

Clinically oriented contour evaluation using geometric and dosimetric indices based on simple geometric transformations

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Research

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Abstract

Background: In radiotherapy, geometric indices are often used to evaluate the accuracy of contouring; however, the ability of geometric indices to identify the error of contouring results is limited, and they do not consider any clinical background. Based on the reference contouring, we systematically introduced the known geometric errors to study the relationship between geometric indices and dosimetric indices and evaluated the clinical feasibility of assessing the accuracy of contouring based on geometric indices alone.

Materials and Methods: A C-shaped target, organ at risk (Core), and intensity-modulated radiotherapy (IMRT) plan outlined in the American Association of Physicists in Medicine (AAPM) TG-119 report (The report of Task Group 119 of the AAPM) were used as references. Translation, scaling, rotation (except for the Core), and sine function transformation were performed to simulate the test contours. The corresponding dosimetric indices were obtained from the original dose distribution of the radiotherapy plan, and correlations (R^2) between geometric and dosimetric indices were quantified through linear regression. The Wilcoxon signed rank test was used to compare the differences between the geometric indices of three different directions of translation transformations.

Results: The correlations between the geometric and dosimetric indices were inconsistent for the contouring of the target and Core after the geometric transformation. Except for the sine function transformation (R^2 : 0.04–0.023, $P > 0.05$), the other geometric transformations of the planning target volume (PTV) had correlations with the dosimetric indices $D_{98\%}$ and D_{mean} (R^2 : 0.689–0.988), 80% of which were strongly correlated. The correlation results for the other geometric transformations in the Core were similar to those in the PTV except for the posterior direction transformation. The results of Wilcoxon signed rank test showed that only the P -values of volumetric geometric indices of PTV were less than 0.05.

Conclusions: The dosimetric indices are heavily influenced by the contour differences, thus highlighting their importance in the evaluation process. Clinically, an assessment of the contour accuracy of the region of interest is not feasible based on geometric indices alone, and should be combined with dosimetric indices.

Background

Contouring of the target and organ at risk (OAR) is a key step in radiotherapy, especially with the highly modulated radiotherapy technology currently in use, such as intensity-modulated radiotherapy (IMRT) and volumetric modulated arc radiotherapy (VMAT). Inaccuracy in the contouring process will cause serious systematic errors to the subsequent radiotherapy work. For instance, the variation of contours may affect the treatment plan, and this error has always existed in the subsequent radiotherapy processes used for patients [1-3]. The commonly used slice-by-slice manual approach or interpolation-based semi-automatic contouring approach is time-consuming and resource-consuming, and the

corresponding results are susceptible to differences between observers; furthermore, the accuracy of contouring depends on the residents' clinical experience and the application of multimodality imaging. Computed tomography (CT) images provide useful anatomical information and electronic density for dose calculation of radiotherapy plans. However, comparing with the results after registration of CT and magnetic resonance imaging (MRI), the contrast of soft tissue in CT images is poor, which is not enough to clearly show the target area and organs at risk [4-6]. Therefore, determining the variation of contouring accurately is very important.

Methods for assessing the accuracy of contouring are generally divided into two categories, namely, subjective evaluations and quantitative evaluations. The subjective evaluation is only based on the experiences and personal preferences of the evaluators. Evaluators were guided to turn off the original contour display and grade all research contours using 3 levels: useful as test contours (= 1), useful with minor edits (= 2), and not useful (= 3). The definition of minor edits was that the test contours would be acceptable after minor modifications [7]. This evaluation method is deeply affected by the individual differences among the evaluators and required considerable time. Wittenstein et al. [8] defined the method of using geometric indices Hausdorff distances (HD) and Dice-similarity coefficient (DSC) to evaluate the contour as quantitative evaluation. Most contour accuracy studies are performed directly by using quantitative evaluation, which involves the employment of geometric indices to characterize the similarity between the test contour and a reference contour. Geometric indices widely used in contour evaluations include distance-type geometric indices (e.g., the maximum (HD), mean (HD_{mean}), and 95% Hausdorff distances (HD95)) and volumetric geometric indices (e.g., DSC and Jaccard) [9]. Although these indices are easy to calculate, they do not consider the clinical effect and may lack clinical relevance [10, 11]. In addition, there is considerable variability between them, and different auto-segmentation studies use different geometric indices to evaluate the contouring results; further, different indices have different properties [12-14]. Under the assumption of a reference contour, the method for clinically assessing the accuracy of radiotherapy (RT) contours is to determine and predict the deviation of its dosimetric indices based on the dose distribution of the radiation treatment plan [10, 15-17]. The relationships between geometric indices and dosimetric indices are yet to be further studied. At present, the research on the evaluation of geometric indices and dose parameters of auto-segmentation results is carried out under the condition of unknown contouring error [10, 11, 16]. The purpose of our study is to explore the evaluation accuracy of the geometric indices for evaluating the contours under the known errors. This study artificially introduced contour errors through the following four geometric transformations: translation, scaling, rotation, and sine function transformation based on the reference contour. Then, based on these four transformations, the following objectives were carried out:

1. Study the correlations between the distance-type (HD, HD_{mean} , HD95) and volumetric geometric indices (DSC, Jaccard) and the dosimetric indices (D98%, D_{mean} , D2%);
2. Explore the ability of geometric indices to distinguish the test contours with the same transformation type but different translation directions.

