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Performance comparison of structure delineation based on image registration methods in head and neck cancer patients

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Original Article

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Abstract

Propose: To investigate the performance of image registration methods for structure delineation in head and neck (H&N) cancer patients.
Methods and materials: This retrospective study randomly recruited 22 patients who had been irradiated in the H&N region between January 2016 and February 2024. The sample group included nasopharyngeal carcinoma (NPC) and oropharyngeal cancer (OPC) patients. The treatment planning structures were delineated as images of computed tomography simulation (CTsim) and were set as the ground-truth. The latest CT diagnostic (CTdiag) image sets of these selected patients were imported into third-party software for delineation. The structures of CTdiag were delineated using an artificial intelligence method except for the target. The performance of rigid and deformable image registration methods (RIR and DIR, respectively) between these two image sets were evaluated using dice similarity coefficient (DSC) and Hausdorff distance (HD). The performance evaluation scores were also compared between NPC and OPC.
Result: The DSC revealed a significant difference in all structures between RIR and DIR, whereas the HD showed no significant difference on the target and the larynx. In terms of a comparison of treatment regions, OPC appeared to sustain the greatest benefit from DIR.
Conclusion: Image registration can provide the benefit of structure delineation, particularly when employing the DIR method. Although the DIR method may not offer a high degree of performance in terms of target delineation, it could effectively serve as a delineation guideline in this process.

Introduction

Treatment planning for radiotherapy is an important process that provides benefits to the patient. Recently, treatment planning and delivery have become more complex, with techniques such as intensity-modulated radiotherapy and volumetric-modulated arc therapy being utilised. These techniques require a treatment planning system (TPS) to create beam geometries and perform dose calculations. Therefore, the target and organs at risk (OARs) must be delineated to localise their location and shape in the TPS. This delineation is an essential process that helps radiation oncologists and patients achieve treatment goals. For highly precise delineation, multiple image modalities are required,[1,2] such as magnetic resonance imaging (MRI), positron emission tomography (PET), single photon emission computed tomography (SPECT), and so forth. Image registration is a key component that facilitates information exchange among different image modalities. Voxel-based or intensity-based image registration methods are widely used in medical image processing,[1] although various other methods have been proposed.[3–5] These methods utilise image intensity information in the registration process. There are two main types of pixel/voxel vector flow, which are rigid image registration (RIR) and non-rigid image registration or deformable image registration (DIR). RIR involves moving image voxels in a single direction, whereas DIR moves these image voxels in multiple directions. In terms of utilising image registration in the delineation process, RIR has been a dominant method of utilisation.[6,7] However, it has limitations, especially when dealing with curved structures like the spine in head and neck (H&N) cancer patients. Several publications have proposed utilising DIR for delineation in H&N cancer cases as a way of addressing these limitations.[8–10]

Although many published studies have investigated the utilisation of DIR in the delineation process, it has only been observed in nasopharyngeal carcinoma (NPC). This study aims to investigate the performance of DIR, not only in NPC subjects but also in oropharyngeal cancer (OPC) patients. This study included a performance comparison between RIR and DIR, as well as the time frame between each pair of image sets.

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Methods and Materials

Ethical clearance

This retrospective study evaluated the performance of RIR and DIR in the image set from the computed tomography simulator to the computed tomography diagnosis. The data included image sets obtained from January 2016 to February 2024. This study has been declared and approved of by Research Ethics Committee of Faculty of Medicine, Chiang Mai University. (Study code: RAD-2565-0057).

Dataset preparation and image registration process

This investigation focused on patients who were treated with external irradiation in the H&N region. Twenty-two treated patients were randomly selected between January 2016 and February 2024, with a sample size that was evenly divided between NPC and OPC cases. Simulated computed tomography (CTsim) was obtained using a computed tomography simulator (SOMATOM Definition AS, Siemens Inc., Healthineers, Germany). The diagnostic image sets of the selected patients were included, with the selection being based on the most recent acquired image set. Diagnostic computed tomography (CTdiag) was obtained using a computed tomography scanner (Ingenuity, Philips Medical Systems, Best, the Netherlands). Patient characteristics are presented in Table 1.

