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Cardiac SABR: Image matching techniques for accurate treatment delivery

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ABSTRACT

Background: Ventricular tachycardia is an irregular heartbeat conventionally treated using invasive cardiac catheter ablation and medication. However, when standard treatments have been exhausted, cardiac SABR provides a final treatment option to this high-mortality condition. Complex diagnostic mapping and planning scans enable multi-disciplinary target delineation for a 25Gy single fraction. However, organs at risk (OAR) near the target make this treatment challenging to plan and deliver. Publications from cardiologists report the efficacy of cardiac SABR, however there is limited data on the treatment delivery and image matching of this complex procedure.

Methods: Four specialist therapeutic radiographers experienced in cardiac SABR reviewed 40 CBCTs from 10 patients treated in the UK. Each therapeutic radiographer conducted five image matches: a manual match (manual), an automatic match to the heart structure (auto) and the auto match followed by manual adjustment to the PTV (PTV), all using three degrees of freedom (DoF) only. The auto and PTV matches were also repeated using 6DoF. Inter-observer variability was quantified using 95% limits of agreement from a modified Bland-Altman analysis.

Results: The limits of agreement were smallest in the automatic matches suggesting the algorithm is reliable. A manual adjustment from the auto match to the PTV is clinically appropriate to optimise target coverage. The limits of agreement were smaller in the 6DoF PTV match 1.06 mm, 1.24 mm, 1.68 mm than the 3DoF PTV match 1.57 mm, 2.06 mm, 2.11 mm (lateral, vertical, longitudinal).

Conclusion: The 6DoF CBCT image match has less variability and therefore suggest using a 6DoF couch for treatment delivery.

Implications for practice: Cardiac SABR CBCT image matching at treatment delivery is complex, optimisation of CBCT acquisition parameters and therapeutic radiographer training is essential prior to implementation.

Introduction

Ventricular tachycardia (VT) is an irregular heartbeat of the lower chambers of the heart and is the main cause of sudden cardiac death.[1] VT is conventionally managed using implantable cardioverter defibrillators (ICD),[2] anti-arrhythmic medication and invasive cardiac catheter ablation.[3–5] Although ICDs improve patient survival, ICD shocks can negatively impact quality of life.[2] There are significant toxicities with anti-arrhythmic medication[6] and invasive cardiac catheter ablation can cause strokes, heart failure and vascular and myocardial injury.[7] While catheter ablation has been shown to improve occurrence of VT storm, ICD shocks and

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death compared to drug treatments,[8] the benefits can be short-lived, with up to 50% of patients experiencing recurrence after 6 months.[9] Additionally, patients with co-morbidities may not be eligible for catheter ablation and therefore are managed with best supportive care.[6] An emerging treatment option for this group of patients is cardiac stereotactic ablative radiotherapy (SABR), where high dose SABR techniques are used to ablate cardiac scar tissue to reduce VT episodes.[10,11]

Initial experience of the efficacy of cardiac SABR have been reported extensively.[2,11–14] To date, most of these studies have had relatively small sample sizes although larger scale clinical trials are now recruiting.[15] Initial publications report 99.9%[11] 87.5%[13] and 94%[14] reduction in VT episodes following cardiac SABR. Understandably, there is much enthusiasm for this novel, non-invasive treatment and when standard treatments have been exhausted, cardiac SABR provides a final treatment option to this high-mortality condition.[14]

The precise definition of the cardiac SABR target is essential for the treatment success and minimisation of side effects.[16] Conventionally radiotherapy is used to target malignant tumours, which are generally easily identified on a radiotherapy planning CT scan. However, the target for cardiac SABR is defined by its electrical properties.[17] Electroanatomic maps are used to identify the target area, however, registering electroanatomic maps with a radiotherapy planning CT is technically challenging and has been the topic of much research.[16,17] Complex diagnostic mapping and planning scans enable the multi-disciplinary team to delineate the target for a 25Gy single fraction. The difficulty in identifying the target and the proximity of organs at risk (OAR) to the target make this treatment challenging to plan and deliver.

While cardiologists have published the efficacy of cardiac SABR, Lydiard et al. (2021)[6] notes the lack of technical information regarding image-guided radiotherapy (IGRT) in cardiac SABR publications, and Weidlich et al. (2018)[7] and Krug et al. (2020)[18] state the necessity of accurate treatment delivery. Miszczyk et al. (2021)[15] suggest in their comprehensive review of cardiac SABR that some treatment failures reported in the literature may be due to suboptimal target delineation. They suggest that small target volumes or inaccurate mapping of the target may be responsible for these anomalies in what is usually a successful treatment. Likewise, inaccuracies in treatment delivery with regard to accuracy of the target or OAR position could also contribute to poor patient outcomes.

Accurate treatment delivery relies on IGRT to an organ that therapeutic radiographers have no prior experience of targeting and is challenging due to CBCT image quality. The CBCT image quality is affected by pacing wires that are synonymous with this group of patients and causes significant artefacts (see Fig. 1.). This multi-centre study investigates therapeutic radiographer CBCT image matching techniques for cardiac SABR treatment delivery.