Methods

Contouring

In order to simplify the experiments, the C-shaped target and Core (OAR) contoured on the water phantoms were regarded as the reference contours. The shape and relative position of the two structures were similar to those of spinal bone metastasis, which can be regarded as a preliminary study of clinical cases to a certain extent (Fig. 1), according to the TG-119 report [18]. The structures of the C-shaped target and Core were exported from treatment planning system (TPS) Raystation (Raysearch, Stockholm, Sweden) in the form of a DICOM file, and the position information of the contours were read by an in-house developed Python software; thereafter, the geometric transformations were carried out. Finally, the transformed structures were imported back to Raystation system in the form of a DICOM file. In order to analyze the contouring errors in detail, translation, scaling, rotation (except for the Core), and sine function transformation were simulated for both the C-shaped target and Core.

In this study, the translation transformations were divided into the following three cases: right, anterior, and posterior direction. Based on the location of the reference contour, at intervals of 1 mm, the data were moved 10 times to each of the right, anterior, and posterior directions to obtain the test contours (see Additional file 1: Figure A, B and C for the contours after the right, anterior, and posterior directions translation, respectively). Scaling transformation represents an equidistant expansion or reduction transformation in reference to the position of the contour. Considering the fast speed of scaling transformation changes, in the patient modeling module of the Raystation planning system, 10 equidistant transformations were performed at 0.5 mm intervals, excluding the anterior and posterior directions (see Additional file 1: Figure D and E for the contours after the expansion and reduction transformation, respectively). The rotation transformation involved taking the origin of the CT image coordinates as the rotation center point, using 1° as the interval, and rotating clockwise 10 times (see Additional file 1: Figure F for the contours after the rotation transformation). For the sine function transformation, we extracted the coordinate values (x_0, y_0) of the reference contour first, and then, we used the function $y = \sin \omega y_0$ ($\omega = 3, 4, 5, 6, \dots, 12$) to carry out periodic transformations 10 times with a fixed amplitude (see Additional file 1: Figure G for the contours after the sine function transformation).

Geometric indices

In this study, we chose five widely used geometric indices for the evaluations, including three distance-type indices HD (maximum, mean, 95%) and two volumetric indices (DSC and Jaccard). These five geometric indices were calculated by 3DSlicer version 4.10.2 [19], which is open source software. The calculation of HD was performed on the RT-DICOM structures. The HD indices calculated by the 3DSlicer represent bi-directional distances, and the bi-directional distance is symmetrical; this type of distance is more stable than the unidirectional distance calculated by other methods.

Dosimetric indices

In this study, PTV and Core were regarded as the reference contours. Similarly, the IMRT plan, which meets the requirements for a simple version in the TG-119 report, was taken as the reference plan. The dose of 5000 cGy received by 90% of the target volume was taken as the prescription, and the dose grid was 2 mm. In order to determine the differences in dosimetric indices caused by different contour errors, the method adopted in this study was to use the existing dose distribution on the reference contour and overlay it on the geometrically transformed contour [20]. After geometric transformation, RTstructure was imported into the radiotherapy plan of the reference contour, and then, on the dose distribution, D98%, D_{mean} , and D2% of the PTV and D_{mean} and D2% of the Core were obtained. According to the ICRU-83 report [21], these dosimetric indices represent the minimum dose, mean dose, and maximum dose received by the target, and the mean dose and maximum dose received by the organs at risk, respectively. In this study, the dose differences () of three dosimetric indices D98%, D_{mean} and D2% were calculated and normalized according to their respective clinical goals. Here, , where x represents the type of dosimetric index.

Analysis

An SPSS version 21.0 software (SPSS, Chicago, IL, USA) was used for linear regression analysis. The correlation coefficient R^2 was used to quantify the correlations between the geometric indices HD (maximum, mean, 95%), DSC, and Jaccard, and the dosimetric indices D98%, D_{mean} , and D2%. Two-sided P -values were obtained, and P -values <0.05 were considered significant. In addition, the geometric indices obtained from the right, anterior, and posterior directions of the PTV and Core translation transformations were compared, and the difference between them was tested for statistical significance using the Wilcoxon signed ranks test in SPSS, and from scatterplots of geometric indices versus dose difference, the feasibility of assessing the accuracy of test contours with geometric indices was analyzed.

