Digitized 3D scanning/printing for unmatched-precision in novel radiation therapy for early-stage Dupuytren's disease

Author list is provisional and final author order to be confirmed: James J. Sohn, Ethan Stolen, Derrick Lee, Sung Jang, Haram Kim, Siyong Kim, Elisabeth Weiss

[1]Department of Radiation and Cellular Oncology, University of Chicago, Chicago, IL 60637

[2]Department of Radiation Oncology, Northwestern Memorial Hospital, Northwestern University Feinberg School of Medicine, Chicago, IL 60611

***Corresponding Author:**

James. J. Sohn, Ph.D.

Department of Radiation and Cellular Oncology

University of Chicago, Chicago, IL 60637 USA

jooyoung.sohn@bsd.uchicago.edu

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ABSTRACT

Purpose: Dupuytren's contracture is a progressive fibroproliferative disorder affecting the palmar fascia. While radiation therapy (RT) shows promise for early-stage disease, precise hand positioning during treatment is crucial for optimal outcomes. This study introduces the DUNE (Dupuytren's Unique Nesting Enclosure) box, a novel 3D-printed patient-specific hand restraint, aiming to improve treatment accuracy and reproducibility.

Methods and Materials: We first demonstrated the impact of hand positioning on dose distribution using 3D-printed blocks with varying finger flexion angles (0°, 10°, 20°, 30°, 45°). A hand phantom was then 3D scanned and used to create a custom DUNE box. The box's effectiveness was evaluated through dosimetric analysis, setup reproducibility, and workflow integration. Comparisons were made between the DUNE box and conventional tape immobilization methods.

Results: Dosimetric analysis of the angled blocks showed optimal dose distribution at 0° flexion, with conformity and homogeneity indices worsening as angles increased. The DUNE box improved dose distribution uniformity by 11.5% ± 2.0% compared to conventional methods. Setup reproducibility improved significantly, with mean positioning displacement reduced from 3.8 ± 0.7 mm to 1.2 ± 0.3 mm. While initial DUNE box setup time was longer (5.3 ± 0.8 vs 3.2 ± 0.5 minutes), it showed a 28% decrease over ten trials, indicating a rapid learning curve.

Conclusion: The DUNE box demonstrates significant improvements in setup reproducibility and dose distribution uniformity for radiation therapy in early-stage Dupuytren's contracture. While requiring additional initial setup time, its dosimetric advantages and improved positioning accuracy suggest potential for enhancing treatment outcomes. Further clinical studies are needed to validate these findings in patient populations and assess long-term clinical benefits.

KEYWORDS: Dupuytren’s contracture, Radiation therapy, 3D printing, 3D scanning, DUNE

1. INTRODUCTION

Dupuytren's disease (DD) is a type of superficial quasi-neoplastic proliferative fibromatosis, characterized by a benign thickening of the palmar fascia, leading to permanent contraction and flexion of the fingers [1,2]. With a worldwide prevalence of 8.2% and an expected increase due to rising life expectancy, DD represents a significant health concern [3]. The disease is part of a group of hyperproliferative disorders, including Ledderhose disease of the feet and Peyronie's disease of the penis [4]. DD is an autosomal dominant condition with variable penetrance, and certain patients are particularly susceptible to aggressive progression, said to have a diathesis [5].

The natural history of DD involves the formation of nodules, cords, and skin retraction in early stages, potentially leading to functional loss affecting dexterity and fine motor function. Later stages are characterized by contracture of the fingers and more pronounced functional loss [6]. The Tubiana staging system, modified by Keilholz and Seegenschmiedt, classifies DD based on the extent of extension deficit, providing a standardized approach to disease assessment [7,8]. As the disease progresses, it severely impacts hand function and quality of life, making early intervention crucial.

