A Geometry-driven Approach for Predicating DVHs of Organs at Risk in IMRT Planning

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Abstract

Given consistent beam characteristics and prescribed target dosage across patients, the dose distributions of organs at risk (OARs) for a specific patient are largely determined by the anatomical structures of the patient, specifically the spatial configuration between each OAR and target. We propose a method that predicates the DVHs of OARs of a new patient in IMRT planning by comparing the spatial configurations between OARs and targets of the new patient with those of prior patients, whose plans are maintained in a database. The overlap volume histogram (OVH) is used to quantify the spatial configuration. The best DVHs among a group of related prior patients identified by OVH analysis are retrieved from the database and applied as the predications for the new patient's DVHs. By incorporating geometric analysis into planning, the DVHs of the new patient are clearly defined ahead of planning. It heralds the possibility of automated IMRT planning.

Keywords

IMRT, OVH, DVH, Database

Introduction

Intensity modulated radiation therapy (IMRT) is an inverse treatment planning approach that optimizes the intensity distributions for each of a set of beams to achieve a tailored or individualized treatment plan. The process is guided by the DVH objectives that score the trade-offs between target coverage and organ at risk (OAR) sparing. Currently, IMRT treatment planning is a time-consuming process of trial and error. Planners do not have prior knowledge of achievable DVHs that account for the trade-offs between target coverage and OAR sparing for a specific patient. The planning process requires many rounds of optimization, as planners repeatedly adjust the DVH objectives to arrive at what personal experience suggests is the best achievable plan.

The underlying difficulty is that we have yet to develop a quantitative way of defining the achievable DVHs that account for the trade-offs between target coverage and OAR sparing for a specific patient. Much of this inability is due to the variability of the anatomical structures between patients, i.e., the spatial configuration between each target and OAR.

Given consistent target coverage and beam characteristics across patients, the dose distributions of OARs heavily depend on the spatial configurations between OARs and targets: OARs distant from the target are easy to spare while proximal or overlapping OARs are not. Currently, this key geometric factor is not quantitatively considered in IMRT treatment planning.

To this end, we propose a geometry-driven method that predicates the DVHs of OARs of a new patient by comparing the spatial configurations between OARs and targets of the new patient with those of prior patients, whose plans are maintained in a database. The database contains the geometric and dosimetric information of prior patients. Before beginning to plan for a new patient, planners search through the database and identify a group of related prior patients by comparing the spatial configurations between OARs and targets of the new patient with those of prior patients. The best DVHs in that prior patient's group are retrieved from the database and applied as the predications for the new patient's DVHs. The predications can be used as the initial goals in IMRT treatment planning.

Material and methods

In our previous work [1, 2], we introduced the concept of a shape relationship descriptor, the overlap volume histogram (OVH), to quantify the spatial configuration between an OAR and a target. In this paper, we use the OVH to compare the spatial configurations of OARs and targets of a new patient with those of prior patients. A review of the OVH is presented below.

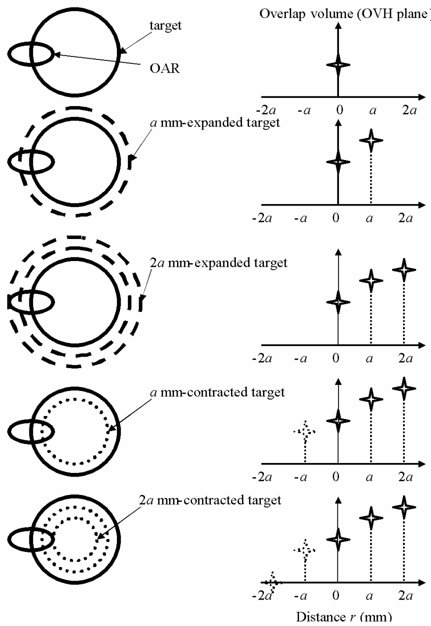

Figure 1: A simple way of conceptualizing the interpretation of the OVH.

Definition of the OVH and its simple interpretation

The OVH describes the fractional volume, v, of an OAR that is within a specified distance, r, of a target: v=OVH(r). Figure 1 illustrates a simple way of conceptualizing the interpretation of the OVH. The circle with a solid line represents a target. The ellipse with a solid line represents an OAR. OVH(0) can simply be interpreted as the overlap volume between the OAR and target, which is represented as a star with a solid line in the OVH plane. We then consider target expansion and isotropically expand the target by a distance of a mm. The overlap volume between this a mm-expanded target and OAR is represented as a star with a solid line at OVH(a). A new 2a mm-isotropic expansion of the target can now be considered, and so on, until the expanded target fully encompasses the OAR, at which point the overlap volume is the volume of the OAR. Similarly, the OVH can be interpreted for negative values by means of target contraction.