Results

Linear regression analysis was carried out on the geometric indices and dosimetric indices (Fig. 2A, B and 2C, D show the results for the PTV and Core, respectively). Except for the sine function transformation (R^2 : 0.04–0.023, $P > 0.05$), the other three geometric transformations of the PTV had strong correlations with the dosimetric indices D98% and D_{mean} (R^2 : 0.689–0.988), 80% of which were strongly correlated with a $P < 0.001$. The D2% of PTV was not included in the correlation analysis because of its small variation range. The correlation results for the other geometric transformations in the Core were similar to those in the PTV except for the posterior direction translation (the relationships between the geometric indices, D_{mean} , and D2% were uncorrelated).

The ranges and trends of the distance-type geometric indices of PTV and Core were the same (Fig. 3A–B, D–E). The change trend of HD_{mean} was slow, and it was lower than that of the other two indices. The volumetric geometric indices DSC and Jaccard of PTV changed more slowly than those of the Core (Fig. 3C, F), and the declining rate of Jaccard was also slower than that of DSC.

Table 1 shows the results of the Wilcoxon signed ranks test analysis between the geometric indices of translation transformation in the right, anterior and posterior directions. For the analysis results of the three translation directions of PTV, the P -values of HD, HD_{mean} and HD95, were all greater than 0.05, while for DSC and Jaccard, the P -values were all less than 0.05, the differences were statistically significant. The analysis results of the three translation directions of Core show that the P -values were all greater than 0.05.

Figs. 4 and 5 show the relationships between the geometric indices of the PTV and Core and the dose difference. We can see that the relationships between the geometric indices and dose difference were not monotonic, and they were inconsistent.

Discussion

Many studies have shown that although it is important to quantify the degree of variation or uncertainty of the contouring, it is more important to determine the dose difference and clinical impact [10, 11, 14, 16, 17, 22, 23]. In earlier work, van Rooij et al. [17] studied the accuracy of automatic delineation of organs at risk in the head and neck region based on deep learning techniques while using geometric indices and dosimetric indices, and they analyzed the correlation between the geometric index SDC (mean value of the DSC) and dose difference. That study found that there was a weak correlation between the SDC and ΔD for all of the OARs through automatic segmentation, $r = -0.24$, $P = 0.002$, but the correlation was not specific to a certain OAR or a certain patient. This is similar to the results described in this study, we found that the geometric indices obtained by geometric transformation were significantly correlated with the dosimetric indices, but for some specific geometric transformation forms, the situations were different. There was a strong and significant correlation between the geometric indices and dosimetric indices in the translation, scaling, and rotation transformations of the PTV, but the results for the sine function transformation were not significant or weak; and the correlation for the PTV posterior direction translation was strong, but the correlation for the Core posterior direction translation was weak and insignificant. The correlation was not consistent for the different forms of geometric transformations and organ types. And compared with the OAR, the target was more sensitive to the geometric transformations.

In this study, the correlation coefficient obtained with the PTV anterior direction translation was lower than that of the other two translation transformation. In order to avoid high dose radiation to the surrounding organs at risk, physicians try to keep high-dose areas away from the organs at risk when designing the reference radiotherapy plan. Therefore, when the anterior direction translation occurs in this area, the minimum dose (D98%) of the target in this area is almost unchanged, thus resulting in a weaker correlation coefficient. This is consistent with the study by Lim et al. [10], which found that the correlation between geometric indices and dosimetric indices was affected by the goals of the treatment plan. Feng et al. [24] considered that the contour changes of oropharyngeal carcinoma OAR had little effect on the dose, but Nelms et al. [1] reported that this had a great effect on the dose. Based on the auto-segmentation, Beasley et al. [25] showed that for parotid gland and larynx, the HD was highly correlated with dosimetric indices, which may be related to the shape of the organ at risk, and the sample size was

small, the correlation also needs to be further verified. In this study, the correlations between geometric indices and dosimetric indices were inconsistent, which was also helpful to explain the contradictory results in the above-mentioned literature. From these studies, it can be shown that the correlation between geometric indices and dosimetric indices can be affected by many factors, such as the method of geometric transformation, the relative positions of the target and organs at risk, the shape and size of the structure, and the constraint goals of the radiotherapy plan.