Radiation oncologists delineated the gross target volume (GTV) and OARs on the image set of the CTsim using MIMsoftware® (MIM Software Inc., OH, United States). These datasets, including images and structures, were then set as ground-truth. On the other hand, the CTdiag image sets were transferred to the contouring system (MIMsoftware®). On the CTdiag, the structures were delineated using Artificial Intelligence Protégé® (AI Protégé®, MIM Software Inc., OH, United States) and confirmed by a radiation oncologist. While the OARs were delineated by software, GTV was manually delineated on the CTdiag by a radiation oncologist. RIR and DIR were utilised in the image registration process, as has been presented in Figure 1. The image registration of this software did not provide quantitative results of the similarity measurement; however, the performance of the registration was evaluated using the three-dimensional normalised cross-correlation coefficient. This public source code was developed by Eaton[11] and has been made available on the MatLab File Exchange community.[12] Results of the similarity measurement are also presented in Table 1. Finally, the structures on the CTdiag were transformed and projected onto the CTsim.

Structure delineation performance evaluation

The performance of the RIR and DIR was evaluated through feature-based measurements. The structures were measured using the CTsim benchmark. The evaluated objects included the GTV, both parotids, both eyes, the spinal cord, the brainstem and the larynx. The quantity measurements were assessed using dice similarity coefficient (DSC) and Hausdorff distance (HD).

Dice similarity coefficient (DSC) is a quantitative method of measurement that evaluates the similarity between two objects. The formula utilises the intersection of the object volumes and is expressed as $2(A \cap B)/(A+B)$. A and B represent the volumes of the objects of interest in this formula.

Hausdorff distance (HD) is a measurement tool that measures the distance between two lines. The lines or curves of the objects of interest are expressed in terms of a series of points. This tool then measures the distance by utilising these points. The value is calculated by $H(A,B) = \max(h(A,B), h(B,A))$, where A and B are the point series of the objects of interest. The nearest point of A on the point series of B is determined by $\vec{h}(A,B) = \max_{a \in A} \min_{b \in B} ||a - b||$, where a and b are the points in the point series of objects A and B, respectively.

Statistical analysis

The performance of the delineation was analysed using SPSS version 25 (IBM Co., New York, United States). A performance comparison of image registration methods was conducted on both treatment regions and the separated treatment regions (NPC and OPC). The student *t*-test was used to analyse data with a normal distribution, while the Wilcoxon rank test was employed for non-normally distributed data. The statistics were analysed with a 95% confidence interval.

Results

An analysis of the patient characteristics revealed that the scanning time interval between CTsim and CTdiag was 61.9 ± 31.4 days. The shortest time interval of the CT scan was 16 days, whereas the longest time interval was 115 days. In the separated treatment regions, the scanning time interval of the NPC was 76.0 ± 19.1 days, whereas for the OPC it was 47.8 ± 35.7 days. The performance of the image registration methods was assessed through a similarity measurement. The publicly available software for three-dimensional normalised cross-correlation coefficient[11] demonstrated that the performance of the RIR method was 62.9 ± 12.7%, whereas the DIR method was 89.3 ± 6.3%.

Structure delineation performance analysis

The performance of the delineation by image registration was evaluated using DSC and HD. DSC indicates the similarity of shape, whereas HD measures the location of the structures. Table 2 presents the results of organ delineation in terms of the DSC and HD values. In the H&N region, using the RIR method has resulted in a significantly lower degree of accuracy of delineation when compared with the DIR method for all structures based on the DSC values. However, the HD values showed significantly better performance with the DIR method for the brainstem, spinal cord, left and right parotid, and eye structures.

In the case of the NPC, the DSC value of the DIR demonstrated significantly higher performance values in delineation when compared with the RIR in all structures except for the right eye. On the other hand, the value of HD revealed that the performance of DIR was significantly higher than the RIR only for the spinal cord, right parotid and left eye. The delineation performance was also analysed for the OPC. The results indicated that the performance of DIR was significantly higher than the RIR in all structures except for the larynx. Additionally, the values for the brainstem, spinal cord, larynx, left parotid, right eye and left eye were significantly lower in the DIR when compared with the RIR.

