A Simple Scoring Method to Calculate the Homogeneity and Coverage Indices of Dose Volume Histogram

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The goal of this study was to develop new indices for effectively evaluating the dose coverage and homogeneity based on the target-volume dose-volume histogram (TV-DVH) of intensity-modulated radiotherapy treatment plans. A new coverage index and a new homogeneity index were developed by integrating a modified TV-DVH and by fitting a TV-DVH with a modified step function, respectively. The coverage index, named the *I*-index, indicates whether the dose coverage for the target volume is adequate based on user-defined criteria. A lower *I*-index indicates higher dose coverage of the tumor volume. The index for assessing dose homogeneity in a target volume, named the *n*-index, is more accurate than the conventional method in evaluating the dose homogeneity in a tumor volume. The baseline treatment plan for a target volume coverage and homogeneity is discussed. The proposed simple indices have been demonstrated to be effective in evaluating the dose coverage and homogeneity for TV-DVHs.

Key Words : Coverage index, Homogeneity index, Uniformity index, Target-volume DVH, Radiotherapy

INTRODUCTION

The objective of radiotherapy is to deliver a therapeutic dose to a well-defined target while minimizing the dose to the surrounding normal tissue and critical organs. Maximizing the probability of controlling a tumor without an excessive risk of radiation damage requires optimization of the (i) conformity of the isodose to the target lesion, (ii) dose homogeneity within the target, and (iii) dose coverage in the planned target volume (PTV) within the tolerance level to the surrounding normal tissue and critical organs.[1-5] To accomplish these goals of radiotherapy it is necessary to have a simple and universal scoring system for evaluating (and comparing) alternative treatment plans.

The dose-volume histogram (DVH) can provide an adequate assessment of target coverage based on a coverage index, which is defined by the percentage of tumor volume receiving a prescribed radiation dose (D_p).[6-10] An ideal tumor DVH (or target-volume DVH: TV-DVH) would be a step function, whereby 100% of the target receives exactly the prescribed dose (i.e., 100% of the prescribed level), but real DVH curves deviate from the step function and hence the tumor receives less than the 100% of D_p under the restrictions of dose constraints. A guideline of the Radiation Therapy Oncology Group (RTOG) specifies the clinically acceptable target volume coverage (TVC).[11] The no-variation conditions recommended by RTOG are (i) no more than 20% of any PTV will receive $>110\%$ of its prescribed dose, (ii) the prescription dose is the isodose that encompasses at least 95% of the PTV, (iii) no more than 1% of any PTV will receive $<93\%$ of its prescribed dose. The last two conditions suggest that coverage indices at D_p and at 93% of D_p should be more than 95% and 99%, respectively. Although such criteria are generally useful in evaluating the dose coverage of the TV-DVH, there are still some remained problems. Firstly, they provide no quantitative index for comparing rival treatment plans. Secondly, the coverage index defined by some points of the DVH may give inaccurate information about the actual

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dose coverage within the tumor volume.

Fig. 1 shows the two TV-DVHs with the same coverage index of 80% TVC at D_p. However, this coverage index gives incorrect information since the dose coverage of the tumor volume is clearly better for DVH 2 than for DVH 1 based on the entire DVH curve. As another example, the two TV-DVHs in Fig. 2 are for the no-variation criterion recommended by RTOG. DVH 1 in Fig. 2 fulfills the no-variation criterion since the dose coverages at D_p and at 93% of D_p are about 95% and 99%, respectively. In contrast, DVH 2 in Fig. 2 fails to meet the RTOG criterion since the dose at D_p is about 90% (i.e., less than 95%). A comparison of the dose coverage for the PTV based on the RTOG no-variation criterion reveals that the coverage of DVH 1 is better than that of DVH 2. However, as seen in Fig. 2b, the actual dose coverage of DVH 2 is much better than that of DVH 1. This discrepancy is due to the definition of the coverage index, which indicates that the dose coverages at D_p and at 93% of D_p do not represent the dose coverage for the entire DVH curve. Therefore, to properly compare the dose coverage for the PTV or tumor controllability between rival treatment plans, it is essential to quantify the dose coverage for the PTV based on entire DVH curves.

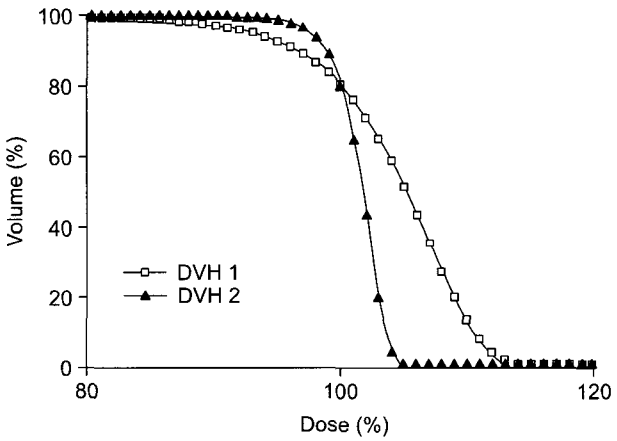

Fig. 1. An example of two TV-DVHs whose coverage indices are the same although the real dose coverages are different.

