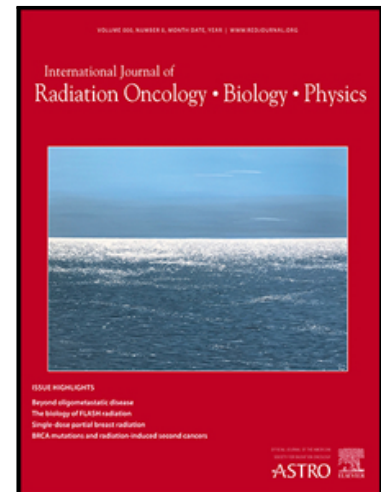


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Three-dimensional radiotherapy target volume definitions for osteoarthritis – Consensus statement of the International Benign Target Volume Group (IBTVG)

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Author Contributions:

DRS: Writing – Original draft; Conceptualization; Methodology; Formal analysis; Investigation; Visualization; Data curation; **MHS:** Project administration; Supervision; Resources; Visualization; Methodology; Conceptualization; Writing – Review & Editing; Formal analysis; Investigation; Resources; Data curation; **RS:** Formal analysis; Supervision; Writing – Review & Editing; Investigation; Data curation; **TW:** Formal analysis; Supervision; Writing – Review & Editing; Investigation; Data curation; **JK:** Writing – Review & Editing; Data curation; Investigation; **FP:** Writing – Review & Editing; Data curation; Investigation; **AMT:** Writing – Review & Editing; Data curation; **FL:** Writing – Review & Editing; Data curation; Investigation; **CW:** Writing – Review & Editing; Data curation; Investigation; **GC:** Writing – Review & Editing; Data curation; Investigation; **AM:** Writing – Review & Editing; Data curation; Investigation; **BA:** Writing – Review & Editing; Data curation; Investigation; **RHL:** Writing – Review & Editing; Data curation; Investigation; **AS:** Writing – Review & Editing; Data curation; Investigation; **SGO:** Writing – Review & Editing; Data curation; Investigation; **FC:** Writing – Review & Editing; Data curation; Investigation; **GR:** Writing – Review & Editing; Data curation; Investigation; **DB:** Writing – Review & Editing; Data curation; Investigation; **BNK:** Writing – Review & Editing; Data curation; Investigation; **MT:** Writing – Review & Editing; Data curation; Investigation; **HE:** Writing – Review & Editing; Investigation; Resources; Supervision; Methodology; Project Administration; Formal analysis

Abstract

Purpose: Low-dose radiotherapy (LDRT) is a minimally invasive treatment option for pain management in selected patients with osteoarthritis (OA). However, standardized and internationally accepted target volume definitions are still lacking.

Methods: An international expert consortium of 15 institutions from Europe and the United States conducted a Delphi consensus process to define joint-specific target volumes based on the three-dimensional concept of the Clinical Target Volume (CTV). A standardized CT dataset (“homunculus”) was used by all participants to ensure uniform anatomical reference for target volume delineation.

Results: Target volume definition includes inflammatory and OA-specific pathological features such as joint effusion, cysts, and subchondral sclerosis. The CTV encompasses the joint capsule and varies in its cranio-caudal extent among individual patients. Using joint-specific isocenter definitions – such as the midpoint between the femoral condyles for the knee joint – the three-dimensional boundaries of the CTV can be determined. This approach enables anatomically precise delineation of the target volume, ensuring inclusion of inflammation-relevant structures while excluding uninvolved bone and soft tissue.

Conclusion: This international consensus statement provides practical guidance for a standardized three-dimensional target volume definition in the radiotherapy of OA. Accurate knowledge of joint anatomy and pathology, combined with precise target volume delineation and careful consideration of the clinical context, such as symptom distribution and the pattern of joint involvement, may support more consistent LDRT treatment planning for OA. These target volume definitions also provide a structured basis for future clinical studies and further clinical validation.

Introduction

Osteoarthritis (OA) is among the most prevalent chronic musculoskeletal conditions (1) affecting an estimated 595 million people worldwide (2) including approximately 50 million in Europe (3) and 32.5 million in the United States (4, 5). Low-dose radiotherapy (LDRT) has been used as a minimally invasive treatment approach for OA, particularly in Europe (6–8), but remains variably adopted internationally (9). Major non-radiation oncology OA guidelines focus on pharmacologic and non-pharmacologic management and do not include LDRT as a standard recommendation (10), because high-quality randomized evidence in OA remains limited. However, LDRT is supported by clinical experience and a biological rationale suggesting that it may be a useful treatment option for selected benign inflammatory and degenerative musculoskeletal conditions, and multiple clinical series and systematic reviews have reported analgesic benefit. Published studies indicate that LDRT provides symptomatic pain relief in 60% to 90% of treated patients, with minimal to no acute side effects (11–14).

Interest in LDRT has recently expanded beyond Europe, with an increasing number of studies being conducted internationally (15, 16). Total doses of 3.0–6.0 Gray (Gy) are delivered in single fractions of 0.5 to 1.0 Gy, administered two to three times a week. A fraction dose of 0.5 Gy is commonly used in some practice settings, based on mechanistic considerations and prior clinical experience (17, 18).

In clinical practice, LDRT is often delivered using direct or opposing field techniques, resulting in interindividual variability among centers worldwide (19). However, OA is a three-dimensional (3D) degenerative and inflammatory disease involving the joint capsule, synovium, periarticular soft tissues, and subchondral bone components. To date, only limited efforts have been made to define target volumes that clearly specify which anatomical structures should be included in the target volume. This is an essential requirement for strengthening the evidence base for LDRT in the treatment of OA.

Defining 3D target volumes enables standardized and reproducible radiation volumes tailored to the individual joint pathology. Despite the use of low radiation doses, a fundamental principle of radiotherapy remains to design treatment volumes that encompass the entire pathological region of the affected joint while, in accordance with the ALARA principle (As Low As Reasonably Achievable), sparing surrounding bone and soft tissue and minimizing unnecessary radiation exposure.