Structure delineation performance comparison between the treatment region of the nasopharynx and oropharynx

The target or lesion can impact the performance of structure delineation. This study evaluated the performance of organ delineation between the nasopharynx and oropharynx. Table 3 demonstrates the statistical differences in organ delineation

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Table 1. Patient characteristics and similarity measure result between CTsim and CTdiag

						Similarity measure (correlation coefficient, %)	
No.	Diagnosis	Stage	Node	Target region	Scanning interval (days)	RIR	DIR
1	NPC	T2	N1	Nasopharynx	70	56.6	81.2
2	NPC	T4	N1	Nasopharynx	83	52.2	94.0
3	NPC	T3	N2	Nasopharynx	86	58.7	90.9
4	NPC	T2	N3	Nasopharynx	93	62.1	79.9
5	NPC	T4	N0	Nasopharynx	51	43.2	79.9
6	NPC	T4	N2	Nasopharynx	78	55.7	94.5
7	NPC	T3	N3	Nasopharynx	81	72.1	79.8
8	NPC	T4	N2	Nasopharynx	105	67.3	81.5
9	NPC	T1	N2	Nasopharynx	61	68.2	97.5
10	NPC	T1	N0	Nasopharynx	88	48.6	94.0
11	NPC	T3	N0	Nasopharynx	40	59.2	96.4
12	OPC	T2	N3	Oropharynx	112	51.8	92.4
13	OPC	T4a	N2	Oropharynx	21	75.8	94.7
14	OPC	T4	N1	Oropharynx	37	63.8	94.9
15	OPC	T3	N2	Oropharynx	115	84.9	93.2
16	OPC	T4b	N2	Oropharynx	58	85.9	96.6
17	OPC	T4b	N3	Oropharynx	55	68.1	88.3
18	OPC	T4b	N3	Oropharynx	16	58.5	86.6
19	OPC	T2	N2	Oropharynx	25	55.9	87.6
20	OPC	T4b	N3	Oropharynx	48	37.2	84.7
21	OPC	T4a	N3	Oropharynx	20	79.7	80.5
22	OPC	T4a	N0	Oropharynx	19	79.3	96.1

Abbreviations: CTsim, computed tomography simulation; CTdiag, computed tomography diagnosis; NPC, nasopharyngeal carcinoma; OPC, oropharyngeal cancer; RIR, rigid image registration; DIR, deformable image registration.

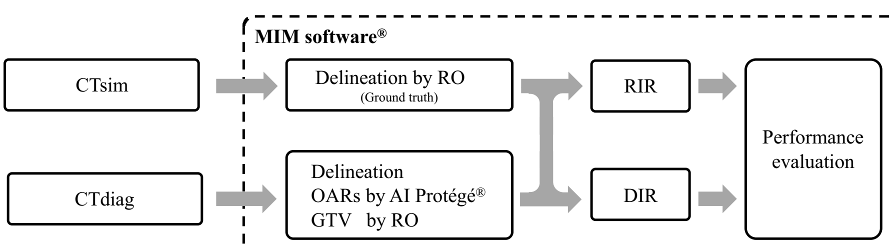

Figure 1. Research methodology diagram.

performance between these two regions. In the case of RIR, the DSC and HD revealed significantly lower values in the oropharynx region when compared with the nasopharynx for the left parotid and left eye. Conversely, DIR revealed significantly lower DSC values for the GTV, as well as the left and right parotids in the nasopharynx region, while HD illustrated no significant difference for all structures.

Discussion

This study investigated the performance of structure delineation by utilising the image registration method provided by commercial software. Although the software provided high performance in structure delineation (image segmentation) by employing AI, this option required an additional affordable expense. Image registration was the basic method used for structure delineation. Several articles[2,13,14] have been published in this research area, but they focused only on NPC. This study expanded the investigation to include not only NPC but also OPC. On the other hand, this study investigated only the image set between CTsim and CTdiag, which were similar image modalities. The most benefit of image registration might conduct in the different image modalities such as CT and MRI, CT and PET, and so forth. A limitation was raised in our centre due to the waiting time of a pre-radiation treatment image acquisition or the

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Table 2. Mean and standard deviation of similarity measurement between CTsim and CTdiag by utilising the RIR and DIR

