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Cone-Beam CT–Guided Online Adaptive Radiotherapy in German- Speaking Countries: A Patterns-of-Care Survey by the DEGRO Working Group on Adaptive Radiotherapy

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Research Article

Keywords: Online adaptive radiotherapy, CBCT, DEGRO, patterns-of-care survey, AI cancer treatment, simulation free radiotherapy, reimbursement

Posted Date: November 26th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11565441/v1

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Additional Declarations: Competing interest reported. Juliane Hörner-Rieber received speaker fees from ViewRay Inc., Pfizer Inc., Accuray Sarl, Sanofi, and Astra Zeneca, as well as travel reimbursement from Varian Medical Systems and research grants from IntraOP Medical and Varian Medical Systems. JHR further took part on an Advisory Board by Johnson & Johnson. Jakob Liermann reports travel reimbursement from RaySearch Laboratories AB, Varian Medical Systems A Siemens Healthineers Company and Micropos Medical, speaker fee form Accuray Incorporated and AstraZeneca GmbH, outside the submitted work. J.L. is Medical Advisory Board member of RaySearch Laboratories AB. Stefanie Corradini received research grants and speaker fees from Varian Medical Systems A Siemens Healthineers Company, Elekta AB, Brainlab, MSD. All other authors report not conflicts of interest related to this work.

Abstract

Background

Cone-beam computed tomography-based online adaptive radiotherapy (CBCT-oART) is increasingly entering clinical practice, but data on its implementation, indications, and workflows remain limited. This patterns-of-care analysis characterized current CBCT-oART use in German-speaking radiation oncology departments.

Methods

An anonymous web-based questionnaire comprising 41 items was conducted between March and April 2026, assessing institutional implementation, indications, workflows, and perceptions of technical and organizational aspects. Responses were analyzed descriptively.

Results

A total of 86 responses from 20 centers in Germany and Switzerland were obtained. CBCT-oART was predominantly implemented at university hospitals and was most frequently used for pelvic malignancies, including prostate, cervical, bladder, and rectal cancer. Simulation-free workflows were used by 63% of responding centers, predominantly for emergency treatment and bone metastases. Most centers treated 4–9 patients per day and allocated 21–30 min per patient. Physicians, medical physicists, and radiotherapy technicians (RTTs) were involved in treatment delivery, whereas adaptation was predominantly performed by physicians. Most centers participated in CBCT-oART-related research. Most respondents reported favorable satisfaction with image quality, but were less satisfied with auto-contouring and plan generation. CBCT-oART was consistently perceived as substantially increasing organizational and personnel demands. Nevertheless, most respondents considered additional efforts justified by the potential patient benefits.

Conclusion

CBCT-oART is established in routine clinical practice at predominantly academic radiation oncology centers in German-speaking regions. Increased personnel and time requirements may hinder broader implementation. Future development should address workflow optimization, appropriate reimbursement, and competency-based task distribution, including advanced training pathways for RTTs within an appropriate professional and regulatory framework.

Introduction

Online adaptive radiotherapy (oART) enables real-time modification of treatment plans immediately prior to irradiation, accounting for the patient's anatomy of the day and thereby facilitating individualized treatment delivery. Compared with conventional image-guided radiotherapy (IGRT), this approach enables the direct incorporation of anatomical changes occurring between simulation and treatment, as well as inter-fractional variations in organ filling, tumor position, and soft-tissue anatomy, into the daily treatment plan. It thereby improves target coverage and might reduce exposure to organs-at-risk (OAR) in various cancer types, but widespread adoption faces challenges like prolonged treatment times and workflow complexity [1, 2]. The availability of integrated high-quality imaging, automated contour propagation, rapid dose calculation, and plan optimization has facilitated the transition of adaptive radiotherapy from predominantly investigational applications toward routine clinical treatment. Current oART systems use either daily magnetic resonance imaging (MRI)-guided radiotherapy (MRgRT) or high-resolution cone-beam computed tomography (CBCT), with both imaging modalities integrated into the linear accelerator (LINAC) [3]. MRgRT provides superior soft-tissue contrast and real-time motion management, whereas CBCT-based oART uses existing LINAC and CBCT hardware, familiar to radiation therapy staff and not requiring additional imaging modalities [4, 5]. The potential clinical value of daily adaptation is particularly relevant for anatomical sites characterized by substantial inter-fractional variation or close proximity of target volumes to OAR [6]. Pelvic malignancies, including prostate, bladder, cervical, and rectal cancer, therefore represent typical applications of CBCT-oART [4, 7–15]. Successful application for thoracic or abdominal malignancies has been reported [2, 16]. No real-time motion tracking or gating is currently available in clinical practice, limiting the application of CBCT-oART, e.g., for stereotactic body radiotherapy (SBRT) in these regions [4]. Simulation-free approaches, in which treatment is performed based on the anatomy acquired at the treatment unit without preceding conventional treatment simulation, may further expand the potential applications of adaptive workflows, particularly in selected palliative or emergency settings [17–22].