To improve anatomical precision, the concept of a Clinical Target Volume (CTV), adapted from oncologic radiotherapy, is introduced as a structured approach. It should include inflammation-relevant structures such as the joint capsule, effusions, cysts, sclerotic areas, and bone involvement. The use of computed tomography (CT) and magnetic resonance imaging (MRI) allows direct visualization of pathological changes and facilitates adaptation of the CTV to each patient's specific joint morphology and disease extent.

This paper presents structural target volume definitions for the radiotherapeutic treatment of OA-affected joints, as developed by the International Benign Target Volume Group (IBTVG) – a multidisciplinary expert consortium from Europe, the United States, and South America. The primary aim of the group is to establish a uniform, clinically applicable, and internationally accepted framework for target volume delineation in the treatment of OA with LDRT. This initiative is intended to support the development of future clinical studies, treatment protocols, and international guidelines. The proposed framework comprises detailed graphical representations, joint-specific target volume illustrations, and standardized anatomical terminology. It also includes corresponding ICD-10 codes for all clinically relevant joints affected by OA.

Methods

Since no standardized 3D target volume definitions currently exist for OA, a modified Delphi process was conducted between March 2024 and April 2025 to achieve expert consensus (20). The Delphi method is a structured, multi-round approach that facilitates consensus-building through anonymized surveys and controlled feedback (21, 22). The scope of this Delphi initiative was to harmonize target volume definitions for benign radiotherapy including OA as well as tendon and bursal disorders, building on prior national guideline efforts and extending them to an international expert level.

The IBTVG comprises 15 international institutions selected for clinical expertise (≥ 2 years' experience in benign radiotherapy and prior peer-reviewed publications). A total of 21 experts participated (18 radiation oncologists and 3 medical physicists; 14 men and 7 women) from university hospitals, community hospitals, and multi-site outpatient practice networks, covering a broad spectrum of clinical practice and treatment experience. Each member of the IBTVG independently contoured target volumes based on anatomical landmarks and clinical experience using a standardized CT dataset of a 65-year-old male body ("homunculus") acquired on a Siemens CT scanner (Somatom Scope, Siemens Healthineers, Erlangen, Germany, 2018). Standard radiotherapy planning CT protocols with adequate spatial resolution and soft-tissue contrast were assumed for target volume delineation. This purpose-built 3D anatomical reference model was deliberately chosen to ensure a uniform spatial framework for all participants and to allow reproducible comparison of contouring approaches across institutions. They received individual login credentials to access and download the homunculus dataset from a centralized server hosted in Germany. Prior to contour submission, participants underwent structured training and standardization, including instruction in the Cartesian coordinate system, imaging-based anatomical orientation, and harmonized definitions of GTV, CTV, and PTV for benign indications, organized by the chairman of the group.

Feedback was collected and redistributed to enable iterative refinement of individual responses, and the process was repeated until the target volumes were discussed and finalized during joint online meetings.

Overall, the consensus process comprised multiple iterative rounds of contour submission and structured group discussion, with final agreement achieved through collective expert review. Consensus was defined a priori as $\geq 90\%$ agreement among participating experts on the final anatomic boundaries for each target structure; residual disagreements were resolved through structured group discussion in the final consensus meeting. Interobserver variability and consensus-derived target extensions are reported separately in Supplementary Table S2. Additional information on the Delphi process and the distribution of participants is provided in a separate document (Supplementary Appendix S1) to ensure transparency and reproducibility of the consensus process.

Eleven joint regions were selected for contouring: the acromioclavicular joint, glenohumeral joint, elbow, wrist, first carpometacarpal (thumb) joint, hip, knee, retropatellar region of the knee, a "small" foot/ankle joint (including fibulotalar and talocalcaneal joints), a "large" foot/ankle joint (including fibulotalar, talocalcaneal, and tarsometatarsal joints), and the

first metatarsophalangeal joint. Uniform color codes were applied to all target volume structures as shown in the following figures. Additionally, defining joint- and OA-specific ICD codes (23) enabled harmonized classification practices, with the aim of facilitating the efficient exchange of clinical information across institutions and promoting international collaboration in both research and healthcare delivery.

Guiding principle of 3D target volume definition for OA

A fixed anatomical isocenter specific to each affected joint was used as the basis for 3D target volume planning. From this reference point, 3D target volumes were derived to incorporate individual pathological structures, following modified oncological volume definitions: Gross Target Volume (GTV), Clinical Target Volume (CTV) and Planning Target Volume (PTV). The standard CT dataset served as the basis for delineating target volumes in the three planes (axial, sagittal and coronal).

1. Use of the Cartesian coordinate system

The Cartesian coordinate system was used to define 3D target volumes for OA treatment based on the anatomical isocenter for each joint. This system enables precise spatial orientation through standardized definitions of the x, y, and z axes, allowing for reproducible and anatomically consistent delineation of the CTV. It was chosen because it ensures compatibility with all modern radiotherapy planning programs, and it offers a clinically practical reference framework identical to that used in CT and MRI – modalities that are essential in the planning and development of LDRT for OA. The coordinates X, Y, and Z were used to describe directional shifts within the anatomical structure, as illustrated in Figure 1A.

2. Definition of the isocenter

Each participant initially proposed a position for the isocenter of each joint, and final isocenter locations were determined by consensus. The isocenter was defined as the midpoint of the joint space or centrally within the pathological area and serves as the primary anatomical reference point for consistent and reproducible target volume delineation.

3. Target Volume Definitions: GTV, CTV, PTV

GTV: The area affected by joint-specific OA was defined as the GTV. Identification of the GTV was based on clinical orthopedic examination and imaging modalities, including CT, X-ray, and MRI. In the treatment planning system, the GTV was visualized using an orange contour.