	Rigid image registration		Deformable image registration		
Organs	DSC	HD (mm)	DSC	HD (mm)	*p*-Value
GTV	0.5 ± 0.1	35.4 ± 19.2	**0.6** ± **0.2**	33.6 ± 20.8	$^{DS}p < 0.001$
Brainstem	0.7 ± 0.2	8.5 ± 3.1	**0.8** ± **0.1**	**7.0** ± **2.3**	$^{DS}p = 0.001$ $^{HD}p = 0.007$
Spinal cord	0.5 ± 0.2	10.9 ± 4.6	**0.8** ± **0.1**	**7.8** ± **5.9**	$^{DS}p < 0.001$ $^{HD}p = 0.005$
Larynx	0.6 ± 0.2	12.9 ± 4.0	**0.7** ± **0.1**	10.8 ± 4.1	$^{DS}p = 0.008$
Parotid Lt	0.6 ± 0.2	12.7 ± 4.5	**0.8** ± **0.1**	**11.3** ± **3.7**	$^{DS}p < 0.001$ $^{HD}p = 0.016$
Parotid Rt	0.6 ± 0.1	14.2 ± 5.0	**0.8** ± **0.1**	**11.7** ± **3.7**	$^{DS}p < 0.001$ $^{HD}p = 0.001$
Eye Lt	0.7 ± 0.2	7.5 ± 4.2	**0.9** ± **0.0**	**3.7** ± **1.2**	$^{DS}p = 0.001$ $^{HD}p < 0.001$
Rt	0.7 ± 0.2	7.0 ± 4.6	**0.9** ± **0.0**	**3.4** ± **0.9**	$^{DS}p = 0.002$ $^{HD}p = 0.005$
Nasopharynx treatment region					
GTV	0.5 ± 0.2	31.8 ± 22.9	**0.5** ± **0.2**	31.8 ± 23.3	$^{DS}p = 0.009$
Brainstem	0.8 ± 0.1	7.4 ± 1.9	**0.9** ± **0.0**	6.5 ± 1.2	$^{DS}p = 0.005$
Spinal cord	0.5 ± 0.2	10.5 ± 5.7	**0.8** ± **0.1**	**7.4** ± **6.1**	$^{DS}p = 0.003$ $^{HD}p = 0.41$
Larynx	0.6 ± 0.2	11.3 ± 3.1	**0.7** ± **0.1**	11.5 ± 3.7	$^{DS}p = 0.042$
Parotid Lt	0.7 ± 0.1	10.6 ± 3.4	**0.8** ± **0.0**	10.5 ± 3.5	$^{DS}p = 0.003$
Rt	0.7 ± 0.1	12.5 ± 4.1	**0.8** ± **0.1**	**10.4** ± **3.3**	$^{DS}p = 0.003$ $^{HD}p = 0.007$
Eye Lt	0.8 ± 0.1	5.6 ± 2.6	**0.9** ± **0.0**	**3.7** ± **1.3**	$^{DS}p = 0.014$ $^{HD}p = 0.005$
Rt	0.8 ± 0.2	5.2 ± 3.4	0.9 ± 0.0	3.4 ± 1.1	
Oropharynx treatment region					
GTV	0.5 ± 0.1	39.0 ± 14.9	**0.6** ± **0.1**	35.4 ± 18.9	$^{DS}p = 0.005$
Brainstem	0.7 ± 0.2	9.5 ± 3.8	**0.8** ± **0.1**	**7.6** ± **3.1**	$^{DS}p = 0.018$ $^{HD}p = 0.033$
Spinal cord	0.4 ± 0.2	11.2 ± 3.4	**0.8** ± **0.1**	**8.2** ± **5.9**	$^{DS}p = 0.003$ $^{HD}p = 0.05$
Larynx	0.6 ± 0.2	14.8 ± 4.4	0.7 ± 0.1	**10.1** ± **4.8**	$^{HD}p = 0.046$
Parotid Lt	0.5 ± 0.2	15.1 ± 4.5	**0.7** ± **0.2**	**12.2** ± **4.0**	$^{DS}p = 0.005$ $^{HD}p = 0.022$
Rt	0.6 ± 0.1	16.2 ± 5.4	**0.7** ± **0.2**	13.3 ± 3.8	$^{DS}p = 0.018$
Eye Lt	0.5 ± 0.2	10.3 ± 4.7	**0.9** ± **0.0**	**3.6** ± **1.2**	$^{DS}p = 0.018$ $^{HD}p = 0.018$
Rt	0.6 ± 0.2	9.4 ± 5.3	**0.9** ± **0.0**	**3.3** ± **0.3**	$^{DS}p = 0.018$ $^{HD}p = 0.018$

Abbreviations: DSC, dice similarity coefficient; HD, Hausdorff distance; GTV, gross target volume; Lt, left; Rt, right.

residential distance. The radiation oncologists would then have to rely on the pre-operative CT image as a guideline of delineation.