Despite these technological developments, implementation of CBCT-oART in routine clinical practice requires substantial organizational resources. In contrast to conventional IGRT, online adaptation involves additional image acquisition, contour review and/or correction, plan optimization, dosimetric evaluation, and treatment verification within the treatment session [1, 6]. Depending on the institutional workflow and degree of automation, this process may require the simultaneous involvement of several professional groups. In Germany, the regulatory framework further requires close involvement of radiation oncologists and medical physicists in individualized radiotherapy planning and treatment. Consequently, the clinical implementation of oART is not determined solely by its technical feasibility. Treatment capacity, personnel requirements, workflow integration, and financial reimbursement are likely to influence whether oART can be implemented beyond highly specialized academic centers. However, contemporary data describing how CBCT-based oART is currently used in routine clinical practice in Germany are scarce.

Patterns-of-care analyses are an established approach to characterize clinical practice and variations in the delivery of radiotherapy [23, 24]. The aim of this survey was therefore to characterize current patterns of clinical implementation of CBCT-based oART in German-speaking countries within the framework of

the German Society for Radiation Oncology (Deutsche Gesellschaft für Radioonkologie, DEGRO). We specifically assessed indications, treatment volumes, workflows, staffing, imaging strategies, simulation-free applications, research activities, and individual perceptions of image quality, auto-contouring, plan generation, organizational requirements, and reimbursement.

Methods

Study design and survey distribution

The questionnaire was developed by the DEGRO Working Group for Adaptive Radiotherapy as a German-language survey and comprised 41 items addressing institutional characteristics, clinical indications, treatment workflows, patient throughput, personnel requirements, imaging protocols, simulation-free workflows, research activities, and technical and organizational aspects of CBCT-oART. The questionnaire was designed to assess both institution-level patterns of care and individual experiences and perceptions of CBCT-oART among different professional groups, including radiation oncologists, medical physicists, and radiotherapy technicians (RTTs). Most items assessing perceptions and attitudes were rated on five-point Likert scales, whereas categorical questions used three response options (yes, no, or not applicable). The full questionnaire, including the wording and response options of all items, is provided in Supplementary Material S1.

The survey was conducted using LimeSurvey (LimeSurvey GmbH, Hamburg, Germany) between March and April 2026 and distributed electronically via e-mail to members of the DEGRO Adaptive Radiotherapy working-group mailing list. Recipients were encouraged to redistribute the survey within their respective institutions across different working groups. Participation was voluntary and anonymous.

Statistical analysis

Categorical variables were summarized using absolute and relative frequencies. Percentages were calculated based on the number of valid responses to the respective question; therefore, denominators may differ between individual survey items because of missing responses or the applicability of specific questions. For institution-level analyses, responses from respondents affiliated with the same center were aggregated, and the response selected by more than 50% of respondents from a given center was used to represent the respective institutional practice. Respondents who did not report their center (n = 20) were excluded from center-level analyses. For respondent-level analyses, each completed response was considered independently. Likert-scale responses were summarized descriptively using frequencies and percentages. For selected exploratory comparisons regarding the oART workflow, responses were compared between radiation oncologists and medical physicists. Given the small number of RTTs, this professional group was not included in inferential comparisons. For comparisons between physicians and medical physicists, the Mann-Whitney U test was used for ordinal Likert-scale variables. These analyses were considered exploratory. No adjustment for multiple testing was performed. A two-sided p-

value < 0.05 was considered statistically significant. All analyses were performed using JASP v0.96 (JASP Team [25]).

Results

Survey participation and institutional characteristics

A total of 86 respondents, including 35 radiation oncologists, 34 medical physicists, and 5 RTTs (Fig. 1), from 20 radiation oncology centers in Germany and Switzerland participated in the survey. A detailed overview of the participating centers is provided in Supplementary Table S2.

As shown in Table 1A, CBCT-oART was predominantly implemented at university hospitals (15/20 centers, 75%), whereas only a small proportion of participating centers were non-academic institutions (Fig. 2). The participating centers reported established clinical use of CBCT-oART for at least 7 months, with nearly two-thirds (11/17 centers) having used CBCT-oART for more than 24 months. The Varian Ethos platform was the most commonly used system among the participating centers (15/18 centers, 83%), while 3 centers (15%) reported additionally using MRgRT.

Clinical indications and treatment concepts

Most centers had integrated CBCT-oART into their routine clinical workflow and reported to primarily chose CBCT-oART for routine primary treatment (14/18 centers, 78%), as well as for selected hypofractionated treatments (13/18 centers, 72%), reirradiation (9/18 centers, 50%), and SBRT (8/18 centers, 44%). Hypofractionated (15/18 centers, 83%) and ultrahypofractionated fractionation schedules (13/18 centers, 72%) were most commonly applied, followed by conventionally fractionated treatments (12/18 centers, 67%).