CTV: The CTV (visualized in pink color) was delineated to encompass the full extent of potential pathological involvement beyond the GTV. This included areas of inflammation, cartilage loss, osteophyte formation, subchondral sclerosis, and cysts. The joint capsule was included as a key anatomical boundary structure, along with adjacent bone and soft-tissue components affected by OA.

PTV: The PTV (marked in red) was generated by expanding the CTV asymmetrically with a joint-specific margin ranging from 0.3 to 0.8 cm. This expansion accounted for institutional variability and uncertainties related to patient positioning, organ motion, and treatment delivery. A margin of 0.2 cm between the outer treatment volume and the skin surface was maintained whenever possible to minimize the risk of skin toxicity.

4. Workflow for target volume delineation

To define 3D target volumes for individual joints, the isocenter plane was first established. Within this plane, deviations of the CTV from the isocenter were determined along the x, y, and z axes, as illustrated in Figure 1B. On CT imaging, the joint capsule was identified by hypodense areas within the joint space, corresponding to intra-articular fluid, which may represent physiological joint fluid or be associated with inflammatory regions. Bony contours, insertion points, and surrounding fat tissue served as indirect references. In cases of osteoarthritic changes such as capsular thickening or joint effusion, identification becomes easier. To support precise delineation of the joint capsule, auxiliary control points were placed in multiple planes using yellow markers within the planning system. These reference points provided consistent anatomical orientation in 3D space and enabled accurate reconstruction of the joint capsule for target volume definition. It proved beneficial to initially assess the extent of the joint capsule and the potential boundaries of the CTV in the sagittal plane, as it offered a clear longitudinal view of the joint. Multiplanar assessment in sagittal, coronal, and axial views has been shown to be essential to fully track the capsule's course. The CTV was then contoured in 3–5 selected planes (e.g., cranial, caudal, isocenter, and a few mid-slices) and interpolated across the remaining slices. Finally, the PTV was generated. As part of the Delphi process, the cranio-caudal, ventro-dorsal, and lateral boundaries of the target volumes were defined based on the anatomical extent of the joint capsule. ICD-10 coding used for harmonized classification is provided in Supplementary Figure S1.

Results

The consensus results for the most common OA indications – shoulder, thumb, hip, and knee – are presented below. All remaining target volumes and corresponding 3D materials are provided in the Supplement. Supplementary Table S1 summarizes the consensus-based anatomical definitions of joint-specific isocenter locations, and Supplementary Table S2 reports the consensus-derived target volume extensions in all three spatial planes at the isocenter level for the homunculus, including inter-institutional standard deviations. Finally, Supplementary Table S4 provides a consolidated, user-oriented summary of the recommended target volume boundaries to facilitate clinical implementation.

ICD-10-M 19.01 – Shoulder – OA of the acromioclavicular (AC) and glenohumeral (GH) joint

The shoulder comprises two joints relevant to OA: The AC joint and the GH joint.

AC Joint

For AC joint OA, the isocenter should be positioned centrally within the joint space (Figure 2A). The GTV includes the articular surfaces of the acromion and clavicle, incorporating visible osteophytes. The CTV encompasses the joint capsule and stabilizing ligaments, including the acromioclavicular and coracoacromial ligaments. It extends to include the lateral third of the clavicle and the medial portion of the acromion. The exact extent of the CTV along the joint capsule can be adapted based on individual pathological findings. Reference points placed in all three imaging planes support visualization and tracking of the capsule's course on CT.

GH Joint

The GH joint, as the main articulation of the shoulder, plays a central role in mobility and is more commonly affected by OA than the AC joint (24). Consequently, the corresponding CTV requires a broader coverage to encompass the anatomical structures involved in the joint. The isocenter should be located at the center of the humeral head (Figure 2B), serving as the anatomical axis of rotation for shoulder movement. Hypodense joint boundaries on CT imaging form the basis for delineating the CTV in axial and coronal planes. The final CTV should include the humeral head, the proximal portion of the humeral shaft, and adjacent structures such as the coracoid process and the acromion.

The cranial boundary of the CTV aligns with the origin of the supraspinatus tendon. Anteriorly, it follows the course of the joint capsule along the subscapularis muscle. Medially, the glenoid rim is included without extending into the scapular body. Laterally, the humeral head must be fully enclosed, excluding the diaphysis. The caudal boundary varies and should be tailored to the capsule's anatomical path, generally limited to the metaphyseal region. Minor irregularities may arise during manual CTV contouring (see Supplementary Figure S2D), particularly at transition points between slices. These can be promptly corrected through cross-verification in axial, coronal, and sagittal planes.

ICD-10-M 18.9 – OA of the thumb carpometacarpal (CMC I) joint

The isocenter is centrally positioned within the joint space between the trapezium and the base of the first metacarpal (see Figure 3A). The CTV should include the whole joint capsule and adjacent pain-relevant periarticular soft tissue. Cranially, it reaches slightly beyond the trapezium without involving the overlying soft tissue. Caudally, it encompasses the metaphyseal portion of the first metacarpal while avoiding unnecessary extension into the diaphysis. Dorsally and palmarly, the volume includes capsule-adjacent tissue while excluding the extensor and flexor tendons, as well as surrounding neurovascular structures. Medial and lateral borders symmetrically encompass the joint, accounting for osteophytes and reactive bone changes when present. During clinical evaluation – supported by imaging modalities such as X-Ray, CT, or MRI – it is important to distinguish isolated CMC I OA from further hand polyarthrititis. If additional joints such as the proximal or distal interphalangeal joints (PIP/DIP) are affected, the target volume should be adjusted and extended, as accurate coverage is essential for therapy success.

ICD-10-M 16.9 – OA of the hip joint

Hip OA affects the articulation between the femoral head and the acetabulum. Due to the possible advanced degenerative changes of the hip joint – such as joint effusion, and occasionally incidental heterotopic ossifications – the CTV of the hip OA should extend beyond the joint capsule to include all visibly affected structures and may require individual adaptation. Editing on the homunculus model (see Figure 3B) did not require expansion of the target volume in the absence of joint effusion or ossifications.