Structure delineation performance analysis

By utilising the image registration method, the structures were transferred from one image set to another image set using geometrical transformation. The results revealed significant differences in DSC between RIR and DIR. This would indicate that RIR provides limited freedom in image registration, with 6–12 degrees of freedom manipulating the direction of all pixels in the image area or all voxels in the image volume.[1,15] The accuracy of image registration depends on the centre/centroid of the image area/volume, respectively, with the area/volume of interest being the most impacted by this method. Larger volumes of interest in the longitudinal direction can result in a lower degree of accuracy

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Table 3 *p*-Value of different treatment region between nasopharynx and oropharynx

Organs	Rigid registration		Deformable registration	
	DSC	HD	DSC	HD
GTV	–	–	$p = 0.028$	–
Brainstem	–	–	–	–
Spinal cord	–	–	–	–
Larynx	–	–	–	–
Parotid Lt	$p = 0.022$	$p = 0.028$	$p = 0.032$	–
Rt	–	–	$p = 0.015$	–
Eye Lt	$p = 0.046$	$p = 0.046$	–	–
Rt	–	–	–	–

Abbreviations: DSC, dice similarity coefficient; HD, Hausdorff distance; GTV, gross target volume; Lt, left; Rt, right.

when compared with smaller volumes.[16] On the other hand, DIR is widely used in radiotherapy for image registration,[17–19] providing numerous degrees of freedom[1] and allowing for pixel/voxel movement. Although the algorithm of DIR can deform the structures by employing feature-based or intensity-based information, the software can effectively utilise the hybrid information of image registration.[20] However, the algorithm may be limited by the sharpness and contrast of the texture structures,[3] as has been illustrated in Figure 2. The boxplot indicates lower DSC values and higher HD values for the GTV, left parotid, and right parotid and highlights the limitations of hybrid image registration for organs with low contrast and unsharp boundaries. The HD values for the GTV and larynx are of interest, as they show significant differences in DSC values but not in HD values. HD measures the structural boundary between image sets, whereas DSC focuses on the structural shape, indicating that different structural shapes may have similar boundary distances. Overall, DIR improves the accuracy of structure delineation when compared with RIR.