According to the Wilcoxon signed ranks test analysis results in Table 1, for the translation transformation results of the PTV and the Core, the distance-type geometric indices HD, HD_{mean} , and HD95 cannot express the difference of the translation transformations in three different directions of right, anterior, and posterior. There were significant differences between the volumetric geometric indices obtained from the three different transformation directions of the irregular shape PTV. However, this case was not applicable to the Core. Core was a symmetrical cylinder whose geometric indices were all the same among the three translation directions, and DSC and Jaccard cannot distinguish the three transformation directions. Meanwhile, it can be seen in Figures 3, 4, and 5 that the quality of the contour is controversial for the two structures of the same HD value. The HD values of the equidistant scaling transformation were the same for both PTV and Core, but the clinical effect on them were different. When $HD = 1.547$, the difference of dosimetric parameters of the Core was more than 5%, while the D98% of PTV was in the range of 5%. The geometric indices obtained from the same type of geometric transformation in different directions were not distinguishable. If there are two different structures and the value of the geometric index is the same, it cannot be used to explain the quality of the contour.

Beasley et al. [25] also reported that when measured with a suitable spatial metric, the higher the geometric accuracy of the contour, the smaller the dose difference should therefore be reflected, and vice versa. Recently, there have been many reports on auto-segmentation technology that only uses geometric indices to evaluate the acceptability of contouring results. If the DSC is higher than the normally reported value of 0.7, the agreement between the reference contour and the test contour is considered to be good [23, 26, 27]. Our research showed that when the geometric index was within the acceptable threshold range, the corresponding dose difference value was large, or when the geometric index was beyond the acceptable threshold range, the corresponding dose difference value was small. It can be seen from Fig. 4.C when the DSC and Jaccard values of anterior direction translation transformation were between 0.5 and 0.7, the corresponding dose differences were very small, which proved that it was unreliable to set 0.7 as the acceptable threshold of the DSC. Although geometric indices reflected the geometric difference between a test contour and a reference contour, the inconsistent relationship between geometric indices and dosimetric indices made it illogical to evaluate the clinical acceptability of contour results using only geometric indices; moreover, the geometric indices cannot predict the clinical dose difference.

This study introduced the known geometric errors through translation, scaling, rotation, and sine function geometric transformation, and analyzed the feasibility of clinical evaluation of geometric indices and the ability of geometric indices to identify the direction of transformation. However, the rigid transformations (such as translation and rotation) and non-rigid transformations (such as scaling and function

transformation) of this study are still not comprehensive enough. In addition, the current research is based on the simulation experiment of two simple phantoms, we should further explore the relationship between geometric indicators and dosimetric parameters by making use of many different structures of actual patients.

Conclusion

At present, there is a lack of guidance for the evaluation of contours by using geometric indices, and therefore, there is a need for a normative framework. We found that the differences between the geometric indices and dosimetric indices were not consistent, which indicates the inaccuracy when using only the geometric indices to evaluate the results of contouring. The clinical acceptability of contouring results cannot be judged by geometric indices alone. Therefore, we suggest that dosimetric indices should be added to evaluations of the accuracy of the results of delineation, which can be helpful for explaining the clinical dose response relationship of delineation more comprehensively, accurately.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

Please contact author for data requests.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

LXX and GJL analyzed the data and drafted the manuscript. QX, ZBL and XBZ performed the experiments. LC and ZYH collected data. SB designed this study, interpreted the results and revised the manuscript. All authors read and approved the final manuscript.

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Abbreviations

IMRT: intensity-modulated radiotherapy; AAPM: the American Association of Physicists in Medicine; TG-119 report: The report of Task Group 119 of the AAPM; PTV: planning target volume; OAR: organ at risk; VMAT: volumetric modulated arc radiotherapy; CT: computed tomography; MRI: magnetic resonance imaging; HD: the maximum Hausdorff distances; HD_{mean} : the mean Hausdorff distances; HD95: the 95% Hausdorff distances; DSC: Dice-similarity coefficient; RT: radiotherapy; TPS: the treatment planning system; SDC: mean value of the Dice-similarity coefficient

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Table

Table 1 the Wilcoxon signed ranks test analysis between the geometric indices of translation transformation in the right, anterior and posterior directions.

		HD		HD _{mean}		HD95		DSC		Jaccard	
		Z-	P-	Z-	P-	Z-	P-	Z-	P-	Z-	P-value
		value	value	value	value	value	value	value	value	value	
PTV	R-	-1	0.317	-0.475	0.631	-0.73	0.465	-2.825	0.005*	-2.848	0.004*
	A										
	R-P	-0.535	0.593	-0.547	0.563	-1.604	0.109	-2.823	0.005*	-2.842	0.004*
	A-P	-1.604	0.109	-0.47	0.572	-1.604	0.109	-2.598	0.009*	-2.121	0.034*
Core	R-	0	1	-0.447	0.655	-1	0.317	0	1	-0.275	0.613
	A										
	R-P	0	1	-0.447	0.655	-1	0.317	0	1	-0.347	0.615
	A-P	0	1	0	1	0	1	0	1	-0.462	0.541

Abbreviations: R-A = Translation transformation in right and anterior direction; R-P = Translation transformation in right and posterior direction; A-P = Translation transformation in anterior and posterior direction. * P-value = the difference was statistically significant.