The isocenter should be positioned at the center of the femoral head. The GTV encompasses the bony articulating surfaces of the femoral head and acetabulum. Anatomically,

the joint capsule follows the contour of the acetabulum and envelops the subchondral regions of the femoral head. Laterally, the CTV extends to the base of the greater trochanter, incorporating adjacent periarticular soft tissue. Medially, it reaches the region of the lesser trochanter, without crossing into the central pelvic cavity. Cranially, it includes the superior rim of the acetabulum; caudally, the CTV ends just above the ischial tuberosity.

Only inner muscle layers closely associated with the joint – such as portions of the iliopsoas and gluteus minimus – should be included. Outer, thicker muscle layers, such as the gluteus maximus, are deliberately excluded to minimize radiation exposure to unaffected tissue.

ICD-10- M 17.9 – OA of the knee joint: Tibiofemoral OA and retropatellar OA

Tibiofemoral OA represents the most prevalent form of knee degeneration. However, isolated patellofemoral (retropatellar) OA – typically involving cartilage loss behind the patella – also occurs and requires separate consideration in target volume delineation.

Tibiofemoral knee OA (Medial, lateral or combined OA)

Tibiofemoral OA is typically associated with mechanical overload, varus or valgus malalignment, meniscal damage, or ligamentous instability (15, 19, 25), making it essential to position the isocenter centrally within the joint space between the femoral condyle and the tibial plateau to ensure a coverage of the affected compartment (see Figure 4A). The GTV includes the subchondral surfaces of both bones, reflecting areas of cartilage loss and osteoarthritic remodeling. The CTV extends beyond the bony contours to include the joint capsule and adjacent periarticular soft tissues. Medially, the contour extends to the inner margin of the adjacent muscle layers while excluding the medial collateral ligament. Laterally, the CTV ends at the medial edge of the intercondylar region to avoid inclusion of the lateral compartment. Superiorly, the contour follows the curvature of the femoral condyle into the supracondylar region; inferiorly, it includes the proximal metaphyseal portion of the tibia, without extending into the diaphysis. Anterior and posterior margins are confined to the depth of the joint capsule, avoiding unnecessary exposure of tendons, neurovascular structures, and deeper muscular planes. Posteriorly, the CTV may extend slightly cranial to the femoral condyles to follow the anatomical course of the posterior joint capsule and capsular recesses, particularly in the presence of synovitis or effusion. Of note, the target volume does not follow a symmetric or square shape, but instead is asymmetrical along the cranio-caudal axis: approximately two-thirds of the total volume are located above the isocenter, while the remaining one-third lies below.

Retropatellar OA

Retropatellar OA differs from classical tibiofemoral OA in both pathogenesis and clinical presentation. It primarily affects the articulation between the patella and the femoral trochlea and often arises from patellar maltracking, muscular imbalances, or anatomical variations such as trochlear dysplasia (26). The isocenter should be centrally positioned within the patellofemoral joint space. The CTV expands beyond the cartilage-bearing surfaces to encompass the joint capsule and adjacent deep soft tissues relevant to the patellofemoral articulation (see Figure 4B). Superiorly, the volume reaches the upper pole of the patella and proximal trochlear entry; inferiorly, it includes the distal patellar region, stopping short of the tibial tubercle. In the mediolateral direction, the contour remains confined to the width of the patellofemoral joint, avoiding adjacent compartments. Anterior expansion is limited to the retro-patellar space, without including the overlying quadriceps or patellar tendons.

Discussion

The evidence base for LDRT in OA remains heterogeneous, and high-quality randomized, placebo-controlled trials are limited, which is reflected in the lack of broad endorsement by major non-radiation oncology bodies. In this context, and considering both the need for higher-quality evidence and the increasing clinical use of LDRT, anatomically grounded target volume definitions are needed to reduce variability in current practice and to provide a consistent basis for future clinical trials. This consensus provides a harmonized 3D framework for target definition to improve reproducibility across institutions, addressing the persistent heterogeneity in published target volume concepts (Table 1). The IBTVG is an independent, multi-institutional collaboration of experts convened to develop consensus-based methodological proposals for radiotherapy in benign conditions, with the aim of informing and supporting future society-led guideline initiatives. Importantly, the present consensus does not claim clinical superiority in terms of analgesic outcome but proposes a conceptually different approach to target definition. By shifting the focus from empiric field sizes to anatomically and pathologically guided, isocenter-based 3D target volumes, the proposed framework offers greater anatomical precision and transparency compared with previously published approaches.

Two principal approaches to target volume definition exist: One approach simply involves placing a 2D field of a standard size; the other involves the delineation of a CTV guided by the joint capsule and adapted to the specific pathological features of the OA-affected

joint. Kaltenborn et al. (27) and Ott et al. (28) both reported improved outcomes using larger field sizes; however, this likely reflects treatment of combined or adjacent joint pathologies rather than implying that larger field sizes are inherently better. Additionally, the underlying pathology is often multifactorial, involving not only degenerative but also inflammatory or periarticular processes, such as those observed in painful shoulder syndromes (which may include rotator cuff tendinopathies and bursitis in addition to OA). Other musculoskeletal conditions, including bursitis and tendinitis (29, 30), may also represent valid indications for LDRT and can clinically mimic OA. This underscores the importance of thorough clinical and imaging-based evaluation to identify overlapping pathologies and to adapt the target volume accordingly.

These clinical considerations complement rather than contradict the standardized target volume concept proposed here. They reflect the principle of function-oriented radiotherapy guided by accurate ICD-10 coding for OA: the CTV should encompass characteristic OA-related pathological features, including joint effusion and inflammatory zones. Conversely, structures uninvolved in the disease should be excluded to avoid overtreatment and adhere to the ALARA principle. This is particularly critical in the treatment of hip OA (10), where nearby organs such as the bladder, rectum, and bowel necessitate precise and conservative volume planning. Overly extensive volumes can increase the risk of side effects and, in the long term, secondary malignancies (31, 32).