Methods

Observers

Four clinical specialist therapeutic radiographers at Northern Centre for Cancer Care, Newcastle upon Tyne, UK experienced in cardiac SABR reviewed 40 CBCTs from 10 patients. The four therapeutic radiographers all had cardiac anatomy training from a radiologist and had experience in delivering cardiac SABR treatment.

Patient set-up

Patients were immobilised using a vacbag (Klarity, Heath, OH, USA) with both arms positioned above their head and had a 4D planning CT. Abdominal compression was used for all patients except patient 5 and 6. A planning CT scan was acquired for these patients with and without abdominal compression to assess the benefit. The abdominal compression reduced motion by less than 2 mm and the compression plate caused artefact on the planning CT in these two patients. Therefore, planning and treatment delivery with these patients was uncompressed. In all patients, if the target was close to the stomach, the patient was asked to fast 2 h before planning CT and treatment to control the size and position of the stomach. The cardiac team were present during treatment delivery to monitor the patient.

Image data

The patients were treated in the UK with 25Gy in a single fraction between June 2019 and July 2021, treated on C-arm linear accelerators (linac). Image data was acquired at 3 different NHS UK radiotherapy centres; Northern Centre for Cancer Care, Newcastle upon Tyne Hospitals NHS Foundation Trust, UK; James Cook University Hospital, Middlesbrough, South Tees Hospitals NHS Foundation Trust, UK; Weston Park Hospital, Sheffield Teaching Hospitals NHS Foundation Trust, UK.

At the Northern Centre for Cancer Care, the CT scan was acquired on Siemens Sensation Open (Siemens Healthineers, Erlangen, Germany) and planned using Raystation (RaySearch Medical Laboratories, Stockholm, Sweden). At James Cook University Hospital, the CT scan was acquired on Siemens Definition AS Open (Siemens Healthineers, Erlangen, Germany) and planned using Monaco (Elekta, Stockholm, Sweden). At Weston Park Hospital, the CT scan was acquired on Philips Big Bore (Philips Healthcare, Cleveland, OH, USA) and treatment planned using Varian Eclipse (Varian Medical Systems, Palo Alto, CA, USA).

Anonymised images were imported into a Varian training system (Varian Medical Systems, Palo Alto, CA) to simulate the online clinical image matching workflow. Each patient had between 2 and 7 CBCTs, all of which were reviewed. This depended on a range of factors such as patient set-up, local protocol for intra-fractional imaging, and the use of a “dummy run” session before the treatment appointment. Patients treated at James Cook University Hospital had surface-guided radiotherapy system to monitor intra-fractional motion, and therefore fewer intra-fractional CBCTs were acquired. CBCT acquisition parameters were optimised by increasing the mAs and the number of projections, which reduced the effect of the artefact on the target area. Table 1 shows the range of acquisition parameters used at the different centres with different radiotherapy vendors; Elekta Agility (Elekta, Stockholm, Sweden) and Varian Truebeam STx (Varian Medical Systems, Palo Alto, CA) linacs.

Image matches

Each therapeutic radiographer conducted five image matches to the heart: a manual match (manual), an automatic match to the heart structure (auto) and the auto match followed by manual adjustment to the PTV (PTV), all using three degrees of freedom (DoF) only. The auto and PTV matches were also repeated using 6DoF. The CBCTs were scored on a Likert scale for image quality by each observer whilst doing the image match.

Likert scoring system:

1 = unsatisfactory, not able to visualise soft tissue to PTV match.
2 = poor, just able to match to PTV.
3 = good, few artefacts, able to match to PTV.
4 = excellent, no artefacts.

Ethics

Each UK centre obtained institutional approval for the use of the established SABR service in a novel compassionate use for the

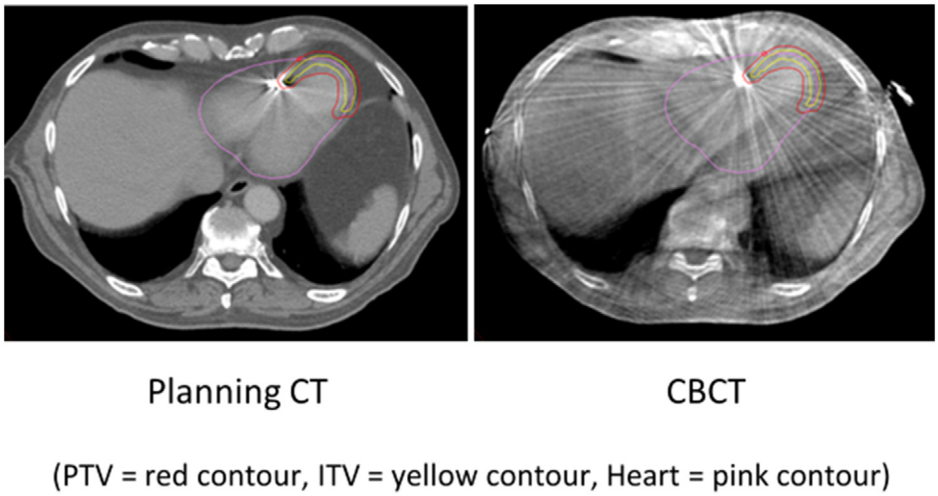

Figure 1. Shows the difference in the image quality of the planning CT compared to the treatment CBCT.

treatment of VT.[2] Patient selection, treatment planning, delivery and follow up were developed with ENCORE-VT trial group.[2,12] Each UK centre listed this retrospective review on their local Clinical Effectiveness Register and had Caldicott approval for the sharing of anonymised data.