The most frequently reported indications for CBCT-based oART were pelvic malignancies (Fig. 3A). Prostate cancer (17/18 centers, 94%), bladder cancer (14/18 centers, 78%), cervical cancer (12/18 centers, 67%), and rectal cancer (12/18 centers, 67%) represented the predominant disease sites. In addition, CBCT-oART was used for selected soft-tissue metastases in 11/18 centers (61%). In 6/18 centers (33%) each, CBCT-oART was planned to be introduced for bladder cancer or head and neck cancer in near future, respectively. All responses regarding indications and treatment schedules at the center level are provided in Table 1B.

At the individual respondent level, cervical cancer (47/67 responses, 70%), bladder cancer (41/67 responses, 61%), and prostate cancer (36/67 responses, 54%) were rated as the indications expected to benefit most from CBCT-oART (Fig. 3B). Potentially improved target volume coverage and OAR sparing were the most frequently reported benefits of CBCT-oART. In contrast, respondents preferred standard image-guided radiotherapy (IGRT) over oART especially for breast cancer (39/67 responses, 58%), bone metastases (33/67 responses, 49%), and lung cancer (21/67 responses, 31%). For these indications, most respondents did not expect improved target volume coverage and reported concerns regarding the

practicability of CBCT-oART, particularly with respect to overall treatment times and technical limitations such as the lack of respiratory gating. Detailed responses at the individual respondent level are provided in Table 2A.

Simulation-free radiotherapy, i.e., direct treatment planning based on on-site CBCT imaging, was reported by 5 of 8 centers (63%). Simulation-free approaches were used predominantly for emergency treatments and in selected patients with bone or soft-tissue metastases (Table 1C).

Treatment capacity and workflow

Eight of 17 centers (47%) reported treating 7–9 patients per day with CBCT-oART, while another five treated 4–6 patients (Table 1A). A time allocation of 21–30 min per patient was reported by 12 of 17 centers (71%). The clinical workflow generally involved radiation oncologists, medical physicists, and RTTs during treatment sessions. However, responsibility for online plan adaptation was predominantly assigned to the radiation oncologist at 17 of 18 centers (94%). All participating centers reported acquiring a second CBCT following the adaptive process. A third CBCT routinely performed at the end of the treatment session was reported by 10 centers (56%, Table 1C).

Research activities

Most participating centers were involved in research related to adaptive radiotherapy. Fourteen centers (93%) reported participation in clinical studies involving CBCT-oART, while 11 of 16 centers (69%) reported conducting their own oART-related studies. Most of these studies were prospective or retrospective physics/technology studies (Table 1D).

Individual perceptions of oART

This part of the survey assessed the individual experiences and perceptions of respondents on 5-item Likert scales (Table 2C). For questions addressing the CBCT-oART workflow, responses were presented graphically in Fig. 4, stratified by the three professional groups.

Overall, respondents reported favorable perceptions of CBCT image quality. Across professional groups, responses predominantly fell within the categories of being satisfied or rather satisfied, with no significant differences in their perception between radiation oncologists and medical physicists ($p = 0.497$). In contrast, most respondents were indifferent or dissatisfied regarding automated contouring. Medical physicists tended to assess the quality of automated contouring less favorably than radiation oncologists ($p = 0.005$). Physicians and medical physics experts were indifferent or unsatisfied regarding the speed of online plan calculation ($p = 0.132$). The quality of the generated adaptive treatment plans was generally rated favorably across both professional groups ($p = 0.514$), with approximately half of responses corresponding to rather satisfied.

Most respondents perceived CBCT-oART as associated with a markedly increased workload compared with conventional IGRT. The organizational effort was rated as substantially increased by 40 of 56

respondents (71%). Similarly, all respondents agreed with the statement that CBCT-oART was associated with increased personnel requirements, with the majority (90%) selecting the strongest agreement category.

The perceived financial coverage of CBCT-oART was less favorable. Most respondents considered reimbursement under the German Uniform Value Scale (Einheitlicher Bewertungsmaßstab, EBM) inadequate, with approximately one-third (13/38; 34.2%) explicitly reporting that the current reimbursement framework did not support economically sustainable clinical implementation. However, 37 of 59 respondents (63%) agreed or strongly agreed with the statement that the additional time and staffing required for CBCT-oART are justified by the benefits for the patients. Furthermore, two-thirds of respondents (38/57) perceived an increase in referrals due to the availability of CBCT-oART at their department, and 38 of 56 respondents have experienced patients actively asking for CBCT-oART as preferred treatment (Table 2C). After excluding respondents who selected “cannot assess,” 88% (38/43) reported an increase in patient referrals. This response pattern likely reflects differences in professional roles, as physicists and RTTs are generally less directly involved in patient counseling and referral coordination than physicians.