The DVH can also provide the dose homogeneity based on the homogeneity index (h-index) defined by the ratio of the maximum dose (D_{max}) in the tumor volume to D_p or the uniformity index (u-index) defined by the ratio of D_{max} to the dose covering 95% of the PTV.[9,12,13] In addition to the h- index and u-index introduced previously, there is another definition for homogeneity index called HI, which is defined as follows.[14]

$$HI = \frac{D_2 - D_{98}}{D_{prescription}} \times 100\% \quad (1)$$

D_2 and D_{98} represent the dose to the 2% and 98% of the volume, respectively. In this definition, D_{98} and D_2 are considered as minimum and maximum doses, respectively. As we can see from the definition, lower HI values are indicative of a more homogeneous target dose. These indices have been considered sufficient for quantifying the dose homogeneity in a tumor volume. However, obtaining a complete understanding of the dose homogeneity of the entire target requires consideration of the entire DVH curve due to the possibility

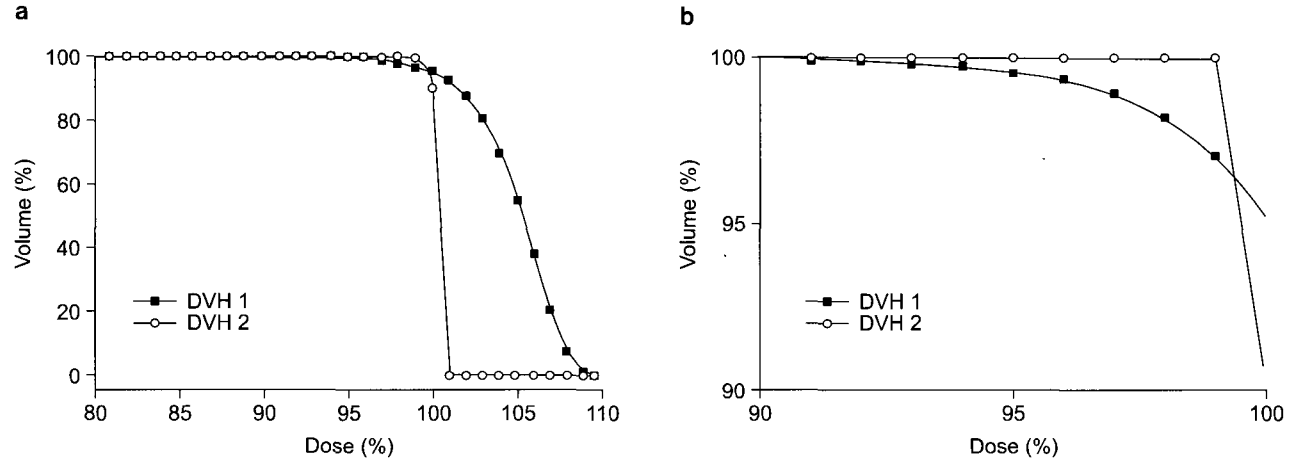

Fig. 2. (a) Two TV-DVHs whose coverage indices are difficult to compare. (b) Magnification of (a).

of the currently used indices producing erroneous information about the dose homogeneity within the tumor volume under certain conditions (as illustrated in Fig. 1 and 2). For instance, consider the two pairs of TV-DVHs in Fig. 3, Fig. 3a shows two TV-DVHs whose *h*-indices are 1.07 (DVH 1) and 1.10 (DVH 2), which seem unreasonable values if the entire DVH curve is considered. Although the *h*-index of DVH 2 is higher than that of DVH 1, the dose homogeneity of DVH 2 is clearly better than that of DVH 1. Like the homogeneity index, the uniformity index could also give incorrect information under certain conditions. Fig. 3b shows an example of this. Although the u-index of DVH 4 in Fig. 3b is higher than that of DVH 3, the dose uniformity (or homogeneity) of DVH 4 is better than that of DVH 3. Like the coverage index, this mismatch between the real dose homogeneity in a PTV and its index is also attributable to the current definition used, which is based on the doses at certain points of the DVH rather than the entire DVH curve. This result suggests the need for a new type of homogeneity index that is based on information from the entire DVH curve.

In this study, we examined the dose coverage and homogeneity for PTVs based on a mathematical approximation of the TV-DVH, and developed new indices that provide objective scores of the dose coverage and homogeneity for the PTV in a radiotherapy treatment plan.

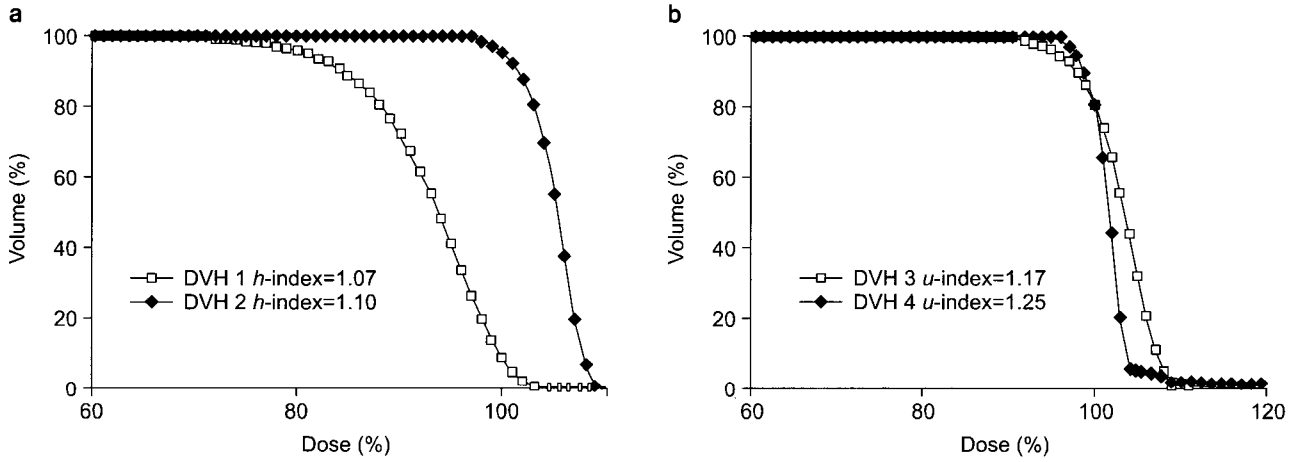

Fig. 3. (a) Two TV-DVHs whose homogeneity indices are difficult to compare. (b) Two TV-DVHs whose uniformity indices are difficult to compare.