We use the total volume of the OAR to normalize the OVH: the y-axis in our OVH plane represents the percentage of the OAR's volume that overlaps with an isotropically expanded or contracted target. In the following discussion, we use notation r_v to represent the expansion or contraction distance that the target needs in order to cover a certain percentage volume v of the OAR: r_v=OVH^{-1}(v).

A head-and-neck example of the OVH

Figure 2 shows an example of the parotids' OVHs for a head-and-neck patient. An IMRT-simultaneous integrated boost (SIB) technique is applied to this patient: three prescription doses, 58.1 Gy, 63 Gy and 70 Gy were simultaneously delivered to the PTV$^{58.1}$, PTV^{63} and PTV^{70} respectively. The 3-D geometric relationships of the left and right parotids to the three PTVs are shown in Figure 2(a), (b) and (c) respectively. Since this patient has three PTVs, each parotid is associated with three OVHs: OVH$^{58.1}$, OVH^{63} and OVH^{70}. The OVHs of the left and right parotids of this patient are illustrated in Figure 2(d).

By utilizing PTV expansion and contraction, the OVH characterizes the distance between the parotids and PTVs. The OVH thus contains enough information to distinguish the ipsi-lateral and contra-lateral parotids. For example, in order to cover 50% volume of the right parotid, Figure 2(d) shows that the PTV$^{58.1}$, PTV^{63} and PTV^{70} must expand $r^{58.1}_{50,\mathrm{R}} = 1.26$ cm, $r^{63}_{50,\mathrm{R}}$=5.81 cm and $r^{70}_{50,\mathrm{R}}$=7 cm respectively. However, less expansion distance is needed to cover the same percentage volume of the left parotid: the PTV$^{58.1}$, PTV^{63} and PTV^{70} need to expand $r^{58.1}_{50,\mathrm{L}} = 0.6$ cm, $r^{63}_{50,\mathrm{L}} = 0.93$ cm and $r^{70}_{50,\mathrm{L}} = 4.57$ cm respectively. Thus, we have $r^{58.1}_{50,\mathrm{R}} > r^{58.1}_{50,\mathrm{L}}$, $r^{63}_{50,\mathrm{R}} > r^{63}_{50,\mathrm{L}}$, and $r^{70}_{50,\mathrm{R}} > r^{70}_{50,\mathrm{L}}$. This indicates that, with respect to v=50%, the right parotid is farther away from the three PTVs than the left parotid. The left parotid is thus an ipsi-lateral parotid with respect to v=50%. Accordingly, D_{50} of the right parotid should be lower than that of the left parotid: $D_{50,\mathrm{R}}<D_{50,\mathrm{L}}$, where D_v represents the dose corresponding to v percentage volume: D_v=DVH^{-1}(v). Figure 2(e) shows the DVH curves of the left and right parotids from the clinical plan, confirming this hypothesis.

Relationship between the OVH and DVH

Our approach is to use the information of previously treated patients who are determined to be more difficult for planning in order to predicate the DVHs for the OARs of a new patient. As indicated previously, the smaller the OVH value is, the closer the OAR is to the target. The closer the OAR is to the target, the higher the dose to the OAR will more likely be. Specifically, we seek prior patients in a reference database with the OVH values smaller than those of the new patient and apply their DVH values as the new patient's DVHs. For example, for two OARs: OAR$_1$ and OAR$_2$, if $r_{v,1} \geq r_{v,2}$ for a certain v, then OAR$_2$ is closer to the target at that v and we expect $D_{v,1} \leq D_{v,2}$. Thus, if $D_{v,2}$ has been obtained from a prior patient, then $D_{v,2}$ is an upper-bound for $D_{v,1}$. The value of $D_{v,2}$ can be directly used for the DVH of OAR$_1$ at percentage volume v. A database containing the OVHs and DVHs of prior patients is thus a prerequisite for this approach.