Recent advances in LDRT underscore the value of standardized diagnostic classifications, such as ICD coding, to enhance documentation, support patient subgroup stratification, and enable controlled clinical trials on a global scale – an approach recently examined by Koneru et al. (16). Their findings also emphasize marked differences between American and European patient populations in obesity prevalence, dietary patterns, and physical activity levels (33, 34). Accordingly, while the proposed target volume framework offers a standardized anatomical basis, individual adaptation to regional or population-specific disease characteristics – such as fat distribution – may be necessary in clinical practice and warrants further investigation.

In the proposed target volume definitions, the joint capsule serves as a key structure because it functionally delineates inflammatory processes (35). Accordingly, posterior CTV boundaries are defined by the joint capsule rather than by osseous landmarks alone. For example, although the femoral condyles serve as important reference points in the tibiofemoral joint, the posterior capsule and its recesses may extend proximally beyond the condylar level,

particularly in the presence of capsular distension or inflammatory involvement. In such cases, a modest posterior–superior CTV extension may be anatomically justified and should be evaluated on a patient-specific basis.

The joint capsule’s involvement in synovial inflammation and fibrotic remodeling during disease progression is well documented (36), a process potentially modulated by LDRT (17, 37). In cases of extracapsular pathology – such as Baker’s cysts, prominent osteophytes, or enthesiopathies – the target volume may be expanded to include these OA-related structures.

Previous contouring frameworks have defined overly large or non-anatomically accurate 2D fields. The German guideline on radiotherapy for benign diseases (38) recognizes the importance of including pathological structures but does not consistently account for the joint capsule, leading to excessive or anatomically inconsistent field sizes. Similarly, the CT-based contouring atlas by Alvarez and Montero et al.(39), also cited by Dove et al. (7), relied on fixed margins around bony landmarks and failed to capture individual anatomical variability or the true extent of OA-related pathology. Despite favorable outcomes reported in those studies, such results may reflect treatment of unnecessarily large volumes—a limitation this consensus seeks to address.

The Delphi method (20) was employed to achieve structured consensus among the international experts of the IBTVG. Potential bias inherent to this method was minimized through independent contributions and anonymized feedback rounds. The 3D target volume definitions were developed using a standardized male body CT dataset (“homunculus”) to ensure consistency while allowing the principles to be transferable to diverse patient anatomies.

In clinical implementation, this framework should be applied as an isocenter-based, capsule-guided 3D concept rather than as fixed centimeter-based fields. The fundamental principle of isocenter placement and capsule-based planning incorporating pathological joint structures remains unchanged. Target extent should therefore be adapted to individual anatomic conditions (e.g., joint size and geometry, soft-tissue thickness affecting surface proximity and PTV cropping, limb alignment/rotation, postoperative changes, deformity, or implants) and to the distribution of OA-related pathology (e.g., synovitis, prominent osteophytes, or cystic changes). Sex-related differences in joint size, including joint dimensions, capsular extent, and osseous anatomy, should be considered (40), forming the basis for delineation along patient-specific capsular boundaries and the distribution of visible pathology, which may necessitate expansion of the CTV. In the hip, sex-related variation in pelvic and acetabular morphology

may alter the relationship between bony landmarks and the capsule on planning CT (41), supporting individualized assessment within the same three-plane framework.

While CT provides a robust and reproducible basis for 3D target volume definition, conventional radiography remains a cornerstone of routine OA assessment, offering readily available information on structural disease severity (e.g., joint space narrowing, osteophytes, subchondral sclerosis) and, in selected joints, indirect signs of effusion. MRI may serve as complementary imaging in selected cases and can improve assessment of bone bruise, synovitis and periarticular soft-tissue involvement when CT findings are inconclusive or discordant with clinical examination. In this setting, MRI supports individualized target adaptation within the same isocenter-based framework, without prompting automatic expansion based on incidental findings. Supplementary Figure S9 illustrates representative CT and MRI examples of typical OA-related pathologies that may be considered for individualized target adaptation when clinically concordant.

Given that imaging abnormalities – particularly on MRI – are frequently observed in asymptomatic individuals, clinical assessment should remain the primary driver of OA diagnosis and management. MRI features of knee OA have been reported in up to 40% of asymptomatic adults, and cartilage, bone marrow, and tendon abnormalities may occur without corresponding symptoms (42, 43). This discrepancy between imaging findings and clinical presentation is likely multifactorial: structural changes may represent non-pain-generating or compensated degeneration, whereas pain is often driven by inflammatory processes, periarticular soft-tissue involvement, and individual pain processing. Accordingly, the proposed target volume framework should integrate clinical history, pain localization and physical examination. Supportive Imaging is used to anatomically contextualize clinically concordant pathology – such as effusion-related capsular distension or periarticular involvement – while incidental or clearly asymptomatic findings are deliberately excluded from target definition to avoid overtreatment.

A limitation of this consensus is the absence of predefined clinical case scenarios, reflecting a deliberate focus on a broadly applicable, anatomy-based target volume framework rather than scenario-specific recommendations. In clinical practice, target delineation nonetheless requires integrative consideration of anatomy, pathology, symptom localization, and patient-specific factors such as pain phenotype, functional impairment, and physical examination findings. Additional limitations include the use of a single standardized male CT dataset, the lack of prospective clinical outcome validation, and the predominantly radiation

oncology-based expert panel, underscoring the need for further clinical evaluation and multidisciplinary input.

Although defining 3D target volumes for OA can be time-intensive and requires specific expertise, the clinical benefits may justify the effort. Anatomically precise, pathology-oriented planning enhances standardization and minimizes irradiation of uninvolved tissue. With appropriate training and experience, the planning process can also be significantly streamlined. While implementation may currently be limited in daily clinical practice, CT-based 3D planning provides a robust foundation for optimized treatment strategies and future research.