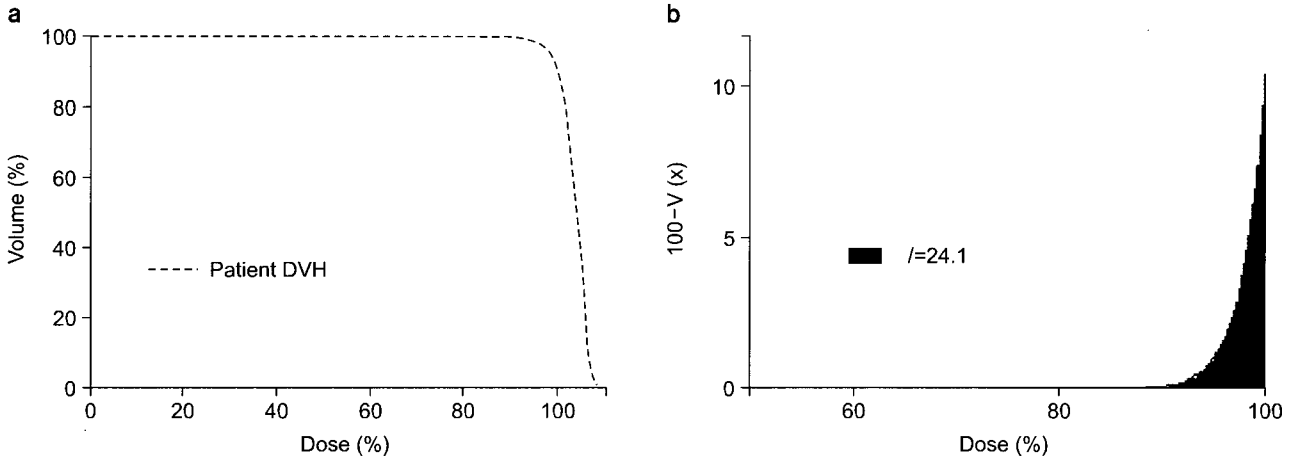

Fig. 4. (a) A patient's TV-DVH and (b) corresponding *I*-index.

MATERIALS AND METHODS

1. Coverage index based on integration of the TV-DVH

As a first step to quantify the TVC for each treatment plan, the TV-DVH was integrated from 0 to 100. By definition, the integration of an ideal TV-DVH (i.e., a step function) is 10,000, and hence a smaller difference between 10,000 and the actual integrated value of a patient's TV-DVH indicates a better dose coverage for the PTV. Based on this fact, we have defined a new coverage index, named the *I*-index, as

$$I = \int_0^{100} 100 - V(x)dx \qquad (2)$$

where V and χ represent the volume and dose percentages of a DVH, respectively. Fig. 4a and b show a patient's TV-DVH and the corresponding *I*-indices defined by Eq. (2).

To confirm the validity of this index, we reexamined the cases shown in Fig. 1 and 2. Fig. 5a and b reveal the *I*-indices for the two TV-DVHs in Fig. 1: the value of 92.9 for the *I*-index of DVH 1 in Fig. 1 is much larger than that of 31.8 for DVH 2 in Fig. 2, which indicates that the TVC of DVH 2 is much better than of DVH 1, and corresponds well with the real dose coverage. As another example, Fig. 5c, 5d show the *I*-indices for the two TV-DVHs in Fig. 2 As for the *I*-index in Fig. 5a, 5b, the *I*-index accurately represents the dose coverage for the PTV based on the integration of entire DVH curves. Although the DVH 2 does not fulfill the RTOG no-variation criterion, the coverage of DVH 2 is much better than the coverage of DVH 1. This result shows that the *I*-