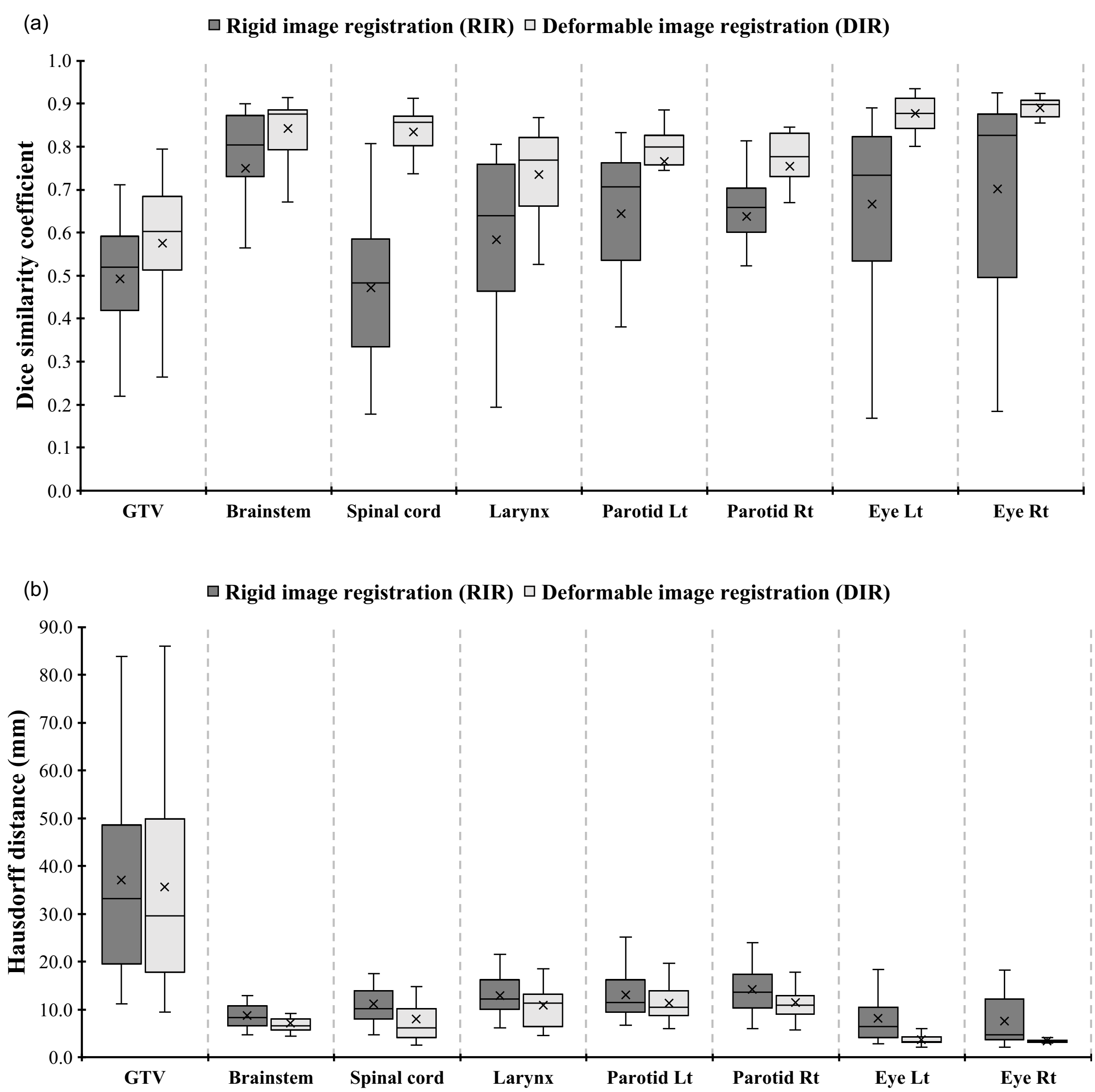

Figure 2. Similarity measure of structure delineation by utilising the RIR and DIR: (a) dice similarity coefficient and (b) Hausdorff distance.

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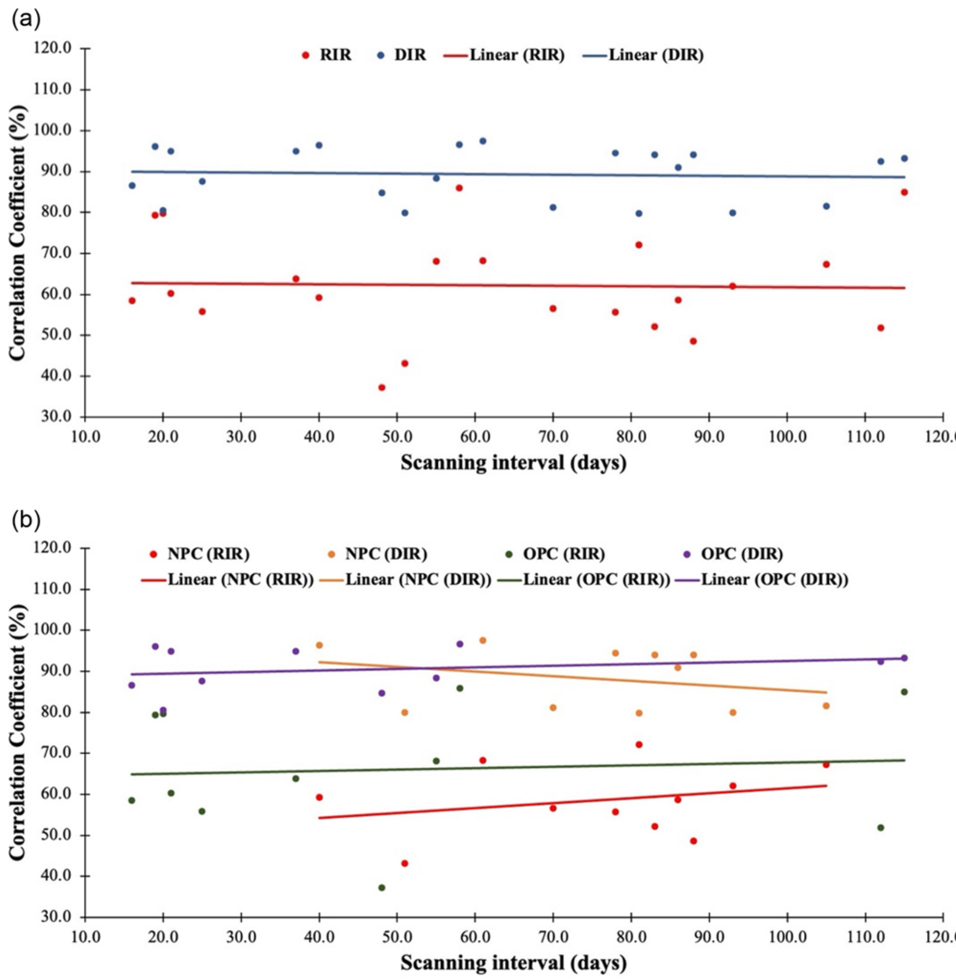

Figure 3. Plots between the correlation coefficient of similarity measure and scanning interval. (a) Image registration methods and (b) image registration methods of each treatment regions.