Conclusion and future outlook

This consensus provides comprehensive recommendations to create 3D target volumes for joints affected by OA. This approach is expected improve anatomical accuracy and enable precise CTV delineation, which will uphold the ALARA principle, minimizing volume and dose to uninvolved structures and focusing on the pathological target. It also serves as a basis for randomized clinical trials, clinical education, and the development of automated planning tools. Future multicenter studies are needed to validate the proposed target volume definitions across diverse patient populations and clinical settings.

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Figure Legends

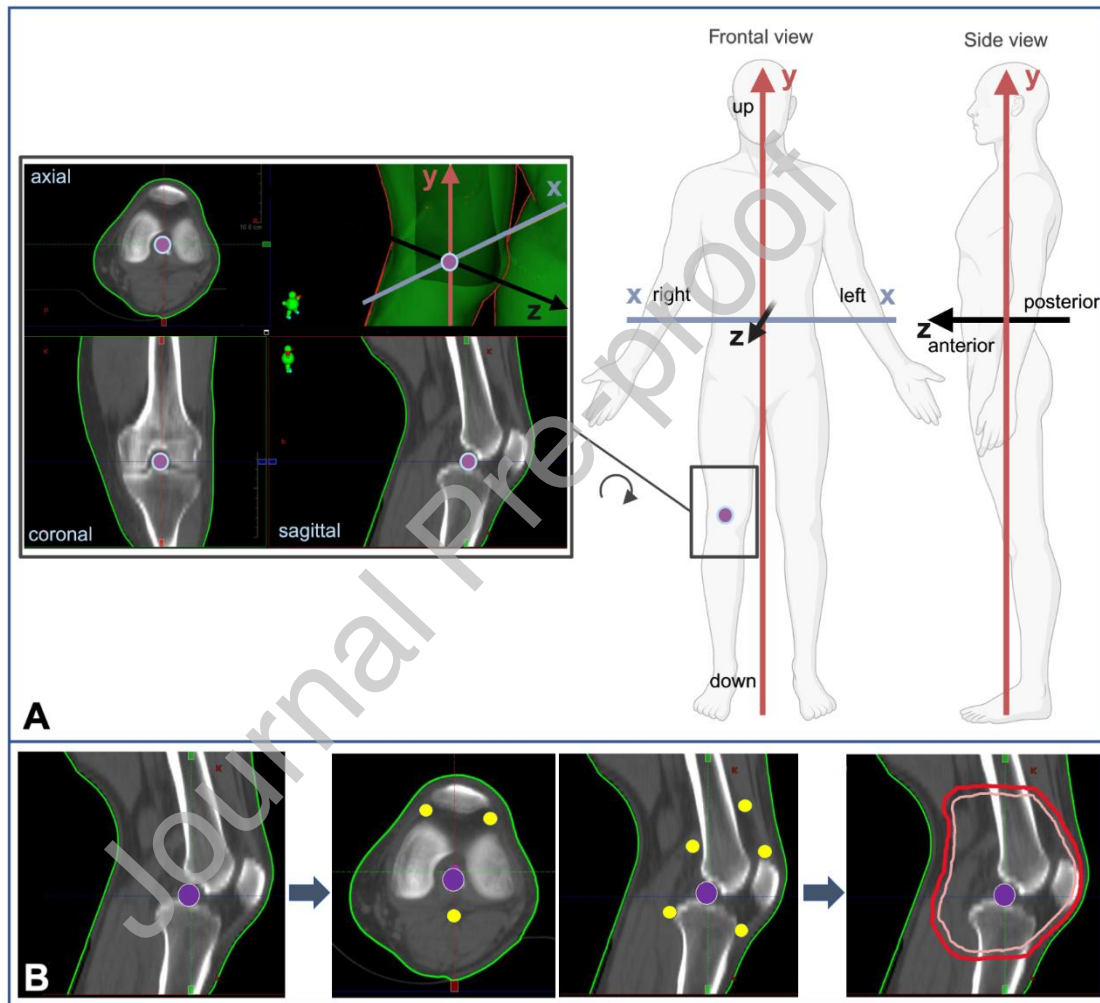


Figure 1. Coordinate system and workflow for 3D target generation

(A) Cartesian coordinate framework: It is used to define 3D target volumes, illustrated for the knee. Isocenter localization and Cartesian axes are shown in three orthogonal planes. Panel A was created using BioRender.com.

(B) Capsule-based CTV generation:

- Starting from the isocenter, the joint capsule is identified on the sagittal plane and marked with reference points.
- The capsule course is inferred from hypodense structural inhomogeneities and, where available, supported by comparative imaging (e.g., MRI).
- The procedure is repeated across all axes to enable 3D reconstruction, which forms the basis of the CTV.
- The central slice containing the isocenter serves as the primary reference for planning.

CTV and PTV definition: Visualization of the isocenter (violet), CTV (pink), and PTV (red). Reference points and lines for the joint capsule (yellow). The PTV is generated by asymmetric expansion of the CTV to account for tissue boundaries (e.g., skin, muscle, bone). Color coding is standardized throughout the manuscript.