Discussion

This patterns-of-care analysis provides a contemporary overview of the clinical implementation of CBCT-based online adaptive radiotherapy in German-speaking radiation oncology centers, extending previous patterns-of-care surveys on oART [26–28]. Three main findings emerge. First, oART has moved beyond a purely investigational technology and is already established in routine clinical practice, particularly at academic centers. Second, current clinical use is concentrated on pelvic malignancies and treatment situations in which daily anatomical adaptation may provide particular clinical value, including hypofractionated treatment, SBRT, and reirradiation. Third, despite generally favorable perceptions of image quality, auto-contouring, plan generation, and patient benefit, personnel and organizational requirements are substantially increased compared with standard IGRT workflows.

The predominance of academic centers among participating institutions might be related to the relatively complex oART-workflows with increased personnel and organizational effort. The high proportion of participating centers involved in oART-related research further emphasizes that the current implementation landscape remains closely linked to academic and clinical research structures. In a recent US nationwide pattern-of-care analysis on CBCT-based oART, 53% of respondents worked at medical schools or university hospitals [28]. The international POP-ART RT survey showed in 2020 that adaptive radiotherapy was used by 61% of centers, predominantly as MVCT/CBCT-based ad-hoc offline adaptation. Daily online replanning was reported by only 6% of centers, most of which used MR-guidance [26]. The available surveys suggest more widespread implementation of daily oART than reported six years ago, although direct comparison is limited by differences in study design and populations.

Pelvic malignancies constituted the predominant application of CBCT-based oART, probably reflecting the assumed benefits related to substantial interfractional variability of pelvic anatomy. Changes in bladder and rectal filling, bowel position, tumor regression, and changes in target-to-OAR relationships may create situations in which the anatomy at treatment differs substantially from that represented by the planning CT [9, 29–31]. Daily adaptation can therefore potentially improve target coverage or facilitate OAR sparing compared with a fixed treatment plan [2, 7, 8, 13, 15, 32]. This is particularly relevant when dose per fraction is increased, as in hypofractionated or stereotactic approaches, or when treatment is delivered in the setting of reirradiation.

In our survey, centers reported treating more patients with CBCT-oART per day while allocating approximately half the time per patient compared with the earlier survey by Bai et al. [28]. Given that 89% of participating centers had been using oART for more than 12 months, this may reflect the development of efficient workflows and increasing operational experience, enabling high patient throughput. The most frequently reported treatment time of 21–30 minutes in our study aligns with the timeframe of 17 to 34 minutes reported across different treatment indications [11–13, 33–35].

An interesting finding was the reported use of simulation-free workflows by more than half of the participating centers. These workflows may be particularly relevant for emergency treatment and selected metastatic indications, where conventional simulation may introduce clinically relevant delays or patient burden. CBCT-based treatment initiation may consequently represent an important extension of adaptive radiotherapy beyond its conventional application as an adaptive modification of an existing treatment plan. However, such workflows cannot be considered routine treatment yet. Available reports indicate clinical feasibility and demonstrate the benefits of direct treatment initiation [17–22, 36].

An important aspect for the future scalability of CBCT-based oART is the distribution of responsibilities within the adaptive workflow. In our survey, as well as in the recent US survey [28], radiation oncologists remained primarily responsible for on-treatment target contouring and plan selection or approval, whereas RTTs mainly performed CBCT acquisition and medical physicists were involved throughout the adaptive workflow. This creates a fundamentally different workflow from conventional IGRT, where image acquisition and online positioning corrections can often be integrated into the routine tasks of RTTs without requiring the simultaneous involvement of all professional groups throughout the adaptive planning process. This distribution reflects current professional responsibilities, but may become a limiting factor as the number of oART treatments increases. According to Bai et al., at least one additional full-time equivalent physicist is required when more than 5 oART cases were treated per day [28]. International experience suggests that more advanced RTT roles are feasible and increasingly being developed. Internationally, RTT roles and competencies remain heterogeneous. A European analysis of radiotherapy education found substantial variation in educational structures and competencies across countries, highlighting the lack of harmonization of radiotherapy education and the need for clearly defined competency frameworks [37]. A systematic review demonstrated a broad range of advanced-practice activities with increased responsibilities and a greater level of autonomy, leading to more efficient workflows [38]. A subsequent European survey identified specific educational needs in image-

guided and adaptive radiotherapy and advanced treatment planning, while highlighting substantial variation in scopes of practice and a need for standardized governance and role regulation [39]. Against this background, a structured qualification pathway for RTTs in CBCT-based oART could be considered, enabling appropriately trained RTTs to assume selected standardized components of image assessment, contour review and modification, and adaptive plan evaluation [40]. Such competency-based task redistribution could reduce routine physician and medical physicist workload while retaining physician oversight for complex cases. Its implementation would require standardized training, competency assessment, and a clear legal framework defining responsibilities. More broadly, the reported heterogeneous implementation of oART across Europe [27] highlights the need for sustainable interdisciplinary workflows, adequate staffing, and standardized quality assurance to support wider oART adoption [41].