Database of prior patients

A database containing the OVHs and DVHs of prior patients is created for predicating the DVHs of a

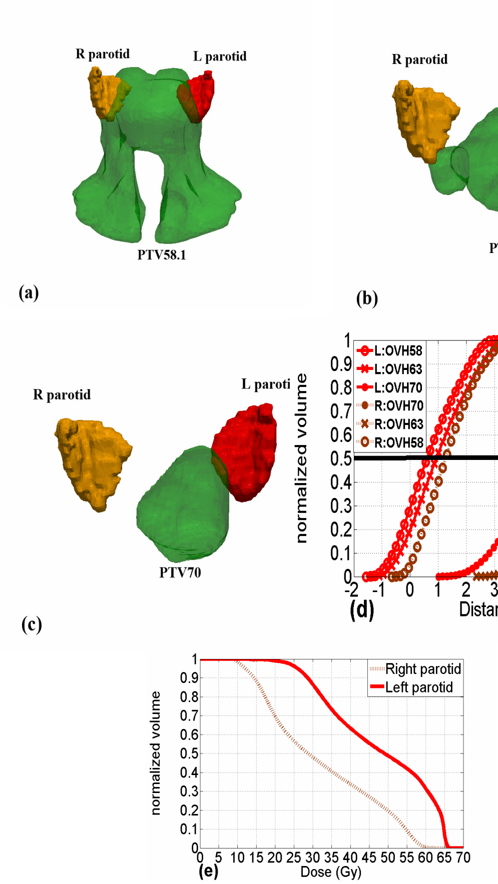

Figure 2: A head-and-neck OVH example. (a) $PTV^{58.1}$ and parotids. (b) PTV^{63} and parotids. (c) PTV^{70} and parotids.(d) OVHs. (e) DVHs of left and right parotids.

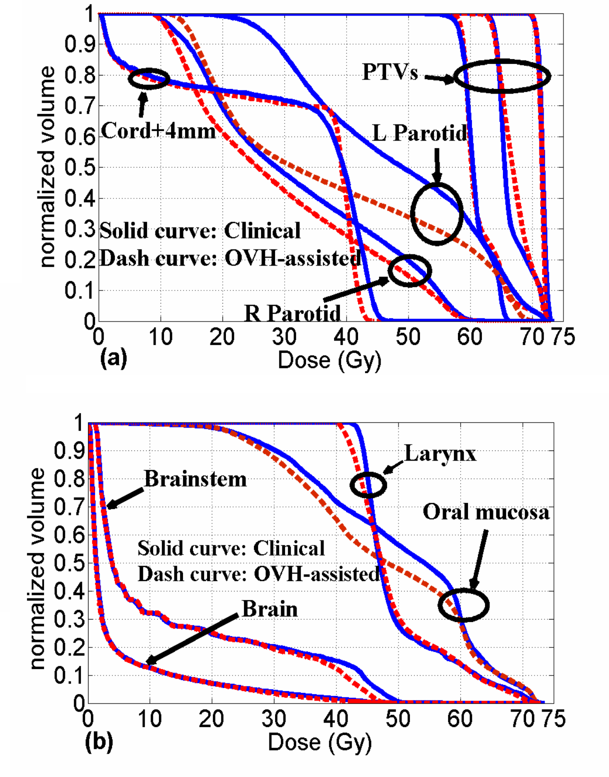

Figure 3: DVHs of the clinical and OVH-predicated plan for patient 57. (a) DVHs of the PTVs, parotid and cord+4mm. (b) DVHs of the brain, brainstem, oral mucosa and larynx.

new patient. The beam characteristics and prescribed target dosage to prior patients are the same as those of the new patient. To create this database, we first extract the geometric files (3-D contours of OARs and PTVs in planning CT) and the DVH values of the PTVs and OARs from the planning system. We compute the OVH for each patient's OAR. A database containing the OVHs and DVHs of the OARs and PTVs of prior patients is then formed.

Method for predicating DVH

After contours of OARs and targets of a new patient are completed, the OVH for each OAR is calculated. Next, the OVH of a query OAR of that new patient at specific percent volume v, $r_{v,q}$, is queried to the database, where symbol q represents the query OAR. Based on the query results, the DVH for that query OAR at v, $D_{v,q}$, is automatically generated from the database. The query has two steps:

1. The OVH of the query OAR, q, at specific percent volume v, $r_{v,q}$, is used to query the database. The query returns the set, S, of prior plans that satisfy the following conditions:

   $$S=\{i: r_{v,q} \geq r_{v,i} \text{ and } D_{95,i} \geq D_p\}, \quad (1)$$

   where $D_{95,i}$ represents the dose at 95% volume of the PTV, and D_p is the prescription dose to the PTV. Condition, $D_{95,i} \geq D_p$, is to confine the searched prior plans to those with good PTV coverage.
2. If the set S of prior plans meeting the conditions of (1) are identified, the DVH at percent volume v of that query OAR, $D_{v,q}$, is set as the minimum of $D_{v,i}$ among the set S of prior patients: $D_{v,q} = \min_{\text{Set } S}\{D_{v,i}\}$.