Data analysis

Inter-observer variability was quantified using the inter-observer error (mean of the per-patient standard deviation in therapeutic radiographer matches) and 95% limits of agreement

Table 1
Acquisition parameters per CBCT.

Patient	CBCT	Centre	Linac manufacturer	CBCT name	mAs	kV	Projections
1	1	Sheffield	Varian Truebeam STx	4DCBCT	670	125	1260
	2			3 min CBCT	552	125	1260
	3			4DCBCT	552	125	1260
	4			3 min CBCT	552	125	1260
	5			3 min CBCT	552	125	1260
	6			3 min CBCT	552	125	1260
2	7	Sheffield	Varian Truebeam STx	3 min CBCT	552	125	1260
	8			4DCBCT	670	125	1260
	9			3 min CBCT	552	125	1260
	10			3 min CBCT	552	125	1260
	11			3 min CBCT	552	125	1260
	12			3 min CBCT	552	125	1260
	13			3 min CBCT	552	125	1260
3	14	Sheffield	Varian Truebeam STx	3 min CBCT	552	125	1260
	15			3 min CBCT	552	125	1260
	16			3 min CBCT	552	125	1260
	17			3 min CBCT	552	125	1260
	18			3 min CBCT	552	125	1260
4	19	Newcastle	Varian Truebeam STx	3 min CBCT	552	125	1260
	20			3 min CBCT	552	125	1260
	21			3 min CBCT	552	125	1260
	22			2 min CBCT	527	125	840
5	23	Newcastle	Varian Truebeam STx	3 min CBCT	552	125	1260
	24			3 min CBCT	552	125	1260
	25			3 min CBCT	552	125	1260
	26			4DCBCT	1072	125	840
6	27	Newcastle	Varian Truebeam STx	3 min CBCT	552	125	1260
	28			3 min CBCT	553	125	1260
	29			2 min CBCT	527	125	840
	30			3 min CBCT	552	125	1260
	31			4DCBCT	1071	125	840
7	32	Middlesbrough	Elekta Agility	3D CBCT	264	120	413
	33			3D CBCT	264	120	413
8	34	Middlesbrough	Elekta Agility	3D CBCT	264	120	413
	35			3D CBCT	264	120	413
9	36	Middlesbrough	Elekta Agility	3D CBCT	264	120	413
	37			3D CBCT	264	120	413
10	38	Middlesbrough	Elekta Agility	3D CBCT	264	120	413
	39			4DCBCT	499	120	975
	40			3D CBCT	264	120	413

from a modified Bland-Altman analysis[19] in Microsoft Excel. The magnitude of the PTV adjustment was quantified by calculating the mean difference of the PTV shift from the auto-match. The modal Likert score was calculated for each CBCT.[20,21]

Results

Fig. 2 shows that most CBCTs were considered “poor”[21] with 14 CBCTs rated “good”. Four CBCTs were rated “unsatisfactory”. No CBCT image was rated “excellent” quality. This is due to the nature of the patients having pacing wires and causing artefacts in the CBCT. Most patients had the same score for each CBCT, however, patients 2, 4, 5, 6 and 8 were rated lower on some CBCTs. This is because different CBCT acquisition parameters were used for mid-treatment or post treatment CBCT as described in Table 1. In patients 2, 5 and 6, lowest scores were given for the 4DCBCT. Patient 6 also had reduced CBCT score for the 2-min acquisition CBCT compared to the 3-min acquisition.

Table 2 shows the limits of agreement were smallest in the automatic matches suggesting the algorithm is reliable. A manual adjustment from the automatic match to the PTV is clinically appropriate to optimise target coverage. The mean difference between the 3DoF PTV match and the 6DoF PTV match is 0.58 mm, which could be clinically significant in a target with small margins and OAR in close proximity to high dose gradients. The limits of agreement were smaller in the 6DoF auto and 6DoF PTV match than the 3DoF matches. This demonstrates that when the rotations are corrected for as part of the match, matching to the PTV is more consistent. Table 3 shows there is no significant difference between 6DoF and 3DoF matches in the magnitude of the PTV adjustment from the auto-match position.

Figs. 3–6 show the observers agreement in translations and rotations. The mean shifts in lateral, vertical and longitudinal are up to 60 mm, 100 mm and 140 mm respectively. This is because the planning scan and the CBCT were not registered at data import, therefore there are large shifts that would not be seen in the clinical setting. However, the difference from the mean of the shifts shows the agreement among the observers which is the aim of this study.

Table 2
Limits of agreement (mm).