The reimbursement findings add an important health-system perspective. A considerable proportion of respondents perceived the current reimbursement as insufficient or substantially limiting for oART. These findings align with a contemporary US survey, where 82% of respondents agreed that oART should be reimbursed more than standard RT treatments [42]. This is relevant because the economic requirements of oART are driven not only by acquisition and maintenance of the technical infrastructure but also by recurring personnel costs and reduced treatment capacity. A reimbursement system that recognizes only the delivery of radiation treatment but does not adequately account for the additional adaptive workflow may therefore create a structural barrier to implementation. Although the current reimbursement structure does not specifically compensate for oART, the provision of CBCT-oART may indirectly benefit departments financially by attracting additional patient referrals, as suggested by our survey. The availability of AI-assisted oART may enhance a department’s profile among patients seeking access to innovative treatment options.

At the same time, the survey suggests a discrepancy between increased resource requirements and perceived clinical value. Despite the additional technical and personnel burden, respondents across professional groups largely considered the additional effort justified by the potential benefit to patients. Moreover, two-thirds of respondents reported that patients specifically asked about oART during consultations. These findings indicate substantial perceived clinical relevance and patient interest. However, perceived benefit should not be interpreted as evidence of clinical superiority. The emerging evidence suggests that CBCT-oART may translate dosimetric advantages into clinical benefits, such as reduced gastrointestinal toxicity in prostate cancer patients [15, 43]. However, larger randomized trials with long-term follow-up are needed to confirm its clinical superiority over conventional image-guided radiotherapy.

The majority of respondents expressed favorable perceptions of image quality, but were less satisfied with the quality and speed of plan generation. In the exploratory comparisons between radiation oncologists and medical physicists, no significant differences were observed for most assessed components. Auto-contouring was the only exception, with medical physicists rating its quality less favorably than radiation oncologists. This difference may reflect distinct professional perspectives and

evaluation criteria, for example regarding contour accuracy and the clinical implications of contouring errors, rather than a general difference in the perceived performance of oART platforms. An earlier survey by Vorbach et al. found no significant differences between physicians and medical physicists in their acceptance of AI-generated OAR contours [44]. In contrast, a multicenter study reported lower acceptance of AI-driven treatment planning among medical physicists, which the authors attributed to additional criteria applied by physicists when evaluating treatment plans [45]. Further technological improvements of AI-enhanced process steps towards automated replanning and treatment delivery are likely to improve the quality and reduce personnel efforts during oART application in future [3].

Limitations

Several limitations should be considered. First, voluntary participation and distribution via DEGRO-related mailing lists may have introduced self-selection bias, favoring respondents with an interest in adaptive radiotherapy. The predominance of academic institutions may not reflect implementation across all German radiation oncology departments. Second, the survey captured self-reported practice rather than independently verified workflows and included both institutional practices and individual perceptions. Although these were analyzed separately, multiple respondents from the same institution may have contributed to respondent-level analyses, limiting statistical independence. Third, professional groups were unequally represented, particularly RTTs. Exploratory inferential comparisons were therefore restricted to physicians and medical physics experts and should be considered hypothesis-generating. Fourth, the survey reflects practice in March–April 2026. Given the rapid evolution of adaptive radiotherapy, implementation patterns and workflows may change over time. Furthermore, different treatment systems and portal imaging systems were different across participating centers. Thus, individual perceptions e.g. of CBCT quality might be biased. Finally, the survey assessed reported practice and professional perceptions, not the clinical effectiveness or cost-effectiveness of CBCT-oART. Perceived patient benefit should not be interpreted as evidence of improved outcomes. Prospective comparative studies are needed to identify patient groups benefiting from daily adaptation and determine whether these benefits justify the additional resource requirements.

Conclusion

CBCT-based oART is already integrated into routine clinical practice in participating German-speaking radiation oncology centers, predominantly within academic institutions. Current use is concentrated on pelvic malignancies and selected treatment scenarios in which daily anatomical information may offer particular clinical value, including hypofractionation, SBRT, reirradiation, and selected simulation-free workflows.

At the same time, CBCT-oART remains resource-intensive, with increased treatment times, substantial personnel requirements, and limited reimbursement potentially hindering broader implementation. Future development should therefore focus not only on technical automation but also on optimized multidisciplinary workflows, including the development of advanced RTT roles with standardized

qualification pathways, and reimbursement models that reflect the actual resources required for adaptive treatment.

Abbreviations

AI	Artificial intelligence
CBCT	Cone-beam computed tomography
DEGRO	German Society for Radiation Oncology (Deutsche Gesellschaft für Radioonkologie)
IGRT	Image-guided radiotherapy
LINAC	Linear accelerator
MRgRT	Magnetic resonance imaging guided radiotherapy
OAR	Organs-at-risk
oART	Online adaptive radiotherapy
RTT	Radiotherapy technician
SBRT	Stereotactic body radiotherapy

Declarations

Ethics approval

The study was approved by the responsible ethics committee at Jena University Hospital (reference number 2026-4120-Bef) and conducted in accordance with the Declaration of Helsinki.