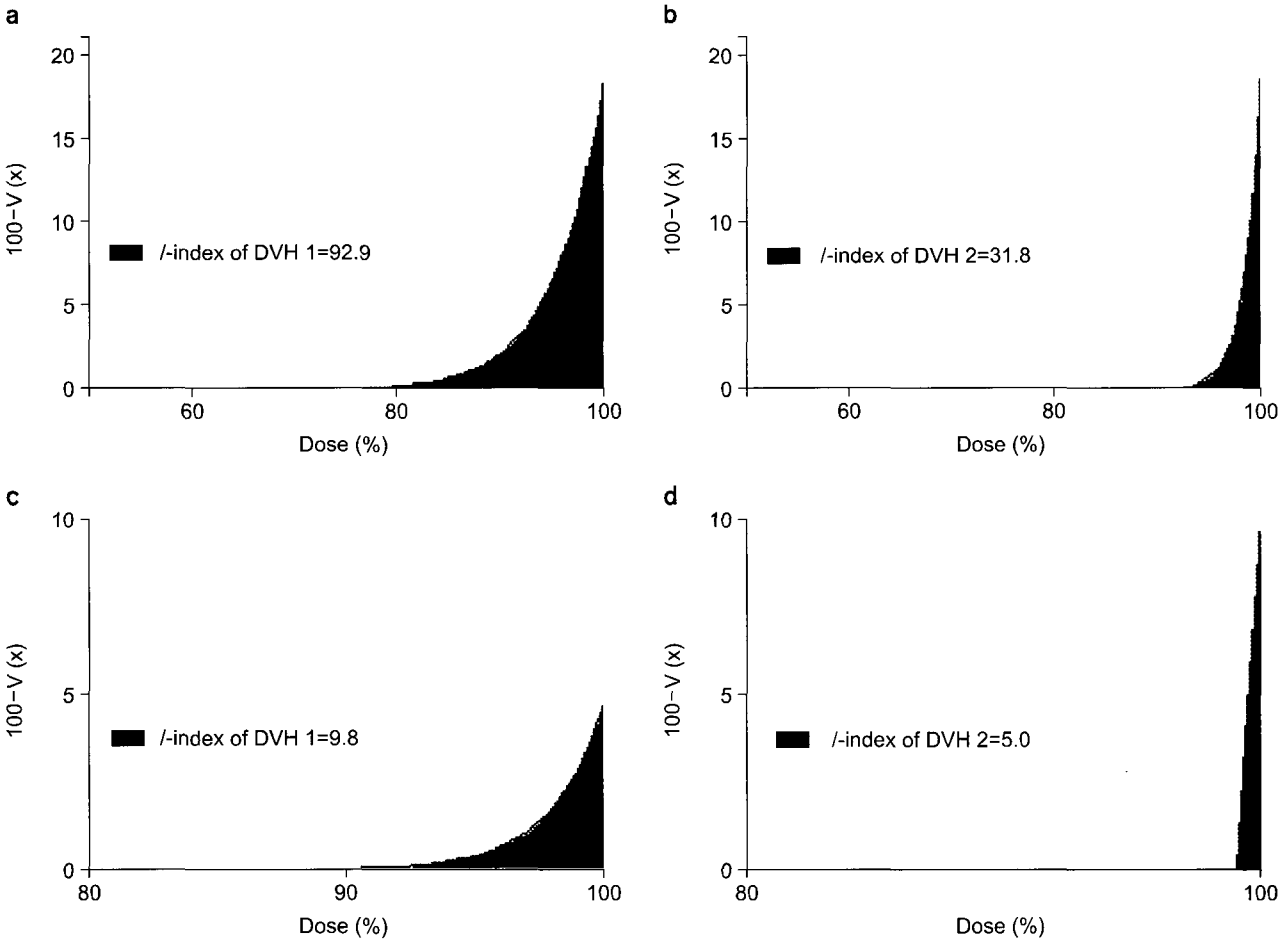

Fig. 5. (a) *I*-index for DVH 1 in Fig. 1. (b) *I*-index for DVH 2 in Fig. 1. (c) *I*-index for DVH 1 in Fig. 2a. (d) *I*-index for DVH 1 in Fig. 2a.

index is more effective than the conventional coverage index. The new index based on the analysis of an entire DVH curve matches the real dose coverage and is suitable for scoring the TVC under various conditions.

2. Homogeneity index based on fitting the TV-DVH to a modified step function

The Heaviside step function H (x), sometimes called the unit step function, is a discontinuous function whose value is 0 for negative arguments and 1 for positive arguments[15-17]:

$$H(x) = \begin{cases} 0 : x < 0 \\ 1 : x > 0 \end{cases} \quad (3)$$

To apply the step function to a TV-DVH, one of the conventional step functions was modified as follows:

$$V(x) = 100 \cdot e^{-e^{\frac{x-a}{n}}} \quad (4)$$

where V and χ represent the volume and dose percentages of a TV-DVH, respectively. The plots in Fig. 6 show this function for various values of n and a. For a fixed a value, as n decreases the plot approaches the ideal unit step function (i.e., with a faster fall-off rate). As a first step to quantifying the dose homogeneity for different treatment plans, a real patient's TV-DVH was fitted by a modified step function. Fig. 6b shows the patient's TV-DVH and its corresponding fitted curve, which indicates that the TV-DVH is well fitted with the step function with the appropriate n and a values

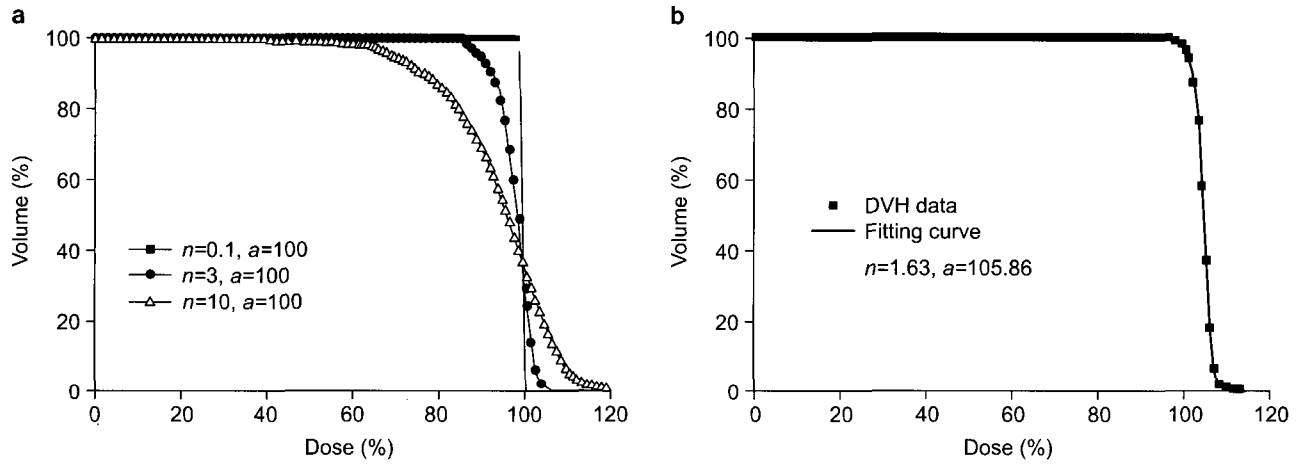

Fig. 6. (a) Example modified step functions for various n values. (b) A patient's TV-DVH and the corresponding fitted function, for which the reduced χ^2 is 0.19.

