective is to irradiate it uniformly to the prescribed dose. For a normal tissue, the objective is to minimize the dose delivered to it. However, it is impractical if not impossible to enumerate all the possible dose distributions for a tissue. This makes it impossible to elicit utility functions for the issue based on the dose distribution in the associated tissue. We will use *proxy attributes* in order to elicit the utility functions. A proxy attribute is one that reflects the degree to which an associated objective is met but does not directly measure the objective [2]. The proxy attribute will be the probability of a bad outcome for the issue. This probability will come from radiobiological models which use the dose distribution in and other radiobiological characteristics of the tissue. The objective of each issue will be to minimize the chance of a bad outcome for that issue, and *utility* will be a function of the probability of a bad outcome for that issue.

Different issues have different levels of morbidity. The morbidity of the issue will be represented by its *weight* which will be from 0 to 1. *Weight* will be used to make trade-offs among the different issues having different levels of morbidities. Furthermore, since the clinical condition of the patient affects the trade-offs made among the various issues, *weight* will encode the clinical condition of the patients. *Weight* of 0 means the issue is irrelevant, and 1 means it is important.

In order to compare and rank competing plans, *utility* and *weight* of the issues need to be combined to obtain an overall utility (*FOM*) for the plan. Let the contribution of each issue to *FOM* be called its *score*. When *utility* of an issue is low and the issue is important, *score* should be low; when *utility* of the issue is high or the issue is irrelevant, *score* should be high. One function which has this behavior is:

$$score_i = 1 - (1 - utility_i) * weight_i \qquad (4)$$

Whenever *score* for any issue is low, *FOM* for the plan should be low. Since *score* is between 0 and 1 for all the issues, a suitable aggregation model which has this behavior is the multiplicative multiattribute model. Thus:

$$FOM = \prod_{i}^{issues} score_i \qquad (5)$$

Thus, the new objective plan-evaluation model is:

$$FOM = \prod_{i}^{issues} (1 - (1 - utility_i) * weight_i) \quad (6)$$

Notice how Eq. 6 is similar to our previous model (Eq. 3), but *utility* (goodness) and *weight* (importance) are more clearly separated now. We will elicit utilities and weights for three tumor sites — prostate, lung, and head-and-neck.

Physician Factors

The treatment preferences of the radiation oncologist are encoded in *utility* of the issues. *Utility* measures how closely the objective for that issue is being met. In the case of radiation treatment, the objective for each issue is to minimize the probability of any untoward clinical event associated with that issue. In our earlier model, we used this probability directly and we observed that due to the low probability values, we were never using the entire range of our utility function. Our new utility function maps the narrow range of observed probabilities onto the entire range of *utility*. This method of scaling the acceptable levels of an issue onto the entire utility range is a common way of constructing utility functions [3].

For any issue i in a treatment plan, we believe that the radiation oncologist considers two key probabilities – the lower threshold probability p_i^l, and the upper threshold probability p_i^u. p_i^l represents the highest probability of occurrence that the radiation oncologist is willing to ignore. For some critical clinical issues, p^l can be 0. p_i^u represents the lowest probability of occurrence above which the radiation oncologist will reject the treatment plan categorically. Thus, the range $[0, p_i^u]$ represents the range of complication probabilities that the radiation oncologist is willing to consider while selecting a treatment plan for a patient. Let U be the utility function. Because the objective for any issue is to minimize the probability of its occurrence, part of the utility function over the probability p is as follows:

$$\begin{aligned} U(p) &= 1 \quad 0 \le p \le p^l \quad \text{(ignore the issue)} \qquad (7) \\ &= 0 \quad p^u \le p \le 1 \quad \text{(reject the plan)} \end{aligned}$$

The region of interest is $p^l \le p \le p^u$ in which $U(p)$ goes from 1 to 0. There are three possible ways this can happen – at a linear rate, at an exponentially increasing rate, or at an exponentially decreasing rate (Fig. 1).

The utility function for the same issue may be different for different tumor sites. This is due to the fact that the tissue being considered may be at a higher risk for damage in one of the tumor sites due to its proximity to the tumor than in the other tumor site. For a given tumor site, we will obtain from radiation oncologists worksheets containing the list of all tumor volumes and normal tissues that appear in the treatment field. For each issue on the worksheet, p^l and p^u will be elicited. We believe that the radiation oncologists will be able to give us these probabilities quite easily as they must regularly be considering subjective values for the probability of complications in a tissue while selecting treatment plans. Eliciting these two probabilities will give us the range of probabilities over which *utility* goes from 1 to 0. Over this range, we will elicit *utility* of the issue in two parts – the shape of the curve, and its steepness.