(mm)	Lateral	Vertical	Longitudinal	Pitch	Yaw	Roll
3DOF Manual	1.69	1.87	2.03	–	–	–
3DOF Auto	0.94	1.05	1.40	–	–	–
3DOF PTV	1.57	2.06	2.11	–	–	–
6DOF Auto	0.85	0.99	1.06	0.58	0.38	0.52
6DOF PTV	1.06	1.24	1.68	0.65	0.44	0.51

Table 3
Mean difference of PTV shifts from automatch (mm).

(mm)	Lateral	Vertical	Longitudinal
3DOF PTV shift	0.00	−0.07	0.51
6DOF PTV shift	0.10	0.14	0.42

Discussion

This study evaluated image matching techniques between CT and CBCT images in cardiac SABR treatment delivery. Manual and automatic 3DoF and 6DoF matching techniques were assessed to identify which technique had the closest agreement among observers. There was large variation in the manual match, and therefore this suggests that the use of an automatic match to the cardiac structure provides reliable registration, followed by a manual adjustment to the target. The PTV match was the most clinically appropriate match where the target position was prioritised. The magnitude of the PTV match was similar in both 3DoF and 6DoF matches. However, there was less variation between users when the rotations were corrected for as part of the match, with 1.06 mm, 1.24 mm, 1.68 mm 6DoF PTV match compared with 1.57 mm, 2.06 mm, 2.11 mm (lateral, vertical, longitudinal) 3DoF PTV match without rotations corrected. Therefore, this suggests the 6DoF PTV match is the most reliable method of matching and a 6DoF couch is recommended for treatment delivery.

Cyberknife vs C-arm linac

Several publications report the use of CyberKnife for cardiac SABR treatment delivery[13,22–27] and several others report the use of conventional C-arm linacs.[11,12,14,18,28–32] CyberKnife provides real time tracking: Gianni et al. (2020)[25] used a spine marker for tracking the target position with CyberKnife. In this study, the bony registration compared to the target position was not evaluated, because, like Miszczyk et al., (2021)[15] the spine was not considered to be an appropriate surrogate for the target position. Neuwirth et al. (2019)[13] used ICD leads for tracking, however, Miszczyk et al. (2021)[15] states that at least three pacing wires are required for

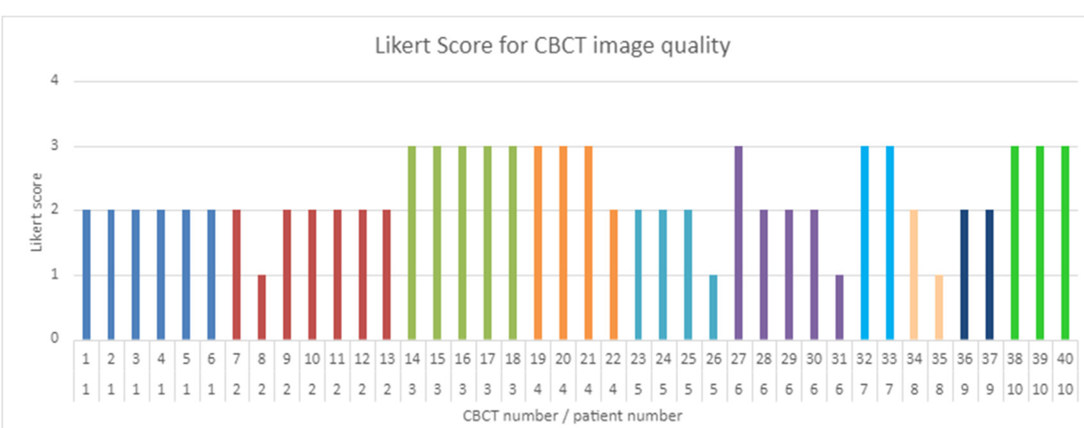

Figure 2. Shows the Likert score for CBCT image quality. Each patient is represented in a different colour. (Likert score: 1 = unsatisfactory, not able to visualise soft tissue to PTV match, 2 = poor, just able to match to PTV, 3 = good, few artefacts, able to match to PTV, 4 = excellent, no artefacts).