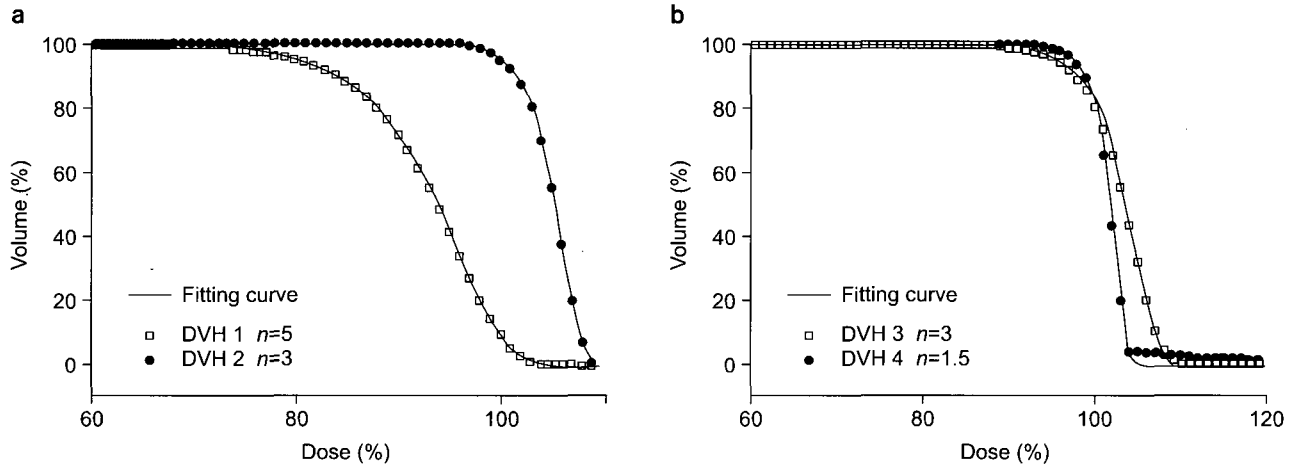

Fig. 7. Examples of the n-index method for (a) the two TV-DVHs in Fig. 3a, and (b) the two TV-DVHs in Fig. 3b.

(reduced χ^2 value of 0.19). This result shows that a conventional TV-DVH can be well approximated by the step function with appropriate parameters.

In general, both the *h*-index and the *u*-index vary with the fall-off rate of a DVH curve, showing values close to one (i.e., higher homogeneity) for a DVH with a faster fall-off rate. Therefore, a lower value of *n* (i.e., the *n*-index) in the fitting function (Eq. 4) indicates a faster fall-off rate of the DVH curve and a corresponding higher homogeneity. The essential difference between the *n*-index and the conventional homogeneity index is that n-index is evaluated based on the entire DVH curve and represents the dose homogeneity based on the fall-off rate. To confirm the effectiveness of this index, we reexamined the two pairs of TV-DVHs in Fig. 3, and show the corresponding *n*-indices in Fig. 7. Unlike the *u*-index and the *h*-index, the *n*-index provides no incorrect information on the homogeneity in the tumor volume: DVH 2 and DVH 4 represent a better dose homogeneity than do DVH 1 and DVH 3, respectively.

RESULTS

Fifty-six TV-DVHs obtained with BrainSCAN planning software (ver. 5.2; Brainlab, Germany) were used to explore the effectiveness of the *I*-index. Fig. 8 shows some typical examples of various TV-DVHs with the corresponding *I*-indices: 99.4%, 93.3%, 88.3%, and 59.0% TVC at the prescription dose. Fig. 8 shows the clear relationship between the *I*-index and the dose coverage: a lower *I*-index corresponds to a better DVH, with higher dose coverage for the PTV. To confirm the

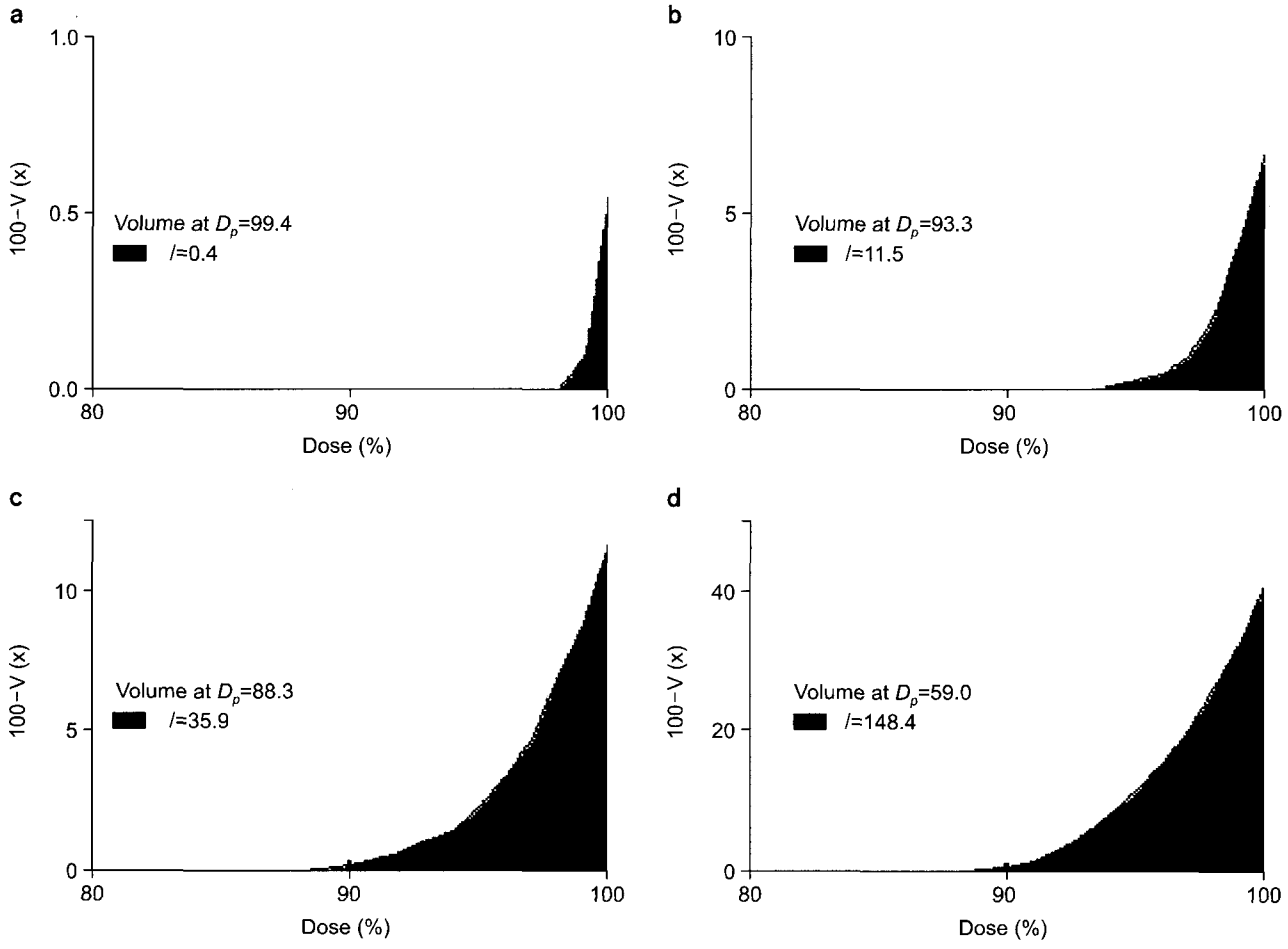

Fig. 8. Typical examples of various dose coverages with the corresponding *I*-indices: (a) 99.4%, (b) 93.3%, (c) 88.3%, and (d) 59.0% TVC at the prescription dose.