Human Ethics and Consent to Participate

Due to the anonymous nature of the survey and the absence of patient-level data, written informed consent was waived. Prior to participation, all participants consented to the storage and processing of the anonymized data collected by accessing the survey.

Consent for publication: not applicable.

Clinical trial number: not applicable.

Availability of Data and Materials

Datasets generated within this study are available from the corresponding author upon reasonable request.

Funding

The present study did not receive funding.

Declarations

Artificial intelligence (ChatGPT, OpenAI) was used for language editing and stylistic refinement of the manuscript. All scientific content was reviewed and approved by the authors.

Conflicts of interest

Juliane Hörner-Rieber received speaker fees from ViewRay Inc., Pfizer Inc., Accuray Sarl, Sanofi, and Astra Zeneca, as well as travel reimbursement from Varian Medical Systems and research grants from IntraOP Medical and Varian Medical Systems. JHR further took part on an Advisory Board by Johnson & Johnson.

Jakob Liermann reports travel reimbursement from RaySearch Laboratories AB, Varian Medical Systems A Siemens Healthineers Company and Micropos Medical, speaker fee form Accuray Incorporated and AstraZeneca GmbH, outside the submitted work. J.L. is Medical Advisory Board member of RaySearch Laboratories AB.

Stefanie Corradini received research grants and speaker fees from Varian Medical Systems A Siemens Healthineers Company, Elekta AB, Brainlab, MSD.

All other authors report not conflicts of interest related to this work.

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Tables

Tables 1 and 2 are available in the Supplementary Files section.

Figures

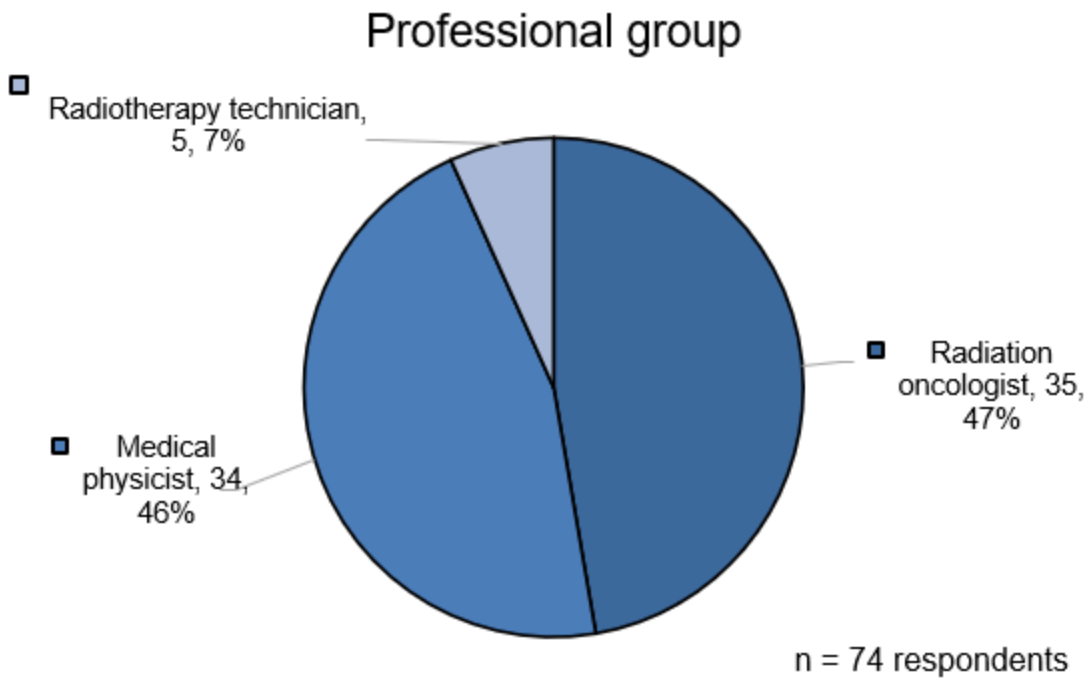


Figure 1

Distribution of respondents by professional group.