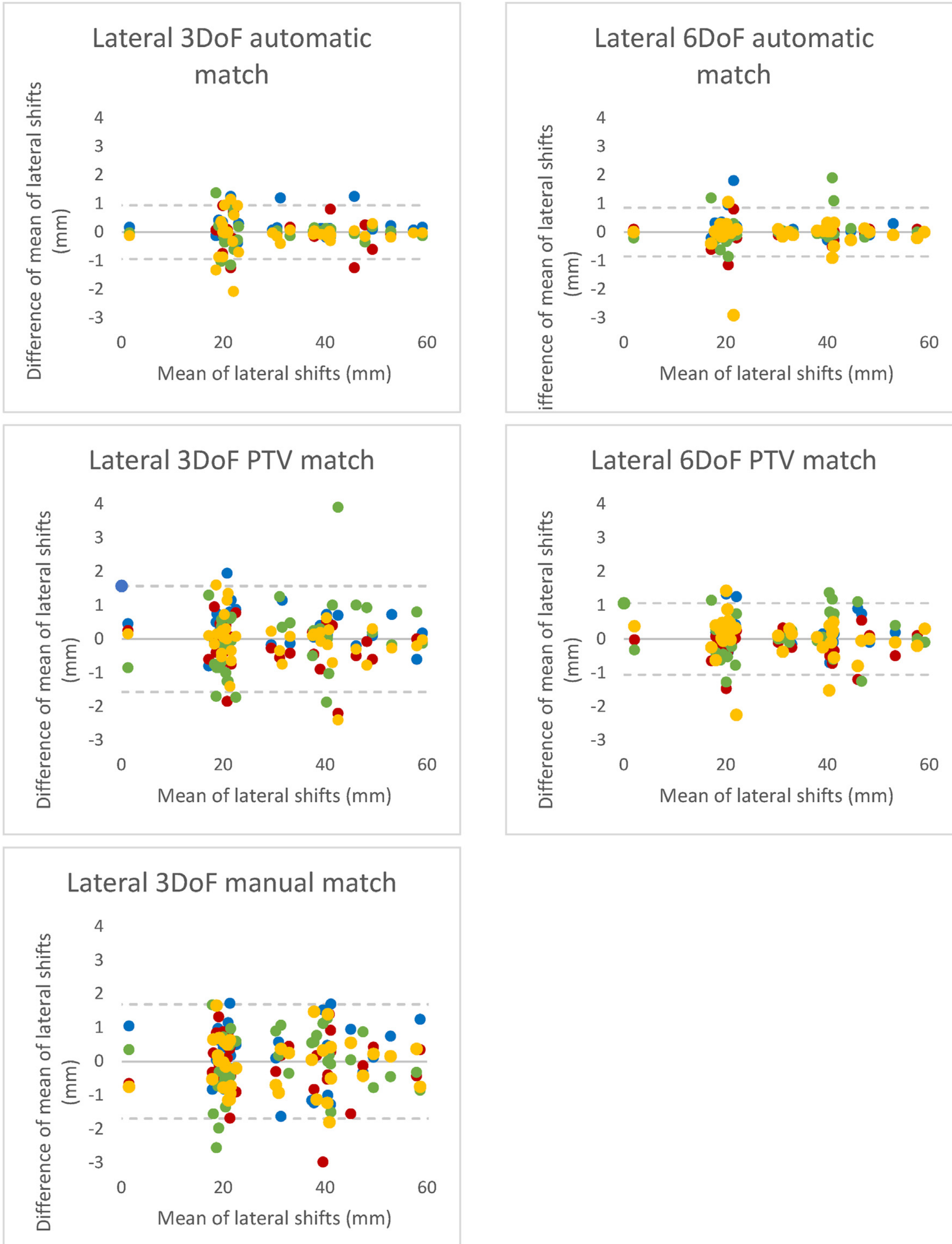

Figure 3. Modified Bland–Altman plots show lateral shifts of each therapeutic radiographer image match compared to the mean of all therapeutic radiographers (each therapeutic radiographer is represented as a different colour) in the 6DoF and 3DoF automatic match, target match and 3DoF manual match. The dotted lines show the limits of agreement.

accurate triangulation for IGRT. Moreover, Wang et al. (2021)[33] suggested the ICD lead might be suboptimal for tracking due to artefacts from the right ventricular coil. Therefore, the accuracy of the CyberKnife tracking is limited and Miszczyk et al. (2021)[15] propose that CBCT is appropriate for target and OAR visualisation. Krug et al. (2020)[18] report using ICD leads as a reference for CBCT image matching which was not investigated in this study. Miszczyk et al. (2021)[15] report the stomach being too close to the target in one patient that was non-compliant with stomach preparation protocols. This was identified on the CBCT, which emphasises the need for visualisation of OAR position, not just target verification by surrogate markers.