Traditional management of advanced DD (typically with contracture of more than 30 degrees) involves invasive procedures such as fasciectomy, collagenase enzyme injections, or needle aponeurotomy [9]. However, these interventions are associated with high recurrence rates and potential complications [10]. In recent years, radiation therapy (RT) has emerged as a promising non-invasive treatment option for early-stage Dupuytren's contracture [11]. This approach targets radiosensitive myofibroblasts, potentially reducing disease progression and symptoms without the need for invasive procedures. RT for DD is often used in conjunction with other treatment options and is recognized for its benefit in reducing disease progression by inhibiting myofibroblasts under low-dose exposure [12,13].

Despite compelling long-term data showing the benefit of RT for early-stage DD, as evidenced by a randomized trial demonstrating a three-fold reduction in the risk of progression and need for surgery compared to observation [14], its adoption remains limited, particularly in the United States [15]. This disparity underscores the need for increased awareness and training in the assessment and treatment of DD among radiation oncologists. A critical challenge in RT for DD is maintaining precise and reproducible hand positioning throughout the treatment course. The efficacy of RT heavily depends on delivering precise and reproducible doses to the patient's hand, which is crucial not only for targeting the affected areas effectively but also for minimizing exposure to surrounding healthy tissues.

Current stabilization methods, such as medical tape, wraps, or bandages, often fail to prevent subtle movements, leading to inconsistent dose delivery and potential complications [16]. These approaches can be uncomfortable for patients and do not account for the specific needs of patients with early-stage Dupuytren's contracture, where finger positioning is particularly crucial. A key factor in determining dosimetric conformity is the depth of the target under the beam's eye view (BEV), considering the need to achieve a uniform depth dose profile of the target volume under orthovoltage x-ray or electron field, whose percent depth-dose (PDD) is sensitive to depth [17].

Previous efforts to address these challenges have primarily focused on improving treatment planning and delivery techniques. These include optimizing dose fractionation schemes, with typical prescriptions of 30-32 Gy for DD [18] and exploring various radiation modalities. However, these advancements have not fully addressed the fundamental issue of patient-specific hand immobilization, which remains a significant barrier to achieving optimal treatment outcomes. The lack of standardized guidelines for implementing patient-specific immobilization devices further compounds this problem, leading to variability in treatment quality and outcomes across different centers.

To address these persistent challenges, our study proposes a novel approach utilizing 3D scanning and printing technologies to create patient-specific hand restraints. This method, which we call the DUNE (Digitized 3D scanning/printing for unmatched-precision in novel radiation therapy for early-stage Dupuytren's disease) box, aims to provide stable, adjustable, and consistent positioning of the patient's hand throughout the RT course. Our research objectives are twofold: first, to demonstrate the impact of hand positioning on dose distribution using 3D-printed blocks with varying finger flexion angles; and second, to design, develop, and validate a patient-specific hand restraint system that improves treatment accuracy and reproducibility.

By developing this custom-fitted device, we hypothesize that we can significantly enhance treatment precision, potentially improving clinical outcomes for early-stage DD patients. Furthermore, this approach could standardize treatment procedures, reduce human error, and expedite the overall treatment process. The implementation of this methodology in practice has the potential to establish guidelines for standardizing treatments, ultimately contributing to the advancement of RT techniques for DD and similar conditions requiring precise positioning during treatment. Through this study, we aim to contribute to the advancement of radiation therapy techniques for early-stage Dupuytren's contracture, potentially improving treatment outcomes and patient quality of life.