The time interval between each image set is one of the most critical considerations. Most patients with NPC received chemotherapy prior to irradiation. The target was then degraded in shape and size, leading to non-similarities between the two image sets if the CTdiag was not acquired after chemotherapy. Although some centres might not be able to manage the time interval of CT scanning between chemotherapy and radiotherapy, the DIR demonstrated performance in OARs delineation but not in the target delineation. This can be observed in Figure 3. Although the time interval was increased, the similarity value in the DIR demonstrated an increasing value as well.

Structure delineation performance comparison between the treatment region of nasopharynx and oropharynx

In the separated treatment region of Table 2, a significant difference in the DSC was observed in NPC and OPC, while the HD value indicated a greater significant difference in the OPC than the NPC. According to the CTdiag scanning protocol, the position of the mount was different between the nasopharynx and the oropharynx.[21–23] This indicates that the DIR delineation of the OPC benefited more than the NPC. Table 3 presents a statistical analysis of the different treatment regions. These revealed no significant differences in the HD of the DIR, but a significant difference was observed in the parotids and eyes. Although the similarity measured value of the eyes showed a significant difference between OPC and NPC, the *p*-value was almost 0.05. The focus then shifted to the parotids, which are located inferior to the ears. This positioning may be influenced by the CTdiag scanning protocol. While DIR has countless degrees of freedom, the deformable vector field is limited by the hybrid information of the image registration, as has been mentioned above. In the case of GTV, there was no significant difference in RIR and DIR, but there was a difference in the DSC of DIR. However, this structure has an irregular shape, as well as varying textures and degrees of sharpness across clinical cases. Consequently, the image registration method cannot provide target delineation but could serve as a guideline.[24]

Conclusion

This study investigated the performance of structure delineation based on image registration methods. The DIR method clearly displayed higher performance than RIR for structure delineation in both the nasopharynx and oropharynx. Although DIR did not provide a good result for target delineation, this method can effectively serve as a guideline in this regard.

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The Statement of Author Contribution.

(1) Komsorn Paitoon: Conceptualisation, Data curation, Investigation, Formal analysis, Writing—original draft, and Writing—review and editing.

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(2) Anirut Watcharawipha: Conceptualisation, Formal analysis, Writing—review and editing, and Supervision.
(3) Ekkasit Tharavichitkul: Formal analysis and Writing—review and editing.
(4) Waris Thongsuk: Formal analysis.