Table 1. Summary of the *I*-index and dose coverage in tumor volumes for 56 patients TV-DVHs.

I-index	Number of TV-DVHs	Average *I*-index	Average TVC at 93% of D_p	Average TVC at D_p	Classification of TVC
$0 \le I < 1$	7	0.2	100	99.7	Outstanding
$1 \le I < 10$	10	6.5	99.9	95.2	Very good
$10 \le I < 20$	8	14.2	99.7	92.4	Good
$20 \le I < 100$	13	40.6	99.2	81.5	Fair
$I \ge 100$	18	673.5	56.8	21.8	Unacceptable

Table 2. Summary of homogeneity and uniformity indices for various *n*-indices.

n-index	Number TV-DVHs	Average *h*-index	Average *u*-index	Average *n*-index	Classification of homogeneity
$0 \le n < 1$	9	1.05	1.05	0.53	Outstanding
$1 \le n < 2$	25	1.08	1.10	1.58	Good
$2 \le n < 3$	9	1.10	1.13	2.53	Fair
$n \ge 3$	13	1.06	1.30	4.62	Poor

relation between the *I*-index and dose coverage, a summary of the homogeneity and uniformity indices for various *n*-indices for the TV-DVHs of 56 patients is provided in Table 1.

For simple evaluation of the dose coverage of the tumor, the TVC of the TV-DVHs have been categorized based on the *I*-index as shown in Table 1. TV-DVHs with an *I*-index of less than 1 are classified as indicating an "outstanding" TVC. The prescription dose in this category is typically the isodose that encompasses at least 99% of the PTV. The next grade of TV-DVHs, for which the *I*-index is greater than 1 but less than 10, was classified as "very good" since it also shows a PTV coverage that is compatible with the RTOG criterion. In contrast, TV-DVHs with an *I*-index greater than 100 are categorized as "clinically unacceptable", since the volume at prescription dose is too low to control the tumor effectively, being on average 21.8% TVC. The extremely low TVC in this category is mainly due to the criteria associated with overdosing normal organs. The above results provide evidence that the TVC is more accurately quantified and evaluated by the *I*-index than by the currently used coverage index.

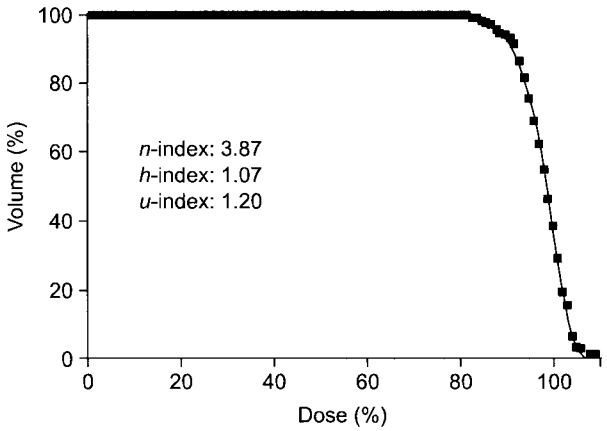

Fig. 9. An example patient TV-DVH for which *n* is greater than 3.

To further investigate how the *h*-index and *u*-index are related to the *n*-index, we performed a statistical analysis. The results are given in Table 2, which clearly show that the *n*-index is generally proportional to both the *u*-index and the *h*-index. In other words, a lower *n*-index indicates better homogeneity and uniformity in the tumor volume, as we expected. The only exception is that the *h*-index reveals abnormal behavior when the *n*-index becomes greater than 3. To investigate this further, we investigated a typical TV-DVH in this category. The *h*-index and *u*-index of the TV-DVH shown in Fig. 9 are equal to 1.07 and 1.2, respectively. The *h*-index indicates good homogeneity, but Fig. 9 contradicts this. We attribute this discrepancy to the underdosed TV-DVH, as already seen in Fig. 3a. Unlike the *n*-index and *u*-index, when the TV-DVH is underdosed the *h*-index is no longer useful for judging the dose homogeneity. This result explains the unusual behavior of the *h*-index in Table 2, and demonstrates that the *n*-index and *u*-index are more accurate in evaluating the dose homogeneity in tumor volume than the conventional *h*-index. The *n*-index is generally as effective as the *u*-index in evaluating the dose homogeneity, and is better than the *u*-index in some cases (see Fig. 3b).