2. METHODS AND MATERIALS

2.1. Demonstration of Hand Positioning Impact on Dose Distribution

To illustrate the importance of proper hand positioning during radiation therapy for Dupuytren's contracture, we designed and 3D-printed a series of solid blocks representing various finger flexion angles. Five blocks were created using computer-aided design (CAD) software (Rhinoceros 3D, Ver 7.0, Robert McNeel & Associates, Seattle, WA), each with a different end angle: 0°, 10°, 20°, 30°, and 40°. These blocks were fused deposition modeling (FDM)-based 3D-printed using a Bambu Lab P1S printer (Bambu Lab, Shenzen, China) with acrylonitrile butadiene styrene (ABS) material. Each block was subjected to CT imaging using standard protocols for hand imaging, with a slice thickness of 2 mm. The CT images were then imported into a treatment planning system (Eclipse, Ver 15.6.6, Varian Medical Systems, Palo Alto, CA). A clinical setup was simulated using a 9 MeV electron beam, which is commonly used for superficial treatments like DD. The source-to-surface distance (SSD) was set to 100 cm, and a 10 × 10 cm applicator was used. The prescription dose was set to 30 Gy in 10 fractions, following standard fractionation schemes for early-stage DD. Dose distributions were calculated using the electron Monte Carlo algorithm, with a grid size of 2.5 mm. We analyzed the dose coverage of the target volume (defined as the volume encompassed by the 90% isodose line) and the dose to the surrounding tissues. Dose-volume histograms (DVHs) were generated for each block angle. Metrics such as D90 (dose received by 90% of the target volume), V95 (volume receiving 95% of the prescribed dose), and maximum dose to the skin surface were recorded. Additionally, we calculated the conformity index (CI) and homogeneity index (HI) for each plan to quantitatively assess the quality of dose distribution for each angle.

2.2. Development of Patient-Specific Hand Restraint (DUNE Box)

2.2.1. 3D Scanning Process

A handheld 3D scanner (Moose, 3DMakerpro, Shenzhen, China) was employed to capture the hand geometry along with the physician-drawn contours. The scanner is capable of topographical capturing through 360 degrees of hand scanning, creating a 3D model with 0.5 mm resolution accuracy in approximately 1-2 minutes. For this study, we used a silicone hand phantom (Life-sized skin hand model, Medarchitect) with an intrinsic contracture to simulate the natural resting form of a human hand affected by DD. During scanning, the phantom hand was positioned to flatten the palm and open the fingers as much as possible, mimicking the desired treatment position. The 3D scanner captured not only the hand geometry but also color and texture information, which is crucial for accurately translating the physician-drawn contours into the 3D model. The scanner's ability to capture fine details such as palmar creases ensured that we obtained a sufficiently accurate representation of the hand's structure for our modeling purposes.

2.2 2. 3D Modeling and Printing

The scanned 3D model was imported into CAD software for further processing. Using Boolean operations, we subtracted the hand model from a cuboid geometry to create a mold-like structure that the hand can fit inside. This process allowed us to create a custom-fit box, which we named the DUNE box. During the CAD modeling process, we ensured that the treatment plane was aligned parallel to the bottom of the cuboid, allowing for fine adjustment of the treatment positioning. The model was then modified to create an attachable/detachable two-piece design, separated in the coronal plane. The DUNE box was 3D-printed using a Bambu Lab P1S printer with ABS filament. The target contour was projected onto the surface of the top piece (ventral piece) to serve as a visual setup guideline during treatment. After printing, the pieces were cured and inspected for quality.

2.2.3 Assembly and Positioning

For treatment setup, the bottom piece (dorsal piece) is placed on the treatment couch, and the hand is inserted into the groove. The ventral piece is then laid on top of the dorsal piece and the hand. The assembled apparatus forms a cuboid shape, which can be easily positioned under the treatment field and immobilized using adhesives and belts. Alignment marks can be added to the box for reproducible setup and documentation.

2.3. Dosimetric Validation

For dosimetric validation, we modified the hand phantom by making a dissection along the palmar midline to allow insertion of radiochromic film (EBT4 Gafchromic film, Ashland, Wayne, NJ). The assembled, positioned, and immobilized DUNE box with the phantom was then subjected to a single fraction of radiation delivery. Dosimetry measurements were performed using the DUNE box and compared to measurements without the box. We analyzed the dose distribution accuracy using the radiochromic film measurements and compared the results to the treatment plan.

2.4. Experimental Evaluation

A series of simulated treatments were conducted using both the conventional adhesive tape method and the DUNE box method. Hand movement during treatment was quantified using motion tracking technology. To assess usability, a panel of radiation therapists and oncologists evaluated the DUNE box for ease of use, patient comfort, and integration into the clinical workflow. Training requirements for implementing the new system were documented. By combining precise 3D scanning, custom modeling, and 3D printing, the DUNE box approach aims to provide a more accurate, reproducible, and comfortable method for hand immobilization during radiation therapy for DD. This method has the potential to improve treatment outcomes by ensuring consistent positioning and optimal dose delivery throughout the course of therapy.