Figures

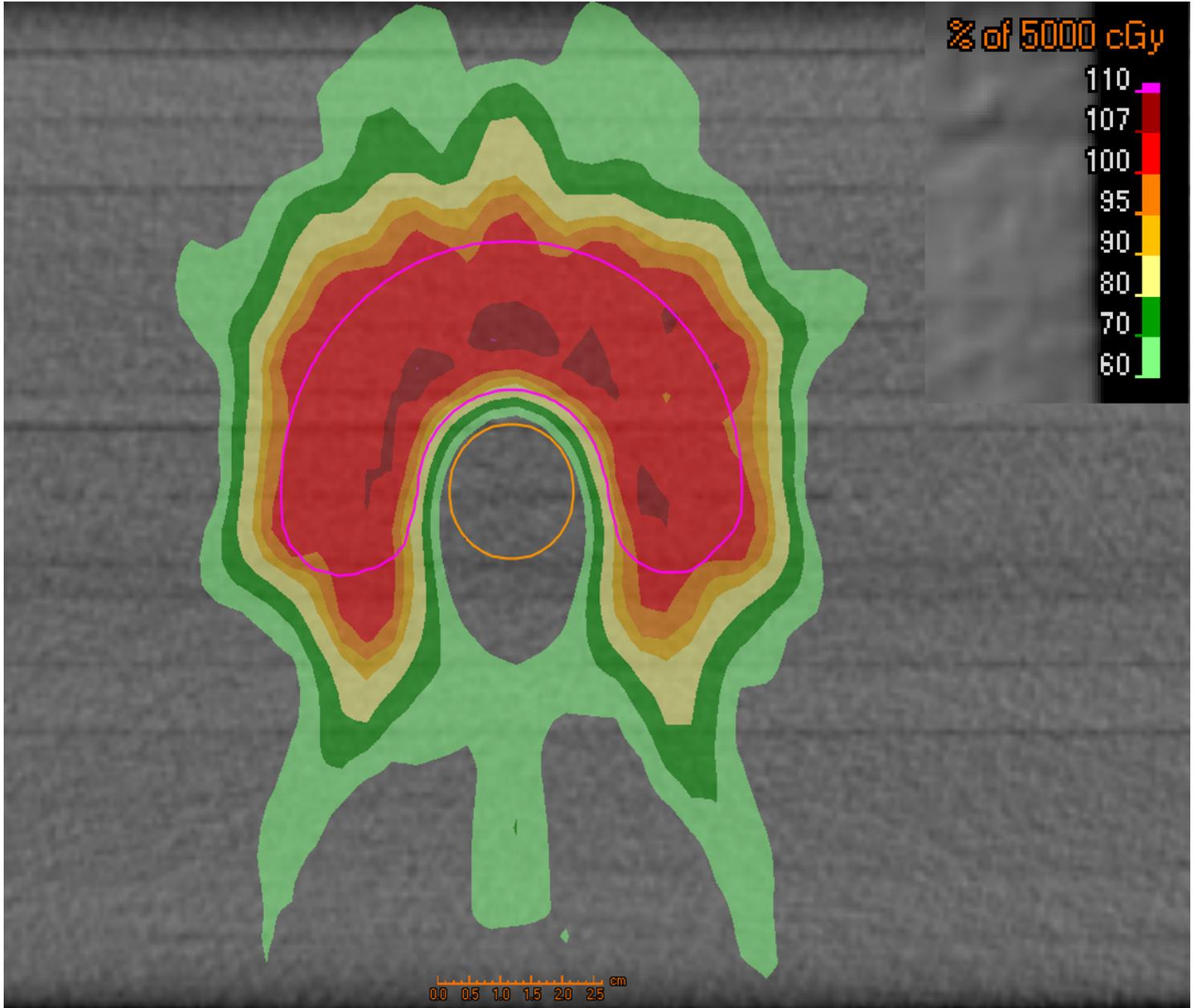


Figure 1

The relative position and dose distribution for the C-shaped target and Core.