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References

1 Brock KK, Mutic S, McNutt TR, Li H, Kessler ML. Use of image registration and fusion algorithms and techniques in radiotherapy: report of the AAPM Radiation Therapy Committee Task Group No. 132. Med Phys 2017; 44 (7): e43–e76.
2 Fortin D, Basran PS, Berrang T, Peterson D, Wai ES. Deformable versus rigid registration of PET/CT images for radiation treatment planning of head and neck and lung cancer patients: a retrospective dosimetric comparison. Radiat Oncol 2014; 9: 50.
3 Watcharawipha A, Theera-Umpon N, Auephanwiriyakul S. Space independent image registration using curve-based method with combination of multiple deformable vector fields. Symmetry 2019; 11 (10): 1210. https://doi.org/10.3390/sym11101210
4 Sotiras A, Davatzikos C, Paragios N. Deformable medical image registration: a survey. IEEE Trans Med Imaging 2013; 32 (7): 1153–1190. https://doi.org/10.1109/TMI.2013.2265603
5 Oh S, Kim S. Deformable image registration in radiation therapy. Radiat Oncol J 2017; 35 (2): 101–111. https://doi.org/10.3857/roj.2017.00325
6 Varadhan R, Karangelis G, Krishnan K, Hui S. A framework for deformable image registration validation in radiotherapy clinical applications. J Appl Clin Med Phys 2013, 14 (1): 4066.
7 Senthi S, Griffioen GH, van Sörnsen de Koste JR, Slotman BJ, Senan S. Comparing rigid and deformable dose registration for high dose thoracic re-irradiation. Radiother Oncol 2013; 106 (3): 323–326. https://doi.org/10.1016/j.radonc.2013.01.018
8 Sanjay-Gopal S, Chan HP, Wilson T, Helvie M, Petrick N, Sahiner B. A regional registration technique for automated interval changes analysis of breast lesions on mammograms. Med Phys 1999; 26 (12): 2669–2679.
9 Barber J, Yuen J, Jameson M, et al. Deforming to best practice: key considerations for deformable image registration in radiotherapy. J Med Radiat Sci 2020; 67 (4): 318–332.
10 Fortunati V, Verhaart RF, Angeloni F, et al. Feasibility of multimodal deformable registration for head and neck tumor treatment planning. Int J Radiat Oncol Biol Phys 2014; 90 (1): 85–93. https://doi.org/10.1016/j.ijrobp.2014.05.027
11 Eaton D. Normxcorr3 (Fast 3D NCC). Website. https://www.mathworks.com/matlabcentral/fileexchange/73946-normxcorr3-fast-3d-ncc. Accessed on 1st December 2023.
12 MatWorks®. File Exchange. Website. https://www.mathworks.com/matlabcentral/fileexchange/?s_tid=gn_mlc_fx_files. Accessed on 1st December 2023.
13 Kai Y, Arimura H, Toya R, et al. Comparison of rigid and deformable image registration for nasopharyngeal carcinoma radiotherapy planning with diagnostic position PET/CT. Jpn J Radiol 2019; 38: 256–264.
14 Yuen J, Barber J, Ralston A, et al. An international survey on the clinical use of rigid and deformable image registration in radiotherapy. J Appl Clin Med Phys 2020; 21: 10–24. https://doi.org/10.1002/acm2.12957
15 Rong Y, Rosu-Bubulac M, Benedict SH, et al. Rigid and deformable image registration for radiation therapy: a self-study evaluation guide for NRG oncology clinical trial participation. Pract Radiat Oncol 2021; 11 (4): 282–298. https://doi.org/10.1016/j.prro.2021.02.007
16 Koide Y, Shimizu H, Miyauchi R, et al. Fully automated rigid image registration versus human registration in postoperative spine stereotactic body radiation therapy: a multicenter non-inferiority study. J Radiat Res 2022; 63 (1): 115–121. https://doi.org/10.1093/jrr/rrab113
17 Yang D, Brame S, El Naqa I, et al. Technical Note: DIRART – A software suite for deformable image registration and adaptive radiotherapy research. Med Phys 2011; 38: 67–77. https://doi.org/10.1118/1.3521468
18 Mencarelli A, Kranen SRv, Hamming-Vrieze O, et al. Deformable image registration for adaptive radiation therapy of head and neck cancer: accuracy and precision in the presence of tumor changes. Int J Radiat Oncol Biol Phys 2014; 90 (3): 680–687. https://doi.org/10.1016/j.ijrobp.2014.06.045
19 Konig L, Derksen A, Papenberg N, Haas B. Deformable image registration for adaptive radiotherapy with guaranteed local rigidity constraints. Radiat Oncol 2016; 11 (112): 1–9. https://doi.org/10.1186/s13014-016-0697-4
20 MIM Software Inc. Deformable image registration quality assurance user guide version 7.3. Ohio: MIM Software Inc. 2023.
21 Tibrewala S, Roplekar S, Varma R. Computed tomography evaluation of oral cavity and oropharyngeal cancers. Int J Otorhinolaryngol Clin 2013; 5 (2): 51–62.
22 Bron G, Scemama U, Villes V, et al. A new CT dynamic maneuver "Mouth Opened with Tongue Extended" can improve the clinical TNM staging of oral cavity and oropharynx squamous cell carcinomas. Oral Oncology 2019; 94: 41–46. https://doi.org/10.1016/j.oraloncology.2019.04.023
23 Wu JL, Ge R-G, Tang GJ. A clinical study investigating whether the tongue-out position improves the quality of the anatomical appearance of the pharynx on CT imaging. Front Surg 2021; 8: 732607. https://doi.org/10.3389/fsurg.2021.732607
24 Kuznetsova S, Grendarova P, Roy S, Sinha R, Thind K, Ploquin N. Structure guided deformable image registration for treatment planning CT and post stereotactic body radiation therapy (SBRT) Primovist® (Gd-EOB-DTPA) enhanced MRI. J Appl Clin Med Phys. 2019; 20 (12): 109–118. https://doi.org/10.1002/acm2.12773

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