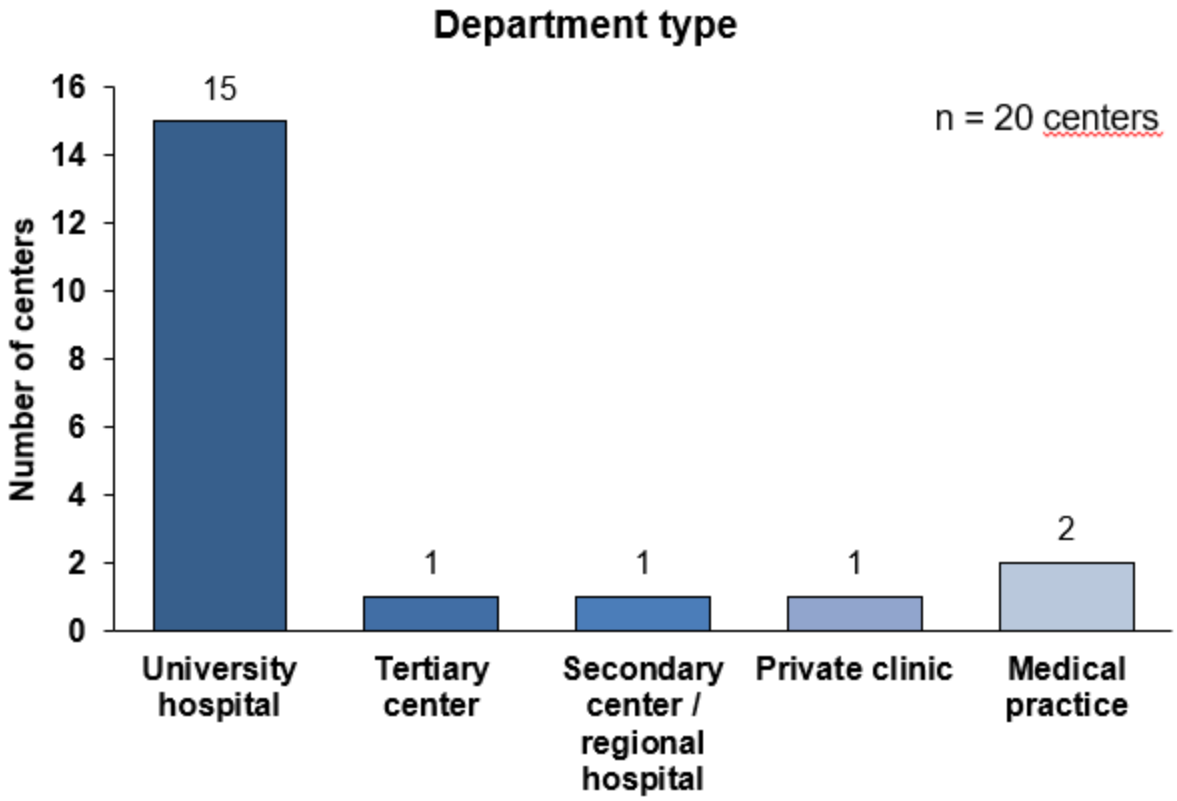


Figure 2

Distribution of participating centers by department type.