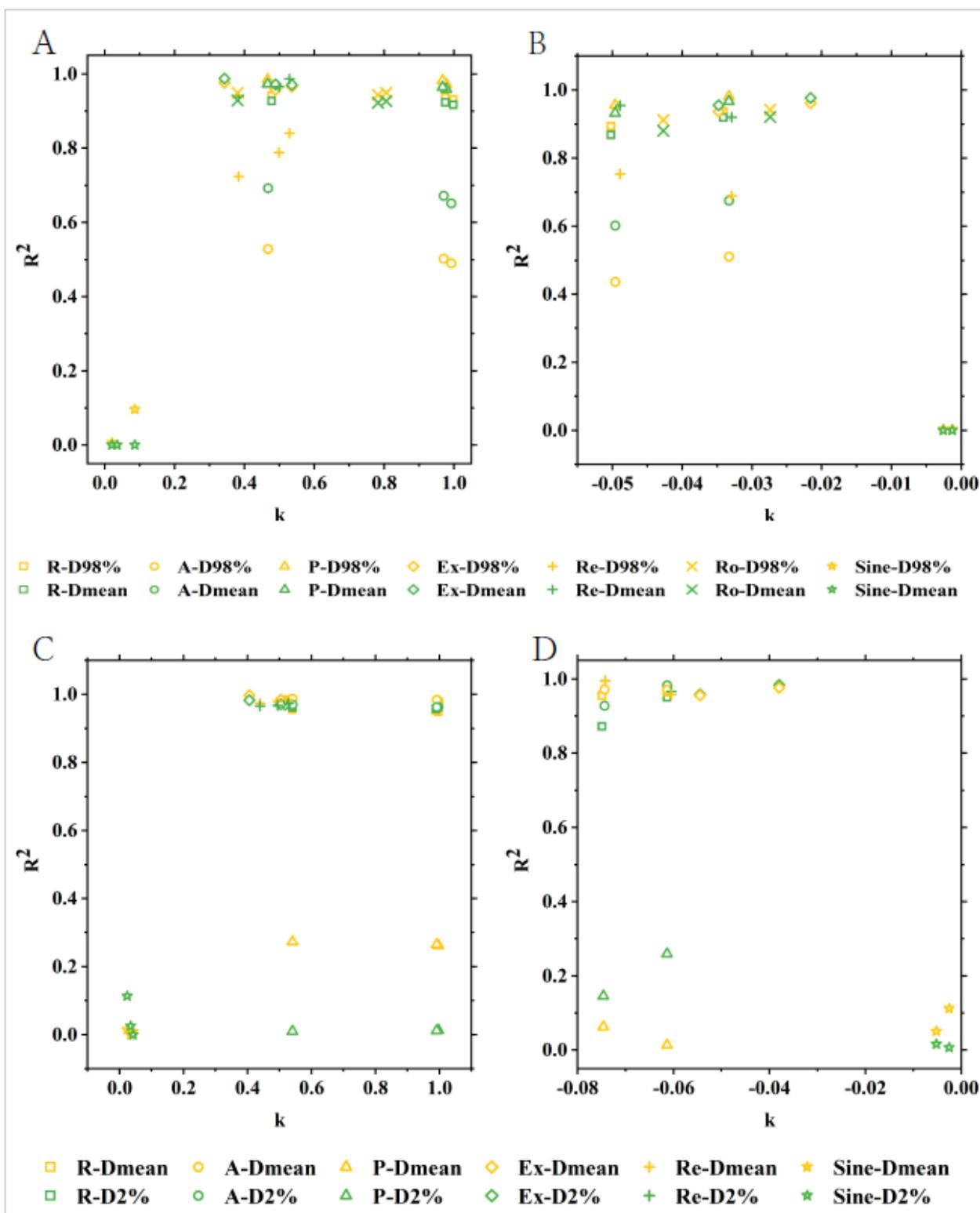


Figure 2

The correlation coefficient between the geometric and dosimetric indices after the geometric transformation. (A, B), (C, D) represent the correlations between the geometric indices and dosimetric indices for the PTV and Core, respectively. The abscissa represents the slope of the transformation trend for the geometric indices, and the ordinate is the correlation coefficient of the linear regression analysis. R-D98% = D98% for right direction translation transformation; R-Dmean = Dmean for right direction

translation transformation; R-D2% = D2% for right direction translation transformation; A = anterior direction translation transformation; P = posterior direction translation transformation; Ex = expansion transformation; Re = reduction transformation; Ro = rotation transformation; Sine = sine function transformation.