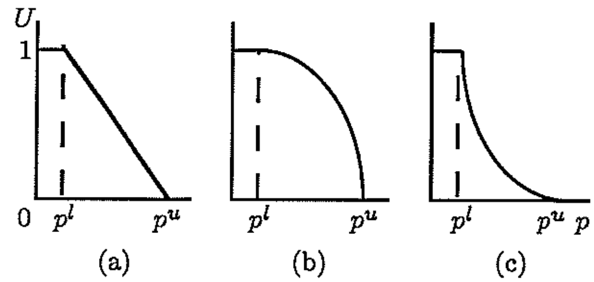

Figure 1: Three possible shapes for utility function U in the range $[p^l, p^u]$. The utility is decreasing at a (a) linear, (b) exponentially increasing, and (c) exponentially decreasing rate.

In order to obtain the shape of the curve, we will provide the following verbal description of the three curves in Fig. 1. For U decreasing at a linear rate (Fig. 1(a)), the preference for the issue goes steadily from 1 to 0 as the probability goes from p^l to p^u. For U decreasing at an exponentially increasing rate (Fig. 1(b)), the preference for the issue is quite high for probabilities slightly over p^l, but it rapidly approaches 0 for probabilities approaching p^u. For U decreasing at an exponentially decreasing rate (Fig. 1(c)), the preference for the issue starts becoming very low even for probabilities slightly over p^l. The radiation oncologist will be asked to pick the curve which best reflects how his/her preference for that issue changes with increasing probability of complication. If the radiation oncologist picks either of the last two cases, then we have to obtain the steepness of the curve. This can be done by determining a point on the curve and calculating the rest of the curve. However, this will be difficult as there is no way of calibrating the intermediate points on the curve so that all the radiation oncologists use it in a consistent manner. Instead, we will approximate the process by presenting the radiation oncologist with three curves of varying steepness. The radiation oncologist will then be asked to select which of these curves best represents his/her preference for the issue. The first of these curves will be a slight deviation from the linear case. The second curve will be quarter of a circle with radius equal to the length of the x-axis from p^l to p^u. The third curve will be even steeper being almost flat (vertical or horizontal) at the two extremes. Thus, there are seven possible utility curves (Fig. 2). This methodology is a variant of the category estimation technique for utility elicitation [6].

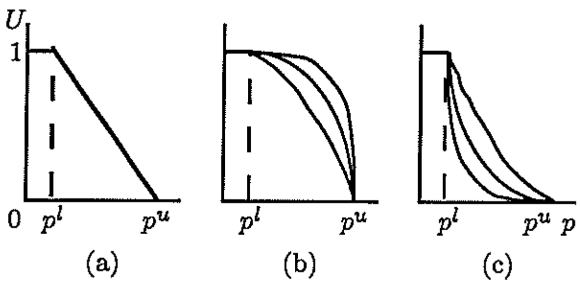

Figure 2: Seven possible utility functions in the range $[p^l, p^u]$. The utility is decreasing at a (a) linear, (b) exponentially increasing, and (c) exponentially decreasing rate.

Patient Factors

The clinical condition of the patient will be encoded through the issue *weight* as it affects the trade-offs to be made among the various issues. For each tumor site, we will elicit a list of patient factors which can affect the trade-offs being made among the various clinical issues. These clinical conditions include the stage of the cancer, the age of the patient, the presence of some other concurrent illness such as diabetes, the functional capacity of an organ such as the kidney, etc. Patients will be classified into categories depending on the presence or absence of the relevant clinical conditions. A set of weights will be elicited for each patient category.

To obtain patient-specific weights, a hypothetical patient will be described to the radiation oncologist based on the patient category for which weights are being elicited. Then, the radiation oncologist will be asked to select from the worksheet a single issue that he/she would consider to be the most critical issue for such a patient. This selection has to be made based on the morbidities of the complications related with each of the issues. Let this critical issue be i_c. Then, $weight_{i_c} = 1$ (most important). Now, for every other issue i on the worksheet, two hypothetical plans p_1 and p_2 will be described. Table 1 contains the probabilities of complication for the issues in these plans. The radiation oncologist will be asked which plan does he/she prefer. Three cases are possible:

Table 1: Probabilities of complication for the issues in the hypothetical plans p_1 and p_2 being used to elicit *weight* of issue i.

	Issue i_c	Issue i	Other issues
Plan p_1	$p^l_{i_c}$	p^u_i	0
Plan p_2	$p^u_{i_c}$	p^l_i	0

1. Plans p_1 and p_2 are equivalent. Since the issues have complementary utilities in the two plans, they must have the same weight in order to obtain the same FOM. Thus, $weight_i = 1$.
2. Plan p_1 is preferred over p_2. In this case, the radiation oncologist will be asked to give a probability p of complication for issue i_c in plan p_2 that will make the two plans equivalent. We are trying to improve plan p_2 till it becomes as good as plan p_1. Equating FOMs, we get $weight_i = 1 - U_{i_c}(p)$ where U_{i_c} is the utility function for issue i_c.
3. Plan p_2 is preferred over p_1. This is inconsistent because it implies that issue i is more important than issue i_c.

This methodology is a variant of the trade-off technique for constructing attribute weights [7].