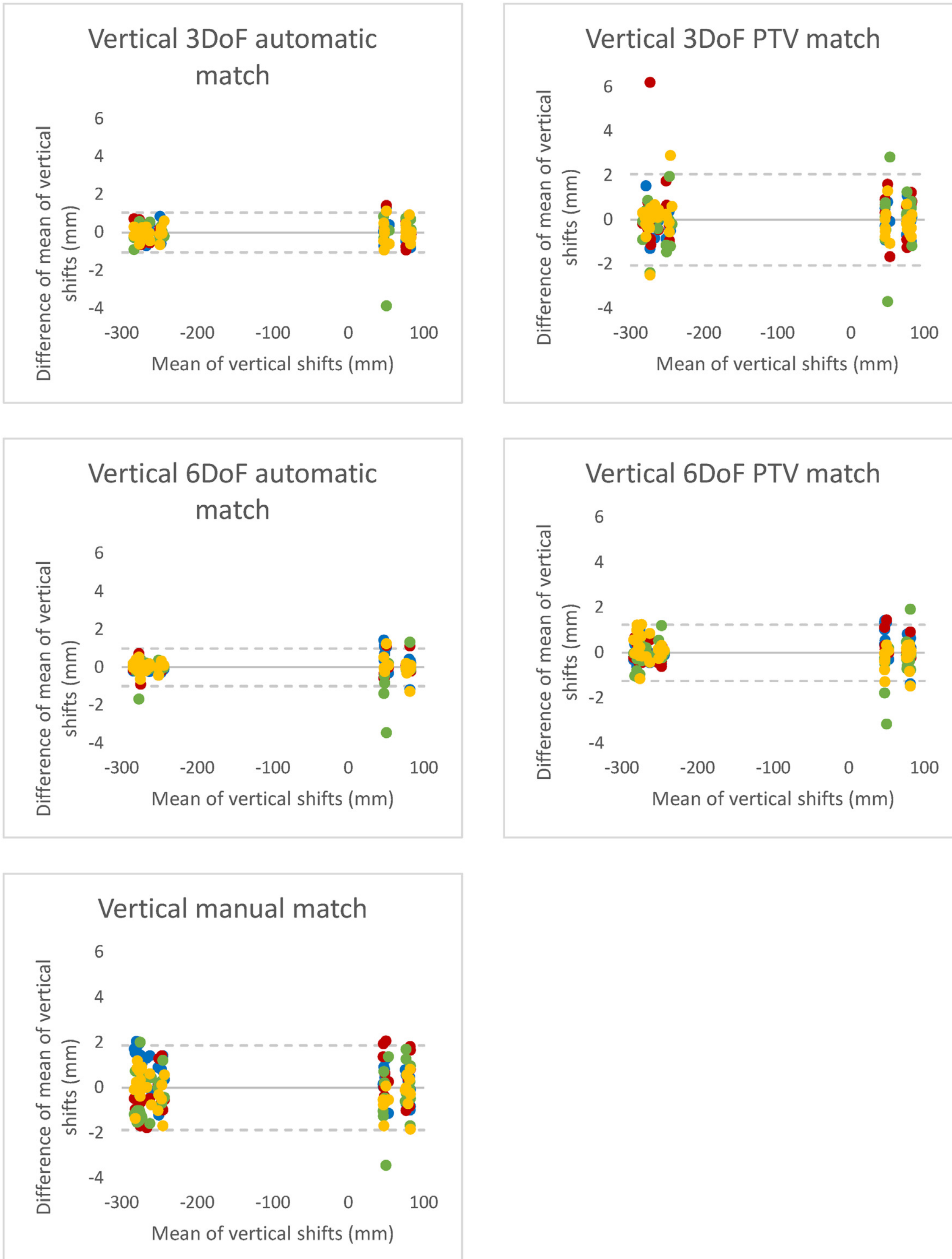

Figure 4. Modified Bland–Altman plots show vertical shifts of each therapeutic radiographer image match compared to the mean of all therapeutic radiographers (each therapeutic radiographer is represented as a different colour) in the 6DoF and 3DoF automatic match, target match and 3DoF manual match. The dotted lines show the limits of agreement.

Image quality

Target matching is challenging on CBCT where there is likely to be significant artefact from pacing wires. Mayinger et al. (2020)[34] report a single case of treating a patient using an MR-linac. There are obvious advantages to the enhanced on-board images in addition to the real-time tracking and gating that they were able to achieve. However, MR-linacs are still a relatively new, scarce technology, and only one patient has been reported to have cardiac SABR on an MR-linac. In this study, CBCT image quality of different acquisition protocols with different linac manufacturers were evaluated using a Likert scale. Three out of the four CBCTs