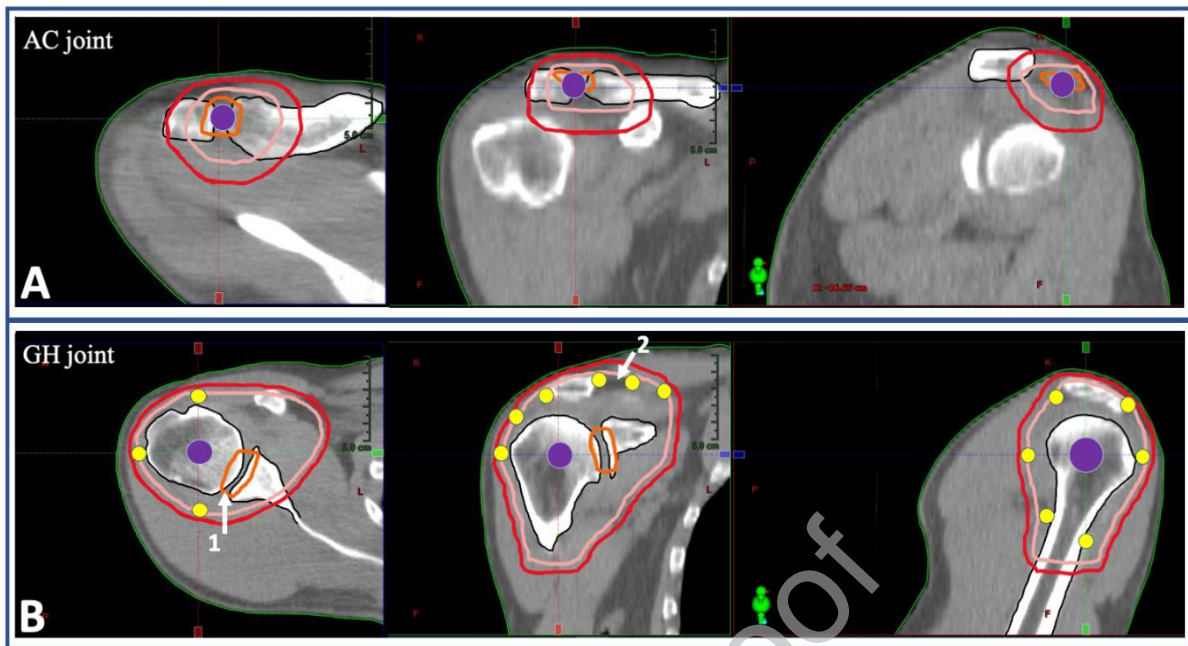


Figure 2. Representative 3D target definition for the shoulder joint (LCD-10-M 19.01)

Axial, coronal, and sagittal views (left to right) showing the defined target and planning volumes for the AC joint (A) and the GH joint (B). Illustration of target generation using reference points and the resulting CTV/PTV.

- The white arrow (1) marks the glenoid rim/joint line (isocenter landmark) and (2) the capsule course, defining joint boundaries and limiting unnecessary extension.
- Key bony landmarks relevant for orientation are contoured in both panels.

Supplementary Material: 3D renderings for both joints and the visualization of the CTV slice/layer reconstruction are provided in Supplementary Figure S2.

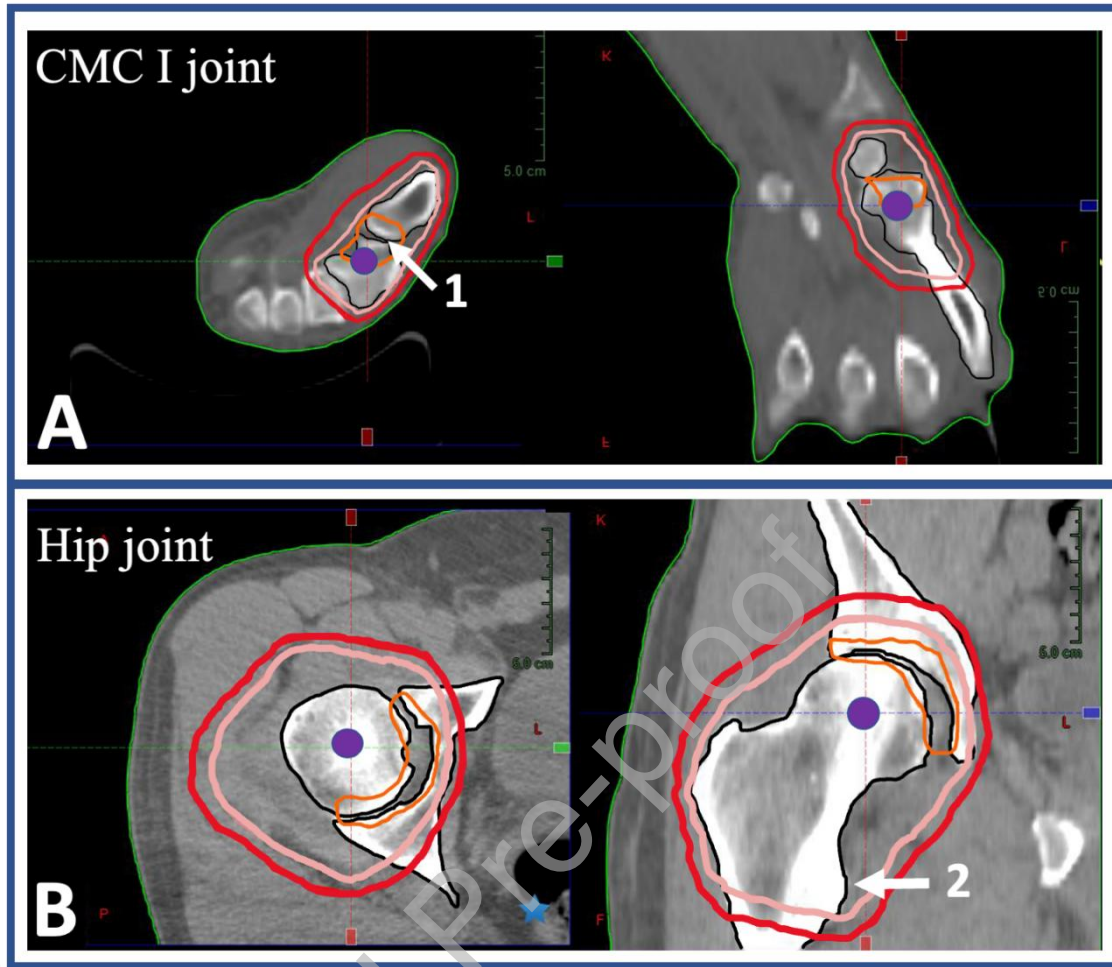


Figure 3. Target volume definitions for CMC I (ICD-10 M18.9) and Hip OA (ICD-10 M16.9)

(A) CMC I OA: Isocenter placed centrally within the joint space

- The white arrow (1) indicates the CMC I joint line (trapezium–first metacarpal), the key landmark of the GTV.
- The CTV encompasses the joint capsule and adjacent pain-relevant soft tissues, and the PTV applies a uniform 0.3 cm margin.