DISCUSSION

We have defined the *I*-index for evaluating the target coverage by the DVH. Table 1 indicates that a lower *I* value indicates a better PTV coverage. However, although this index

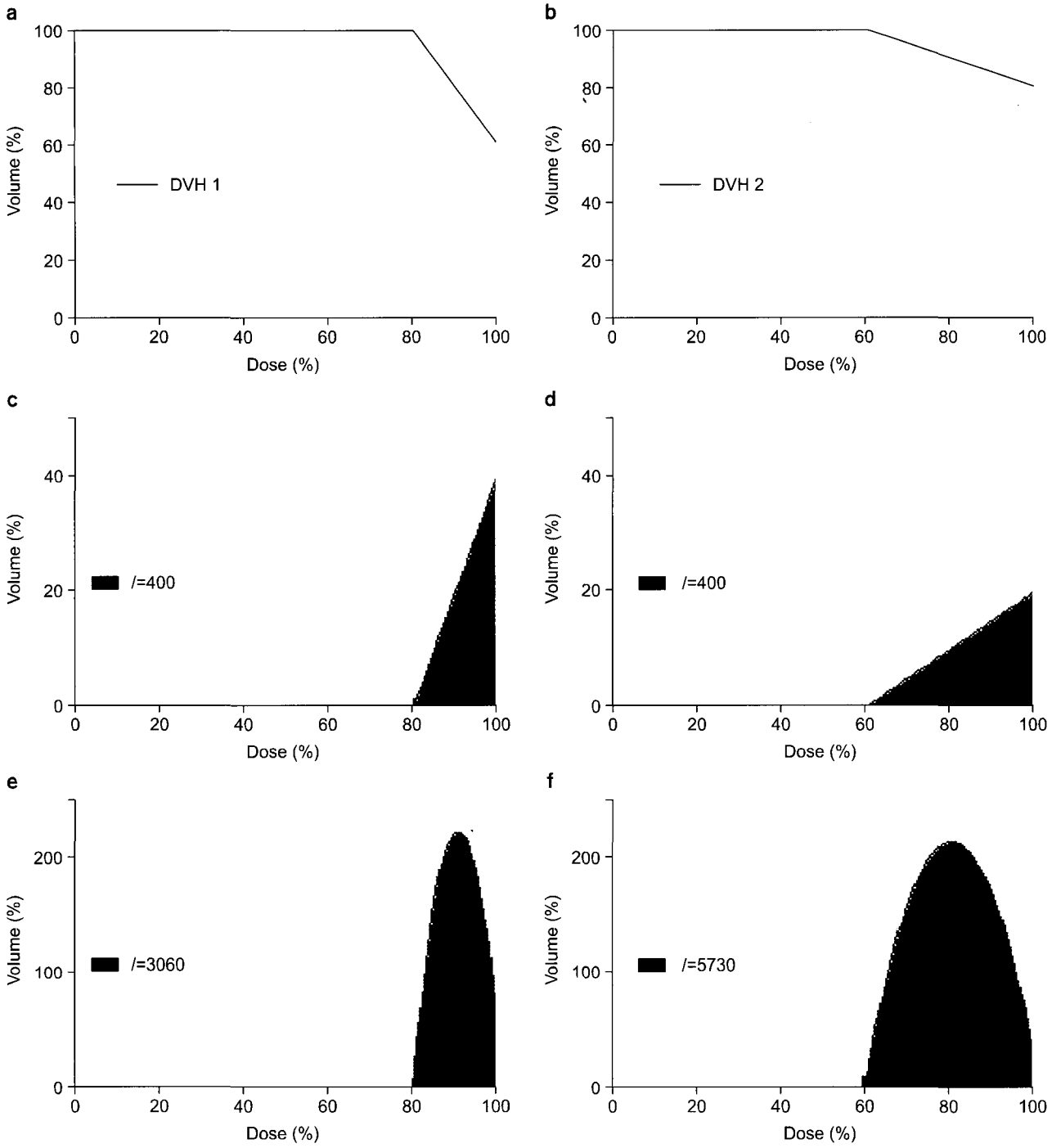

Fig. 10. Two TV-DVHs whose *I*-indices are same with (a) a fast fall-off rate and (b) a slow fall-off rate. (c) *I*-index of the TV-DVH in (a). (d) *I*-index of the TV-DVH in (b). (e) *I*-index of the TV-DVH in (a). (f) *I*-index of the TV-DVH in (b).

is good for most TV-DVH curves, it is insufficient for comparing the TVCs of rival treatment plans. For instance, the two quite-different TV-DVH curves in Fig. 10a, 10b produce the same *I* indices, as seen in Fig. 10c, 10d. Clinically the coverage of DVH 1 is considered better than the coverage of DVH 2, since DVH 2 will result in more under-dosing within

the tumor volume than will DVH.[18-21] This problem can be solved by using a coverage index that is dependent on the fall-off rate. We therefore modified the *I*-index with a weighting factor and named it the *i*-index:. The *i*-index is strongly dependent on the fall-off rates of DVH curves, and hence is a better coverage index for DVHs with a fast fall-off rate. We recalculated the coverage of DVH 1 and DVH 2 in Fig. 10a, 10b using the *i*-index. As expected, Fig. 10e, 10f indicate that this new index works very well, in that it has a lower value (higher coverage) for DVH 1 than for DVH 2.

There is another aspect to consider when comparing rival treatment plans for the same PTV. Fig. 11a, 11b show two TV-DVHs with their corresponding *I*-index and *n*-index values. While the *n*-index indicates that the homogeneity of DVH 1 is better than that of DVH 2, the *I*-index suggests that the coverage of DVH 2 is better than that of DVH 1. It is therefore difficult to compare these TV-DVHs based only on these indices. Although DVH 1 shows good homogeneity, it is basically underdosed since it shows low coverage. In contrast, the DVH 2 shows good coverage but is overdosed with low homogeneity. In general, the beam intensity can be altered to ensure that doses to critical organs are maintained at acceptable levels, and this will shift the TV-DVH. When comparing rival treatment plans, the TV-DVH should be considered under the same conditions, and hence should be normalized. Among many possible normalization techniques, we chose the simple method of shift the TV-DVH curves to ensure that 95% of the PTV received the prescription dose. In