Technician Factors

The complexity of a treatment plan will include the difficulty of administering it. For each plan, *complexity score* will be computed as a number from 0 to 1. This is similar to *utility* for the clinical issues. *Complexity score* of 1 means that the plan is very easy to administer to the patient, and 0 means that this plan is either impossible or impractical to administer.

Our approach is similar to the one used by researchers in case-based reasoning where the solution to a new problem is found by adapting the solution to a similar old problem which has been previously solved [8]. To serve as the case base, we will build a library of treatment plans that have been administered in the past to patients at our institution. Radiation oncologists, physicists, and technicians will be asked to assign *complexity scores* to those plans. The plans will be stored in the plan library using a number of indices including the number of beams in the plan, their gantry angles, the number and kind of treatment machines, etc. Each time our objective plan-evaluation model is evaluating a treatment plan, it will select a similar treatment plan from the plan library. The similarity metric for comparing the two plans will be based on the indices used for storing the plans in the plan library. *Complexity score* for the plan will be calculated by suitably adjusting *complexity score* of the selected plan to compensate for the difference between the two plans.

Given *complexity score* for a plan, there are two ways of incorporating it into our objective plan-evaluation model. The treatment plan complexity can be considered as another attribute in our multiattribute utility model. In that case, *complexity score* will be used as *utility* in Eq. 6. Its *weight* can be elicited using a modified version of the methodology described in **Patient Factors**. An alternate approach is to keep the treatment plan complexity separate from *FOM* leaving *FOM* comprised of only the clinical issues. *Complexity score* can be used to break ties among plans having the same *FOM*. The complexity score will be presented for all the plans; it will be left up to the radiation oncologist to make the appropriate trade-off depending on *FOM* and *complexity score* of the treatment plan.

CONCLUSION

We have presented a decision theoretic model for the objective evaluation of radiation treatment plans. We envision many potential uses for it. It can be used by radiation oncologists for evaluating, selecting, and manually optimizing radiation treatment plans. An objective plan-evaluation model has tremendous pedagogical value. Residents can learn from the evaluation skills of the senior radiation oncologists. *FOM* can be used as an objective function by computer programs that try to obtain an optimal treatment plan by using mathematical optimization techniques. Qualitative results can be used by computer programs that try to obtain an optimal treatment plan using artificial intelligence techniques [9, 10]. In the future, with the promise of real-time dose calculation [11], the treatment planners may obtain an instantaneous evaluation as they move the beams during the design of a treatment plan. We are also planning to use this model to investigate a new preference acquisition methodology [12].

ACKNOWLEDGEMENT

Supported in part by NLM Training Grant 5-T15-LM07049, NLM Grant 5-R29-LM05387, NCI Contract N01-CM97564, Office of Human Genome Research Grant 1-R01-HG00223.

Reference

[1] Perez CA, Brady LW, eds. *Principles and Practice of Radiation Oncology*. Philadelphia, PA: J. B. Lippincott, 1987.

[2] Keeney RL, Raiffa H. *Decisions with Multiple Objectives: Preferences and Value Tradeoffs*. New York, NY: John Wiley and Sons, 1976.

[3] von Winterfeldt D, Edwards W. *Decision Analysis and Behavioral Research*. Cambridge, UK: Cambridge University Press, 1986.

[4] Jain NL, Kahn MG. Ranking radiotherapy treatment plans using decision-analytic and heuristic techniques. Comput Biomed Res 1992;*25*:374–83.

[5] Jain NL, Kahn MG, Drzymala RE, Emami B, Purdy JA. Objective evaluation of 3-D radiation treatment plans: A decision-analytic tool incorporating treatment preferences of radiation oncologists. Int J Radiat Oncol Biol Phys 1993;In press.

[6] Edwards W. How to use multiattribute utility measurement for social decision making. IEEE Trans Sys Man Cybern 1977;*7*:326–40.

[7] Dyer JS, Sarin R. Measurable multiattribute value functions. Oper Res 1979;*27*:810–22.

[8] Hammond KJ. *Case-based Planning: Viewing Planning as a Memory Task*. Boston, MA: Academic Press, 1989.

[9] Berger J. ROENTGEN: Case-based reasoning and radiation therapy planning. In: Frisse ME, ed. *Proceedings, Sixteenth Symposium on Computer Applications in Medical Care*. New York, NY: McGraw-Hill, 1992: 210–4.

[10] Kalet IJ, Paluszyński W. Knowledge-based computer systems for radiotherapy planning. Am J Clin Oncol 1990;*13*:344–51.

[11] Rosenberger FU, Matthews JW, Johns GC, Drzymala RE, Purdy JA. Use of transputers for real time dose calculation and presentation for 3-D radiation treatment planning. Int J Radiat Oncol Biol Phys 1993;In press.

[12] Jain NL, Kahn MG. A methodology for reconciliation of inconsistencies in physicians' preferences through clinical use of decision-support systems (abstract). Med Decis Making 1992;*12*:349.