(B) Hip OA: Target volumes encompass the femoral head and extend to the lesser trochanter (white arrow 2), using the joint capsule boundaries as the primary anatomical guide and the lesser trochanter as the caudal limit.

Supplementary material: Target Volume definition of the wrist and full axial/coronal/sagittal views with 3D renderings are provided in Supplementary Figures S3 and S4.

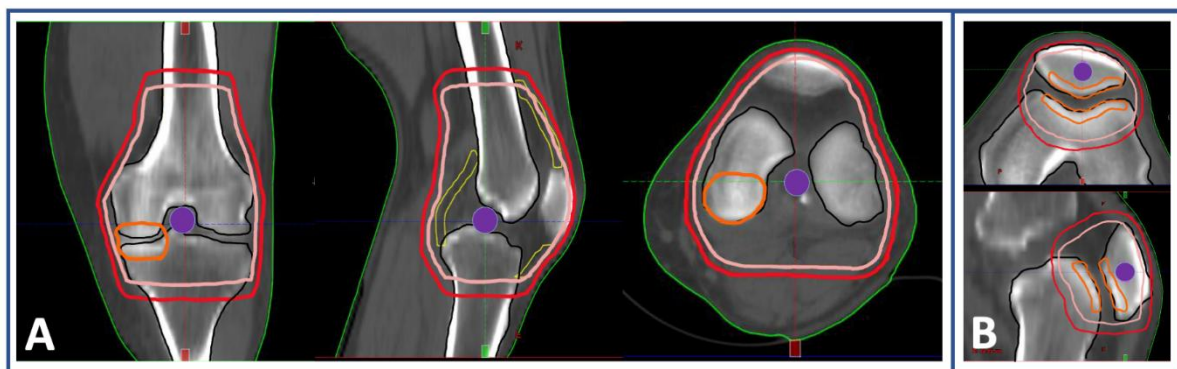


Figure 4. Knee OA (M17.9): Target volume definitions for tibiofemoral and retropatellar disease

- (A) Tibiofemoral OA: Isocenter placed centrally within the joint space; the GTV reflects the affected tibiofemoral compartment.
- Yellow markers indicate reference points along the joint capsule to guide capsule-based target definition.
 - The CTV includes the joint capsule and adjacent pain-relevant periarticular soft tissues; the PTV is generated by margin expansion and may be adjusted to patient-specific anatomy and visible pathology.
- (B) Retropatellar OA: Target volumes encompass the patellofemoral articulation and adjacent periarticular soft tissues involved in the degenerative process.
- Supplementary material:** An MRI example as an extension of diagnostic assessment is provided in Supplementary Figure S5. Full axial/coronal/sagittal views for the patellofemoral joint and the corresponding 3D panels are also shown in Supplementary Figure S5.

Table 1. Overview of studies addressing radiotherapy target definitions (field- or volume-based) for benign conditions

Summary of radiotherapy target definitions for benign conditions, outlining the target-definition concept and the main limitation of each approach. More study details are provided in Supplementary Table S3. Note: Target definition is used as a collective term, as several publications report 2D field-based setups rather than 3D volume-based targets (CTV/PTV).

Authors/Group, Journal	Indication/Joint	Target definition (field/volume; summary)	Key limitations
Alvarez and Montero et al. Br J Radiol 2021 (39)	Benign conditions (atlas; incl. skeletal/soft tissue)	CT atlas; bony landmarks (fixed PTV)	No GTV/CTV; fixed bony PTV ignores OA features/variability
Booth et al. Med Dosim. 2024 (24)	Shoulder OA	Bone-based PTV	Bony landmark fields may overcover; proximity to lung
German Cooperative Group on Radiotherapy for Benign Diseases (GCG-BD). S2e guideline of the German Society for Radiooncology (DEGRO) Version 3 2022 (38)	OA (unspecified joint)	Guideline; imaging-based PTV (3D planning)	Joint capsule/pathologies not explicitly integrated; no standardized 3D CTV
Hermann et al. Int J Radiat Oncol Biol Phys 2013 (44)	Calcaneodynia (non-OA)	Smaller fields achieved similar outcomes as larger fields	Field-size definitions were not specified
Kaltenborn et al. Strahlenther Onkol 2016 (27)	Thumb CMC OA	Field-size recommendation (>6×4 cm)	Field-size concept only; may include unrelated bone; no pathology adaptation
Koneru et al. Int J Radiat Oncol Biol Phys 2025 (16)	OA (multiple joints)	Retrospective practice fields (field-based: knee/hip)	Non-specific sample fields; anatomical joint course not respected

Seegenschmiedt et al. Radiotherapy for Non-Malignant Disorders. Book, Springer New York, 2008 (45)	OA (multiple joints)	Atlas with OA examples (field-based)	No explicit delineation rationale; PTV definition unclear
Woodley et al. J Bone Joint Surg Am 2008 (46)	Greater trochanteric bursitis (non-OA)	Field-size recommendation (7 cm craniocaudal margin)	Overlarge PTV; key soft tissues omitted
Yu et al. Pract Radiat Oncol. 2025 (47)	OA (multiple joints)	Field-based example: joint space + 2–3 cm margin	No GTV/CTV; limited guidance on pathology-specific structures/indications