The v value selection is OAR-specific and is governed by the Radiation Therapy Oncology Group (RTOG) protocol. For example, one of the dosimetric guidelines in the RTOG 00-22 [3] for parotid sparing is: $V(30\text{Gy})<50\%$, so we set the values of v at 50% for the parotid based on the intuition that the 50% volume closest to the PTV will be the most influential to the doses of the parotid.

Results and discussion

A database containing the OVHs and DVHs of 64 prior head-and-neck patients underwent 9 fixed co-planar 6 MV photon beams (IMRT-SIB) with the three dose levels, 58.1 Gy, 63 Gy and 70 Gy are created. Consecutive numbers are used for representing the identity of patients. Parotids of patient 57 are selected from the database to illustrate the proposed method. The geometric relationships between the parotids and PTVs for that patient are shown in Figure 2.

	D_{50}	$r_{50}^{58.1}$	r_{50}^{63}	r_{50}^{70}	PTV$^{58.1††}$	PTV^{63††}	PTV^{70††}
57: L parotid*		0.6 cm	0.93 cm	4.57 cm			
61: L parotid†	30.1 Gy	0.48 cm	0.91 cm	1.92 cm	58.4 Gy	63.9 Gy	70.8 Gy
67: L parotid†	38.7 Gy	0.32 cm	0.7 cm	0.95 cm	58.2 Gy	64.3 Gy	65.9 Gy
63: L parotid†	29.3 Gy	0.56 cm	0.7 cm	0.88 cm	57.9 Gy	64.6 Gy	69.7 Gy
40: R parotid†	24.4 Gy	-0.06 cm	0.35 cm	2.24 cm	57.8 Gy	63.1 Gy	69.7 Gy
58: R parotid†	62.8 Gy	-0.47 cm	0.28 cm	2.49 cm	58.1 Gy	63.6 Gy	68.6 Gy

*: query parotid †: query result ††: D_{95}, dose corresponding to 95% volume

Table 1: Query results for the left parotid of patient 57(57L).

Table 1 shows the query results of the left parotid for patient 57 (57L). The leave-one-out methodology is used in the query so that 57L is queried against the 126 parotids of the other 63 patients. The input to the query is $r_{50,57L}^{58.1}$, $r_{50,57L}^{63}$ and $r_{50,57L}^{70}$, where v=50%. The output (query results) is the set of the candidates of parotids, S, as defined in (1). Through a database search, D_{50} of 57L is determined to be 30.1 Gy, which corresponds to D_{50} of 61L. 24.4 Gy and 29.3 Gy, corresponding to 40R and 63L, are not selected since D_{95} of the PTV$^{58.1}$ of those two patients is below 58.1 Gy. Similar procedure is applied to the right parotid of patient 57, and the predicated value is D_{50}=25.3 Gy.

Next, the predicated values of the parotids are input to the planning system to verify the achievability. Figure 3 illustrates the DVH curves of the clinical and the OVH-predicated plan for that patient. It shows that the predications of the parotids are much lower than the values in the clinical plan. Additionally, both predications are achieved without compromising any PTV coverage and other OAR sparing.

Discussion

The DVHs predicated by our method are patient-geometry specific. It is achieved by comparing the spatial configurations between OARs and targets of a new patient with those of prior patients in a database. Our method thus makes the predications very likely to be achieved for the new patient.

Our method is data-driven and founded on the experience of prior plans. The predicated DVHs are directly generated from the database of prior patients, which is built upon clinically approved treatment plans that reflect the clinical trade-offs between target coverage and OAR sparing made in prior planning. Those predicated DVHs thus inherently reflect prior physician's decision on such clinical trade-offs. In addition, the lowest doses (more favorable) among those related prior patients indicated by OVH analysis are applied as the predications for the new patients' DVHs. As a result, the predicated doses of OARs of new patients usually are consistent with the lowest doses in the database.

In this paper, parotids of a single patient are selected to illustrate the proposed method. The results are promising. A comprehensive retrospective study will be carried on to demonstrate the effectiveness of the method in the future.

Generalization of our method to other disease sites and OARs requires further investigation. Our method is based on the spatial relationship between OARs and targets characterized by the OVH. It implicitly assumes "OAR-independence": the dosimetric influence of other OARs on each other is assumed to be a second-order effect. More research will be carried on in this direction.

Conclusion

The proposed method is an efficient means of predicating achievable DVHs of OARs based on the DVHs and OVHs data retrieved from a database of prior plans. By utilizing this method, the DVHs of the OARs of new patients are clearly defined ahead of planning. It heralds the possibility of automated IMRT planning.

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