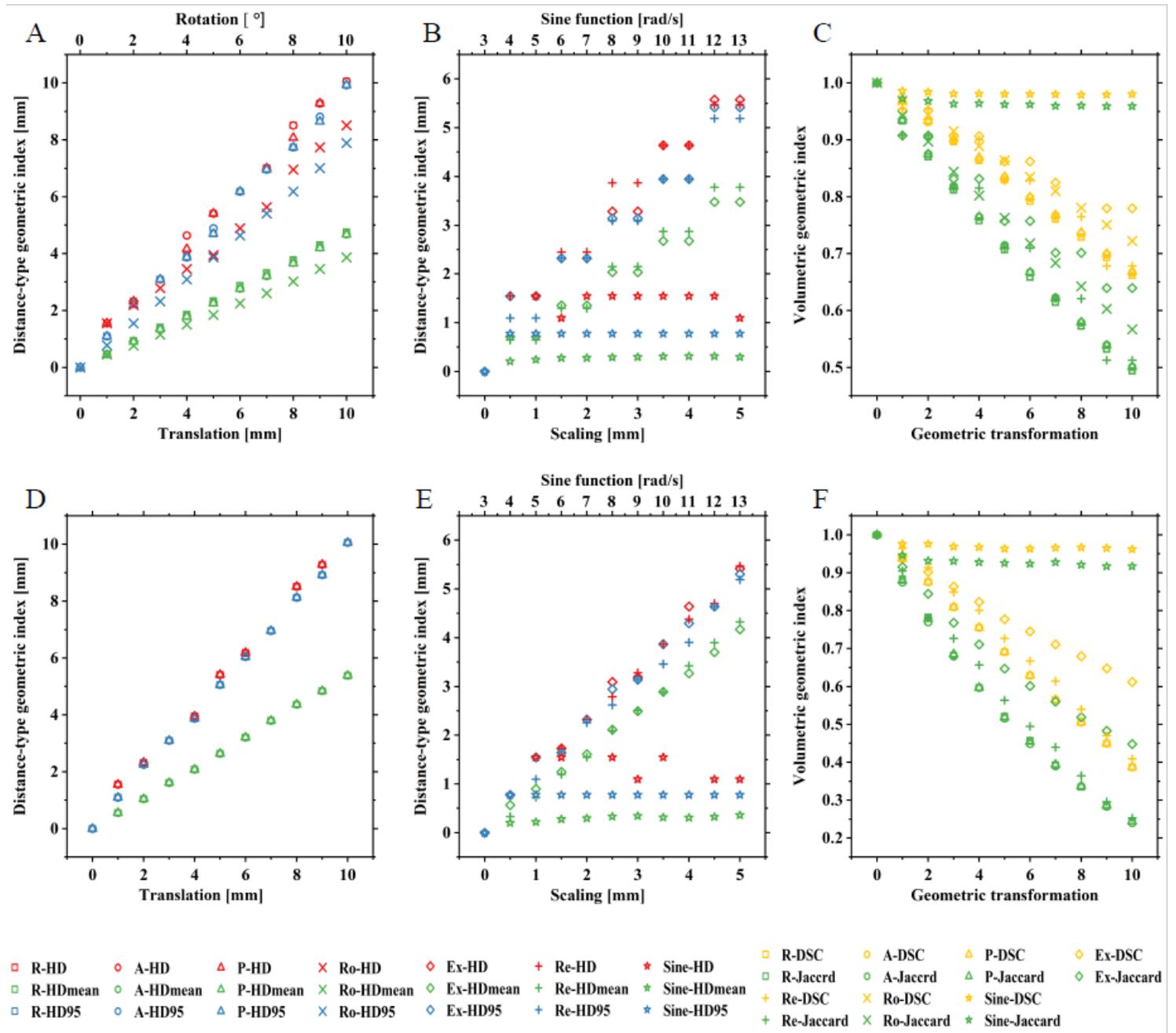


Figure 3

Geometric index value of contour after geometric transformation. (A–C) and (D–F) depict the distance-type geometric indices (HD, HDmean, HD95) and volumetric geometric indices (DSC, Jaccard) after geometric transformation of the C-shaped target (PTV) and organ at risk (Core), respectively. R-HD = HD for right direction translation transformation; R-HDmean = HDmean for right direction translation transformation; R-HD95 = HD95 for right direction translation transformation; R-DSC = DSC for right

The relationship between the geometric indices of PTV and the dose difference. (A-C), (D-F) and (G-I) are the relationships between the geometric indices of PTV after geometric transformation and the dose difference D98%, Dmean and D2%, respectively. R-HD = dose difference corresponding to HD value after right direction translation transformation; R-HDmean = dose difference corresponding to HDmean value after right direction translation transformation; R-HD95 = dose difference corresponding to HD95 value after right direction translation transformation; R-DSC = dose difference corresponding to DSC value after right direction translation transformation; R-Jaccard = dose difference corresponding to Jaccard value after right direction translation transformation; A = anterior direction translation transformation; P = posterior direction translation transformation; Ex = expansion transformation; Re = reduction transformation; Ro = rotation transformation; Sine = sine function transformation.