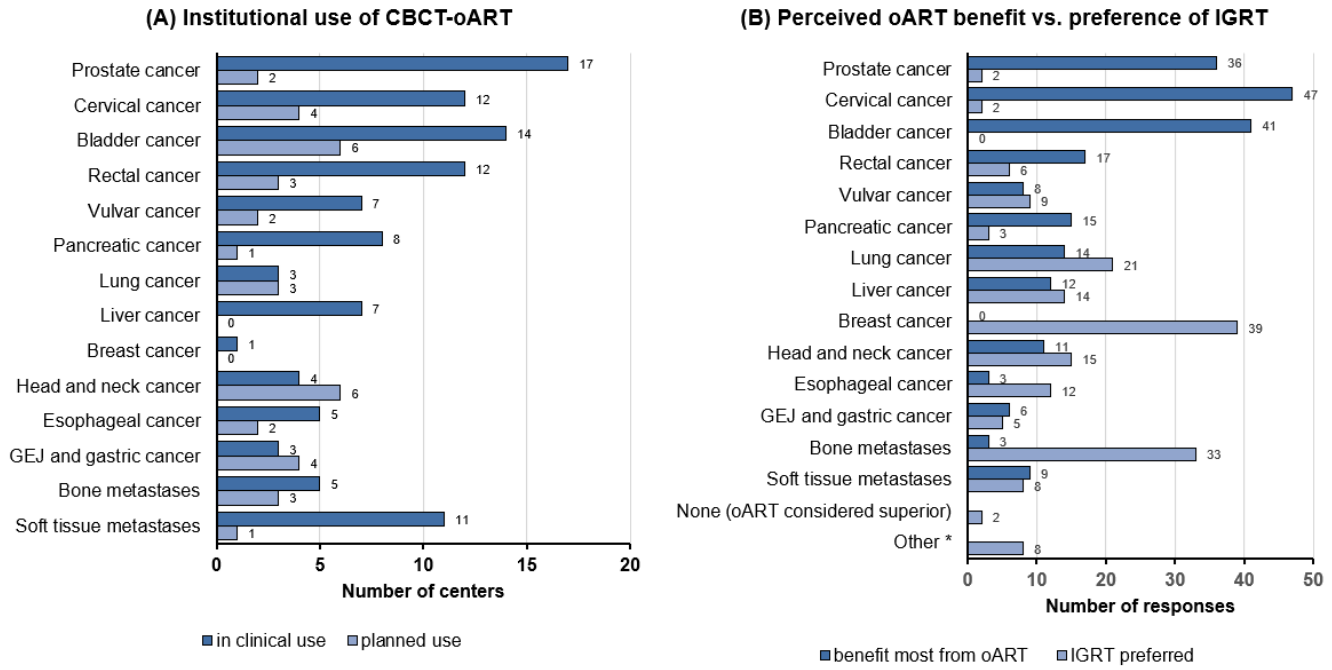


Figure 3

(A) Current and planned CBCT-oART indications among participating centers (n=18). (B) Indications perceived by respondents as benefiting most from CBCT-oART and those for which conventional IGRT workflows were preferred (n=67 respondents); Other* whole-brain radiotherapy (n=2); Patients with hip arthroplasty (n=1); dependent on individual anatomy (n=3); Patients not tolerating increased treatment times (n=2).

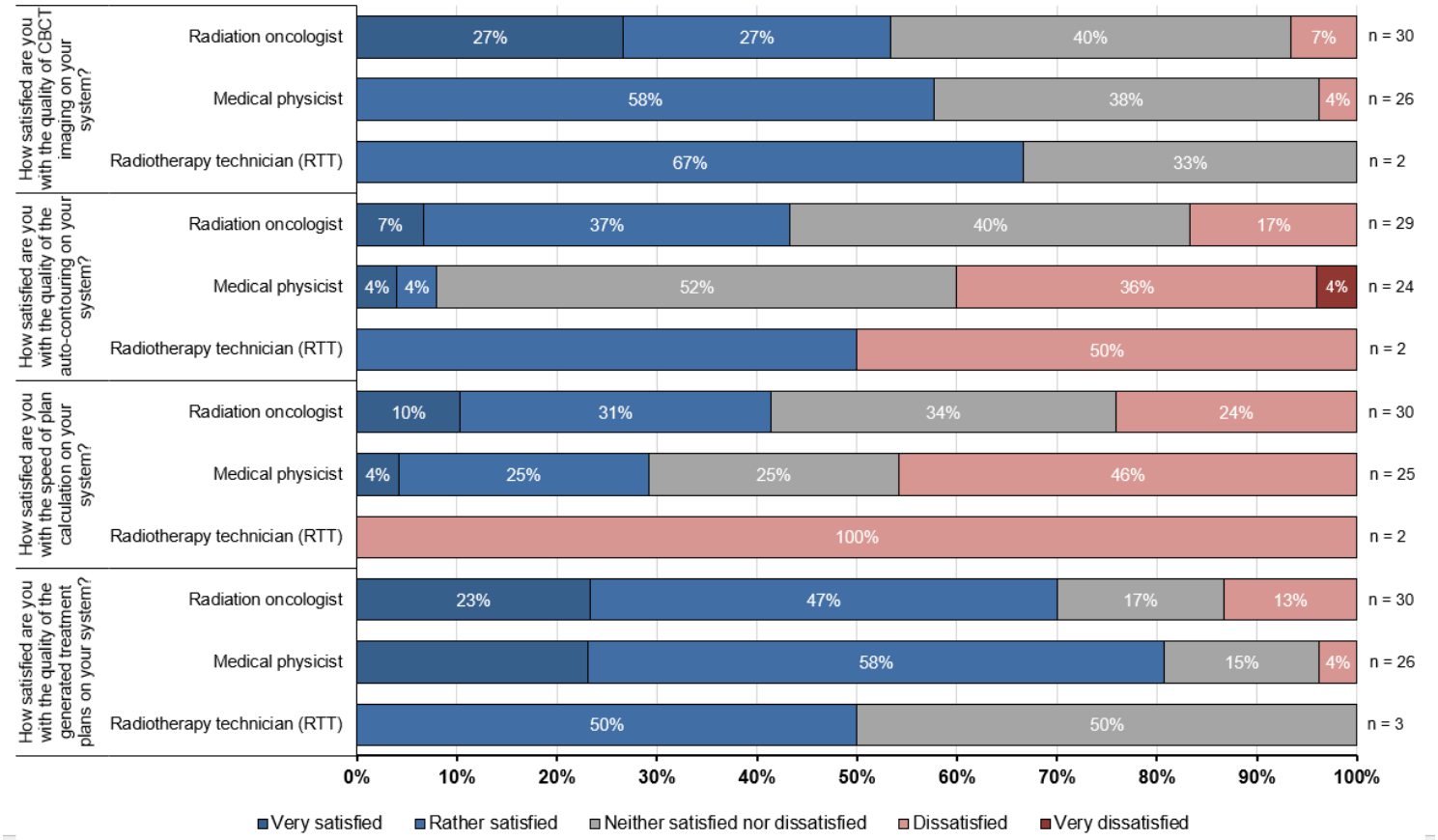


Figure 4

Respondents' perceptions of the CBCT-oART workflow, rated on a 5-item Likert scale and stratified by professional group.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- tablesv5.docx
- supplements2.2.pdf
- supplements1questionnaireENG.pdf