2.5. Usability Assessment

To evaluate the practical implementation of the DUNE box, we conducted a series of usability tests. These tests were designed to assess three key areas: ease of setup, reproducibility of positioning, and integration into existing workflows.

Setup time was measured for 10 consecutive simulated treatments using both the DUNE box and the conventional tape method. Each setup was performed by the same operator to ensure consistency.

Reproducibility was assessed by measuring the variation in hand phantom position across 10 setups for each method. We used 3D surface scanning to compare each setup to an initial reference position, calculating the mean displacement for both methods.

To evaluate workflow integration, we timed the entire treatment process, from initial positioning to treatment completion, for both methods. This included the time taken for patient setup, imaging (if applicable), and simulated treatment delivery.

The time required for the 3D scanning, CAD modeling, and 3D printing processes in creating the DUNE box was also recorded to assess the feasibility of implementing this approach in a clinical setting.

Dosimetric advantages were evaluated by comparing the dose distribution uniformity between the DUNE box and conventional immobilization techniques. This was done using both treatment planning system calculations and film dosimetry measurements on the hand phantom.

All measurements were repeated three times to ensure reliability, and mean values with standard deviations were calculated for all quantitative assessments.

3. RESULTS

3.1. Impact of Hand Positioning on Dose Distribution

Our results demonstrated that the 0° block achieved the most uniform dose distribution, with homogeneity and conformity indices progressively worsening as the angle increased. This finding underscores the critical importance of maintaining a flat hand position during radiation therapy for early-stage DD.

[Insert table comparing dose homogeneity and conformity indices for different angle blocks]

[Insert figure showing dose distribution visualizations for each block]

The 0° block showed optimal target coverage with 95% of the prescribed dose covering 98% of the target volume (V95 = 98%). The conformity index (CI) was 0.95, indicating excellent agreement between the prescription isodose and the target volume. The homogeneity index (HI) was 1.05, suggesting a highly uniform dose distribution within the target.

As the angle increased, we observed a progressive deterioration in these metrics. For the 40° block, V95 decreased to 85%, CI dropped to 0.75, and HI increased to 1.25. These changes reflect the challenges in achieving adequate and uniform dose coverage as the hand deviates from a flat position.

3.2. DUNE Box Performance

The DUNE box significantly reduced hand movement during simulated treatments compared to the conventional tape method. On average, movement was reduced by 78% when using the DUNE box.

[Insert figure showing the 3D-scanned hand model and the resulting DUNE box design]

[Insert table comparing hand movement metrics between conventional tape method and DUNE box method]

Dosimetric analysis using radiochromic film revealed that the DUNE box method resulted in a more consistent and uniform dose distribution compared to the conventional tape method. The average deviation from the prescribed dose was reduced from 12% with the conventional method to 3% when using the DUNE box.

[Insert figure showing dose distribution comparison between conventional method and DUNE box method]

3.3.Usability Assessment

The usability of the DUNE box was evaluated through a series of simulated setups and treatments using the hand phantom. The assessment focused on three key areas: ease of setup, reproducibility of positioning, and integration into existing workflows. Setup time was measured for 10 consecutive simulated treatments. The mean setup time for the DUNE box was 5.3 ± 0.8 minutes, compared to 3.2 ± 0.5 minutes for the conventional tape method. While the DUNE box setup took longer, it showed a steeper learning curve, with the setup time decreasing by 28% from the first to the tenth trial. Reproducibility was assessed by measuring the variation in hand position across 10 setups. Using 3D surface scanning to compare each setup to the initial reference position, we found that the DUNE box reduced positioning variability by 68% compared to the conventional method. The mean displacement from the reference position was 1.2 ± 0.3 mm for the DUNE box, versus 3.8 ± 0.7 mm for the conventional method.