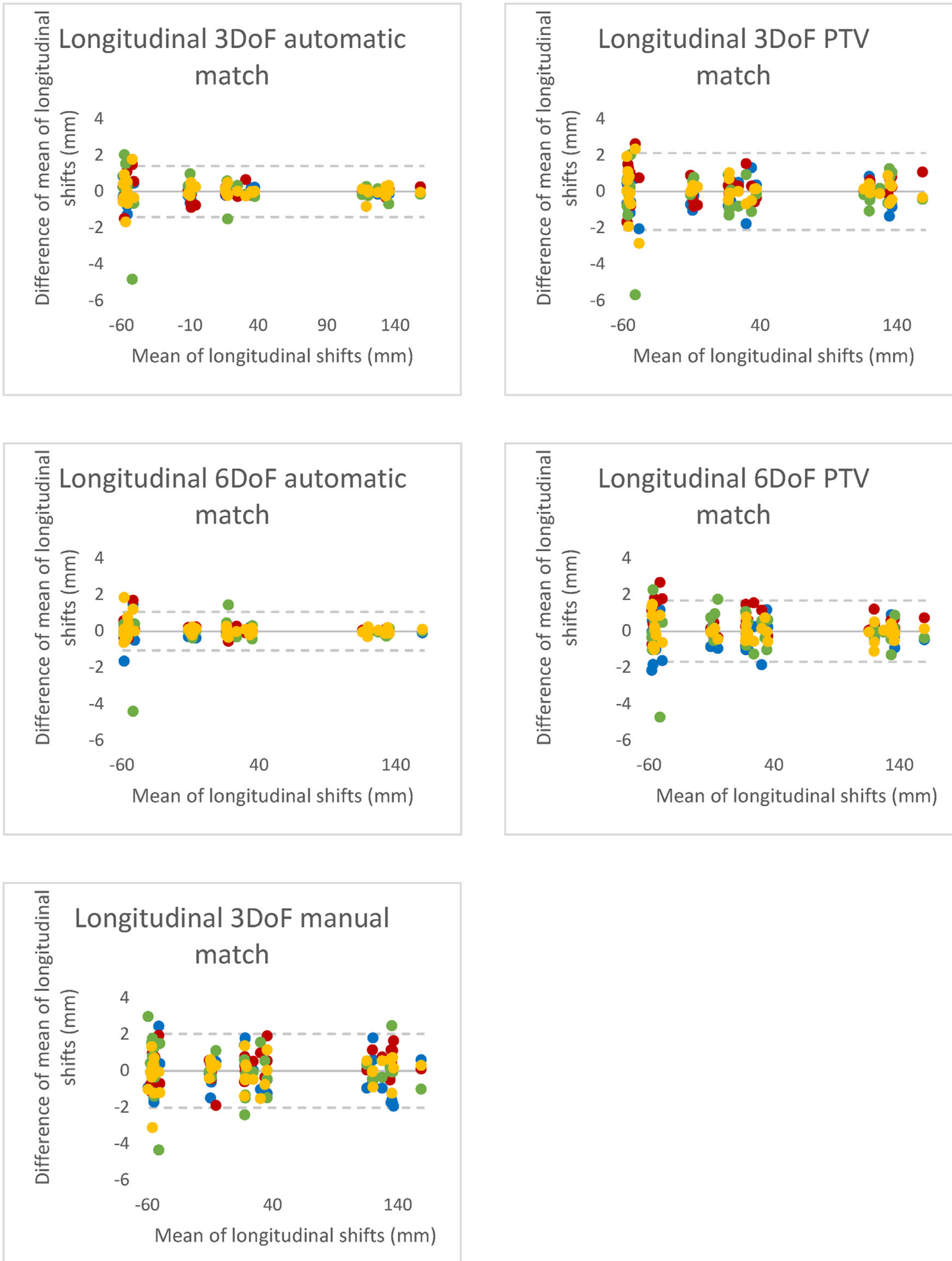

Figure 5. Modified Bland–Altman plots show longitudinal shifts of each therapeutic radiographer image match compared to the mean of all therapeutic radiographers (each therapeutic radiographer is represented as a different colour) in the 6DoF and 3DoF automatic match, target match and 3DoF manual match. The dotted lines show the limits of agreement.

rated "unsatisfactory" were 4DCBCT. Although 4DCBCT is useful for motion visualisation, the image quality is noticeably compromised for target matching. This suggests that 4DCBCT should not be used in isolation of 3DCBCT. Patient 4 and patient 6 had reduced CBCT score for the 2-min acquisition CBCT compared to the 3-min acquisition. This demonstrates that the increased projections noticeably improve CBCT image quality to an extent that is detectable by the observers, this makes matching easier, and therefore more consistent. Therefore, CBCT optimisation is essential in this group of patients to be able to achieve adequate quality images to make clinical IGRT decisions at the point of treatment delivery.