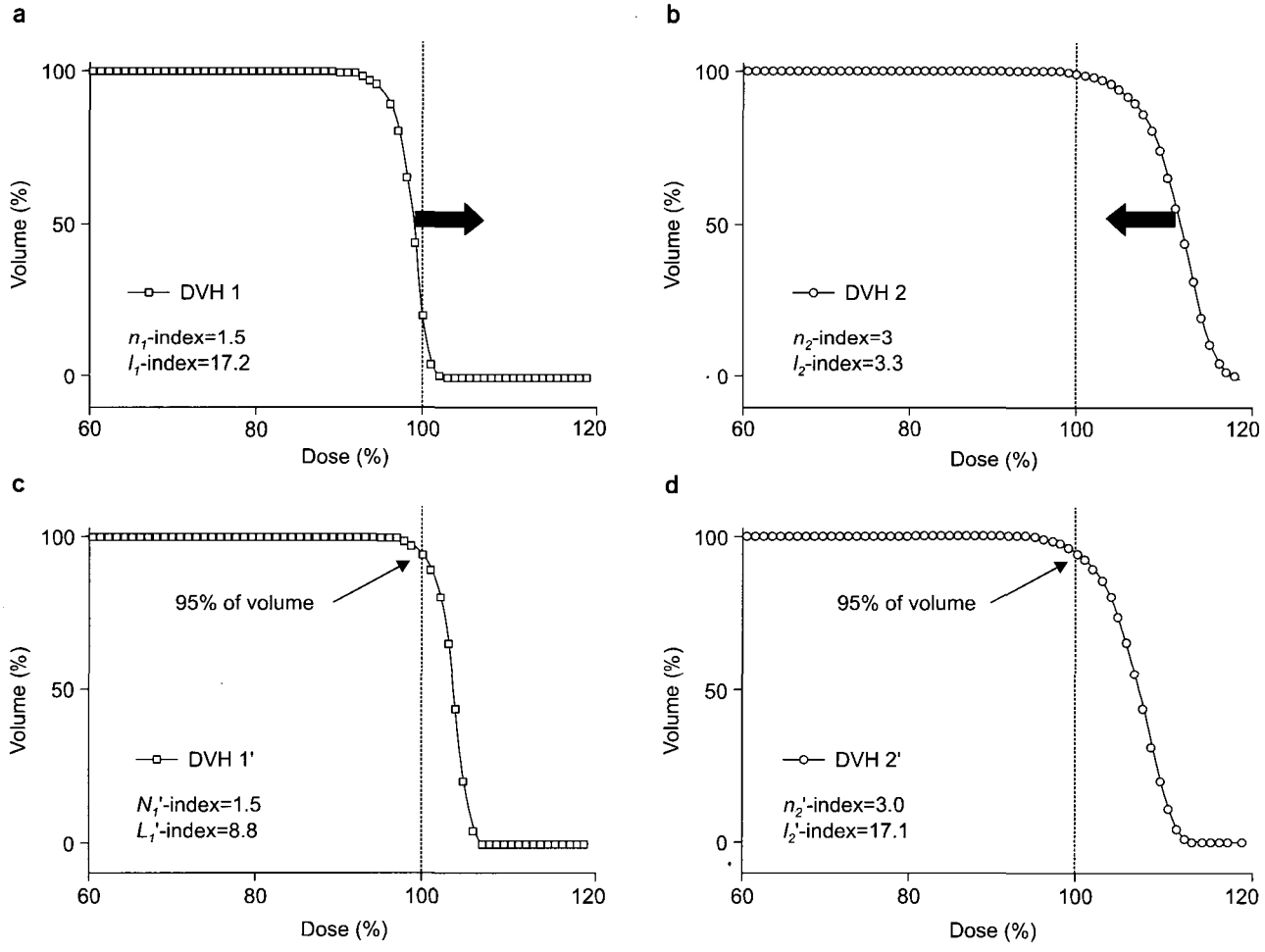

Fig. 11. Comparison of various TV-DVHs for the same PTV. (a) DVH 1, an underdosed TV-DVH. (b) DVH 2, an overdosed TV-DVH. (c) DVH 1', a normalized DVH 1. (d) DVH 2', a normalized DVH 2.

the example considered here, DVH 1 in Fig. 11a was shifted in the positive dose direction, and DVH 2 in Fig. 11b was shifted in the negative direction. Fig. 11c, 11d clearly indicate that DVH 1 is much better than DVH 2, both in homogeneity and coverage. Therefore, whilst the *I*-index and the *n*-index are very simple scoring methods for the dose coverage and homogeneity, it may be necessary for the DVHs to be normalized when comparing rival treatment plans.

CONCLUSIONS

Based on the functional approximation of the TV-DVH, we propose new indices for the objective assessment of the dose coverage and homogeneity of radiotherapy in a tumor volume. We believe that newly proposed *n*-index supplements conventional methods such as the uniformity index, the homogeneity index and *HI* by providing complete information of the entire DVH curve in a treatment plan. The result shows that the proposed new homogeneity index is more accurate in evaluating the degree of dose homogeneity and providing quantitative information of dose homogeneity than the conventionally used indices. It has been also shown that the new coverage index indicates more accurately the degree of dose coverage for the target volume revealing whether it is adequate based on user-defined criteria.

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DVH를 이용한 선량 균등률 및 덮임률 지수에 관한 연구

국립암센터, 양성자치료센터

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본 연구의 목적은 세기변조 방사선 치료법(IMRT)에 의해 만들어진 DVH를 이용하여 선량의 균등률(homogeneity) 및 덮임률(coverage) 지수를 구하는 간편한 방법을 제시하는 데 있다. 새로 개발된 지수들은 DVH 곡선을 수학적으로 계단 함수에 fitting 함으로써 구해졌다. 새로 제안된 지수 I는 종양에 대한 선량의 덮임률을 잘 나타내고 있으며 이 지수가 작으면 작을수록 더 좋은 덮임률을 보여주고 있다.

또한 종양의 균등률 지수로 제안된 n 지수는 기존에 사용되고 있는 균등률 지수들보다 좀 더 정확하게 선량의 균등성을 나타내고 있음을 확인하였다. 이들 지수를 이용하여 치료계획에 바탕이 되는 토대를 제시하였으며 여기에서 제안된 지수들이 선량의 균등성과 덮임성에 대해 매우 효과적인 방법이 될 수 있음을 보여주고 있다.

중심단어: 덮임률 지수, 균등률 지수, Uniformity index, 선량-체적 히스토그램, 세기변조방사선치료