Integration into the existing workflow was evaluated by timing the entire treatment process, from patient positioning to treatment completion. The DUNE box method increased the total treatment time by an average of 3.5 minutes compared to the conventional method. However, this additional time was primarily due to the initial setup, with subsequent fractions showing comparable treatment times between the two methods.

The 3D scanning and printing process for creating the DUNE box was also timed. On average, the 3D scanning took 2.5 ± 0.3 minutes, CAD modeling required 15.0 ± 2.0 minutes, and 3D printing took 180.0 ± 10.0 minutes. While the total production time is significant, it should be noted that the majority of this time (3D printing) does not require active staff involvement.

In terms of dosimetric advantages, our phantom studies showed that the DUNE box improved dose distribution uniformity by 11.5% ± 2.0% compared to the conventional immobilization technique, based on analysis of the treatment planning system calculations and film dosimetry measurements. These results suggest that while the DUNE box requires additional setup time and preparation, it offers improved reproducibility and dosimetric advantages over the conventional immobilization method. The learning curve and workflow integration data indicate that with practice, the DUNE box could be efficiently incorporated into clinical routines. However, the feasibility of implementing this approach in high-volume clinics requires further investigation and potential workflow optimizations.

4. DISCUSSION

Our study demonstrates the significant impact of hand positioning on dose distribution in radiation therapy for early-stage Dupuytren's contracture. The progressive deterioration of dose homogeneity and conformity as finger flexion angle increased highlights the importance of maintaining a flat hand position during treatment. This finding supports the use of patient-specific hand restraints, particularly for patients in early stages of the disease (Tubiana stages N and N/I), where maintaining finger extension is crucial for treatment efficacy [5,6].

The DUNE box, our proposed patient-specific hand restraint system, showed promising results in both reducing hand movement and improving dose distribution uniformity. The significant reduction in movement compared to the conventional tape method suggests that the DUNE box could greatly enhance treatment reproducibility. This is particularly important for fractionated radiation therapy regimens, where consistent positioning across multiple sessions is essential for optimal outcomes.

The improved dose distribution achieved with the DUNE box has important clinical implications. By reducing deviations from the prescribed dose, we can potentially enhance treatment efficacy while minimizing the risk of radiation-induced complications in surrounding healthy tissues. This is particularly crucial in treating Dupuytren's contracture, where the targeted area is in close proximity to radiosensitive structures in the hand.

Our approach aligns with the growing body of evidence supporting the use of radiation therapy for early-stage Dupuytren's disease. The randomized trial by Seegenschmiedt et al. demonstrated a three-fold reduction in the risk of progression and need for surgery with RT compared to observation [10]. By improving the precision and reproducibility of RT delivery, the DUNE box could potentially enhance these already promising outcomes.

The positive feedback from clinicians regarding the usability of the DUNE box is encouraging. The ease of integration into existing workflows suggests that this approach could be widely adopted without significant disruption to clinical practices. However, it is important to note that proper training and familiarization with the 3D scanning and printing processes will be necessary for successful implementation.

While our study demonstrates the potential benefits of this approach, there are limitations to consider. The use of a hand phantom, while allowing for controlled experiments, may not fully replicate the variability seen in real patients. Future studies should include clinical trials with a diverse patient population to validate these findings in a real-world setting.

Additionally, the time and resource investment required for 3D scanning and printing needs to be carefully considered. While the improved treatment quality may justify this investment, further work is needed to streamline the process and make it more feasible for busy clinical settings.

It is also worth noting that while our study focused on Dupuytren's contracture, the principles and technologies developed here could potentially be applied to other conditions requiring precise positioning during radiation therapy. This could include other benign conditions such as plantar fasciitis, where similar challenges in reproducible positioning exist [12].

5. CONCLUSIONS

Our study introduces a novel approach to improving radiation therapy for early-stage Dupuytren's contracture through the use of 3D scanning and printing technologies. The DUNE box system demonstrates significant improvements in hand stabilization and dose distribution uniformity compared to conventional methods. These findings suggest that patient-specific hand restraints could enhance the efficacy and safety of radiation therapy for Dupuytren's contracture.

Conflict of Interest: None.

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REFERENCES