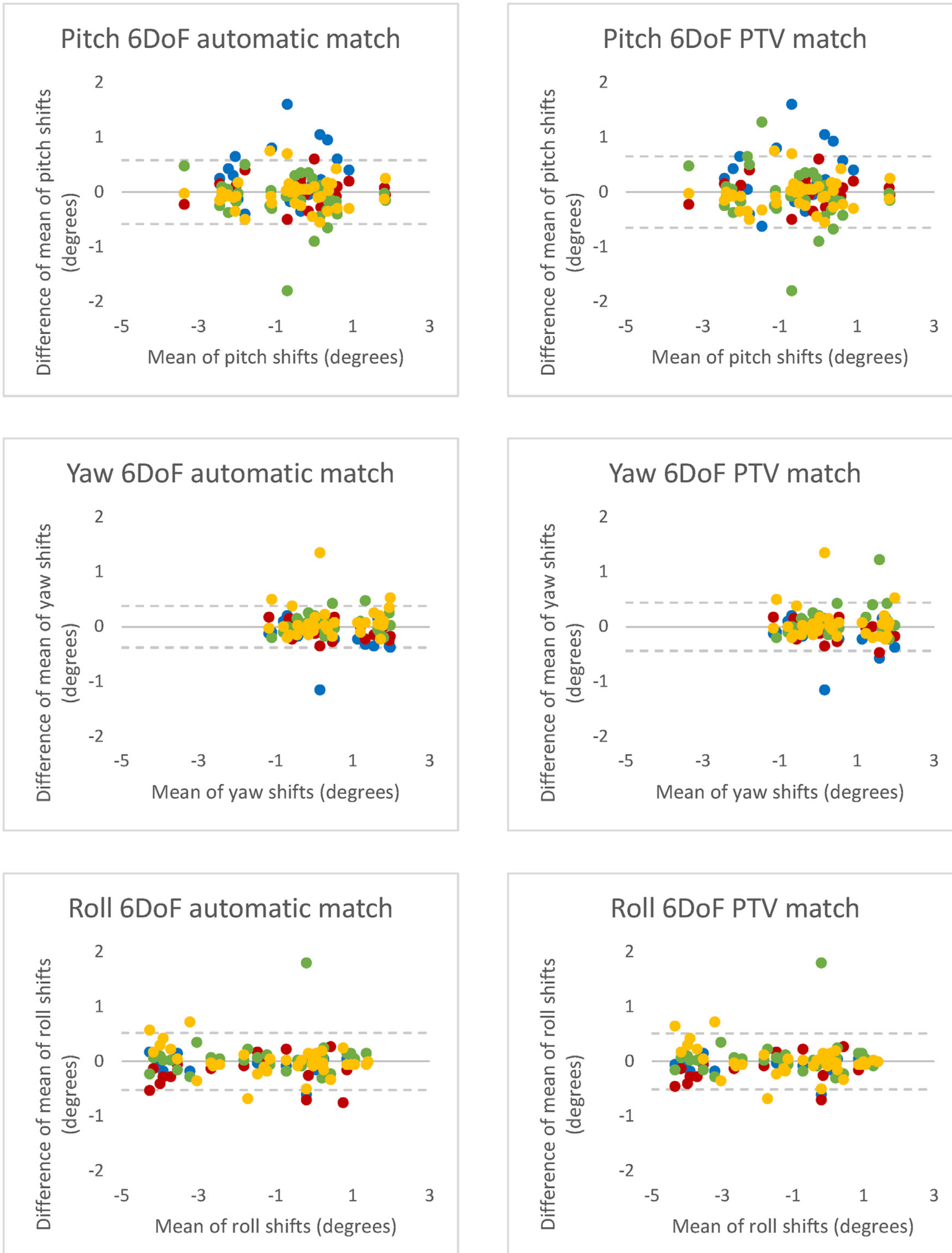

Figure 6. Modified Bland–Altman plots show pitch, yaw and rotation shifts of each therapeutic radiographer image match compared to the mean of all therapeutic radiographers (each therapeutic radiographer is represented as a different colour) in the 6DoF automatic match and 6DoF target match. The dotted lines show the limits of agreement.

Although the use of abdominal compression was not fully evaluated in this study, the two patients that were uncompressed had CBCTs scoring “unsatisfactory, poor, and good”. This suggests that artefacts and CBCT image quality is impacted by the acquisition parameters rather than the use of compression devices. Having said that, there is limited data in this study to comprehensively evaluate the use of compression with cardiac SABR patients.

Therapeutic radiographer training

Therapeutic radiographers have no clinical experience of image matching planning CT and CBCTs to a target within the heart, therefore therapeutic radiographer training should be considered imperative prior to introducing cardiac SABR. An additional challenge for the therapeutic radiographer is that there is no clear tumour target, the target has been defined on the planning CT using electroanatomic maps and the therapeutic radiographer must simply use the CT to match to, with no clearly defined borders. Miszczyk et al. (2021)[15] suggest that despite significant artefacts on CBCT from ICD leads, the target position can be verified using reference points such as calcified atherosclerotic plaques. Therapeutic radiographers require training in cardiac anatomy to be able to identify these structures. Although a radiologist is well placed to provide this training, they may not be aware of the limitations of CBCT image quality. Like many IGRT training packages, a range of resources is required to build competence and decision making in image matching for cardiac SABR. All three centres reported multidisciplinary team presence at treatment delivery to build a knowledge base for the therapeutic radiographers image matching and decision making. Additionally, effective communication from planning team to therapeutic radiographers is necessary to ensure therapeutic radiographers understand the dosimetric planning constraints unique to each cardiac SABR patient since the OAR can range from left anterior descending artery to the stomach depending on the location of the VT scar.

Limitations

The patient numbers presented in this study are small, however this is a novel technique currently approved for compassionate use. There is much interest in this technique in the radiotherapy community. Therefore, patient data from the first three centres to implement cardiac SABR has been evaluated to inform the radiotherapy community of IGRT techniques for this group of patients.

Conclusion

Cardiac SABR is a technically challenging radiotherapy treatment technique to plan and deliver, and yet, this is a well-tolerated, non-invasive treatment for patients with few other options. The efficacy of this treatment relies on accurate planning and delivery. To the best of our knowledge, this is the first study to investigate and report therapeutic radiographer CBCT image matching techniques for cardiac SABR treatment delivery. This data shows that a 6DoF CBCT image match has less variability and therefore more accurate treatment delivery on a conventional linac. Our investigation also shows that CBCT optimisation is essential to acquire CBCTs images sufficient for clinical image-matching decisions. Finally, therapeutic radiographers have no clinical experience of matching to a target in the heart therefore training is required. This multi-centre study addresses the gap in the knowledge base of therapeutic radiographer matching techniques for treatment delivery of cardiac SABR.

Conflict of interest statement

None.

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