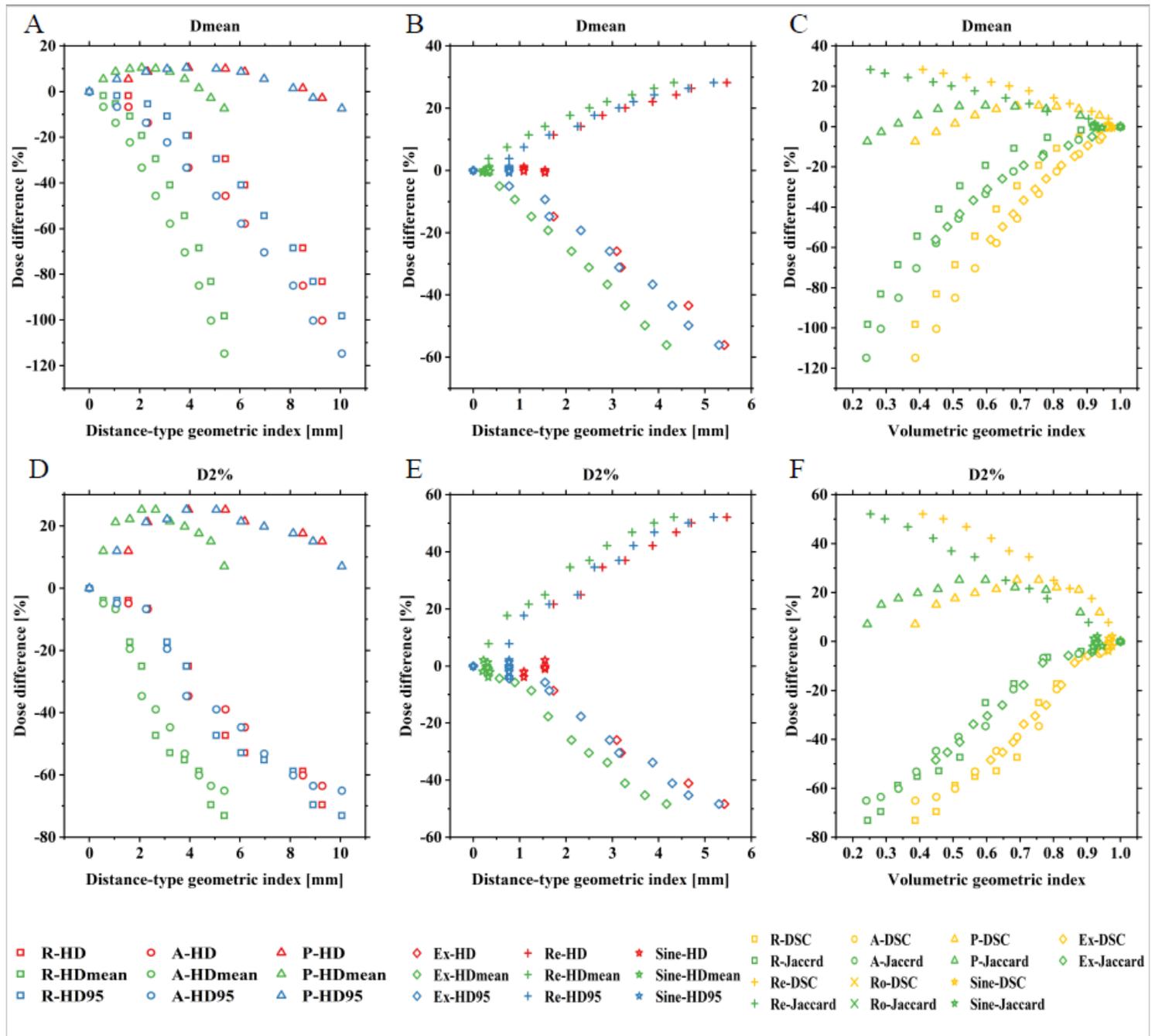


Figure 5

The relationship between the geometric indices of Core and the dose difference. (A-C) and (D-F) are the relationships between the geometric indices of OAR after geometric transformation and the dose difference Dmean and D2%, respectively. R-HD = dose difference corresponding to HD value after right direction translation transformation; R-HDmean = dose difference corresponding to HDmean value after right direction translation transformation; R-HD95 = dose difference corresponding to HD95 value after right direction translation transformation; R-DSC = dose difference corresponding to DSC value after right direction translation transformation; R-Jaccard = dose difference corresponding to Jaccard value after right direction translation transformation; A = anterior direction translation transformation; P = posterior direction translation transformation; Ex = expansion transformation; Re = reduction transformation; Ro = rotation transformation; Sine = sine function transformation.

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