Design of an Anthropomorphic 3D-Printed Left Breast Phantom for End-to-End Quality Assurance of Advanced Radiotherapy Techniques In Small Island Developing States

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MEDICAL PHYSICS COMMUNITY INSPIRATION INNOVATION IMPACT
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WHY create a left breast phantom?

1. Clinical significance for phantom creation

- **HIGH** incidence- 2.3M cases, 670K deaths; >75% mortality in LMICs
- Left sided breast and regional lymph node irradiation - HIGH **variability** (3DCRT, IMRT, VMAT, Knowledge-based etc.)
- Treatment prescriptions have evolved in breast radiotherapy:
  - Sequential → Simultaneous Integrated Boost,
  - Dose escalation : 2 Gy/F → 5.2 Gy/F
- Previous IMRT audits discovered errors > 20% between their TPS calculation and their actual output factors [1]
- Dosimetry impact studies of residual errors for Left breast RT showed **REDUCED target coverage, INCREASED OAR toxicity [2,3]**
- Residual errors significantly affect dose distribution despite CBCT-based translational correction. [3]

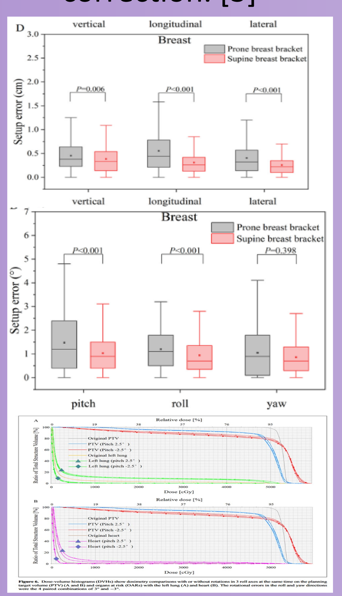


Figure 1: Dosimetric impact of residual errors illustrated by J Appl Clin Med Phys. 2025;26(7).

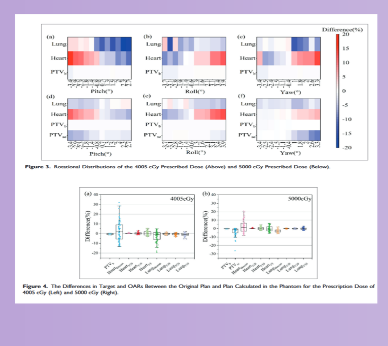


Figure 2: Dosimetric impact of residual errors illustrated by Wang et al. Sage Journal, Vol 24:1-8, 2025

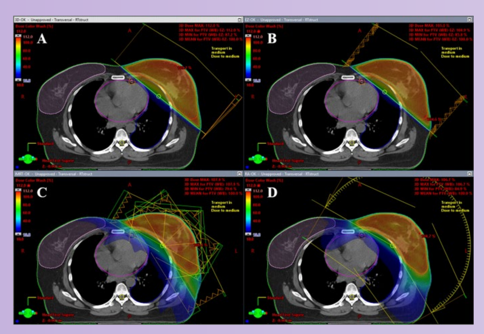


Figure 3: Variations in breast treatment planning techniques illustrated by Strahlentherapie und Onkologie, Springer Nature Link, Vol 193: 800-811, 2017

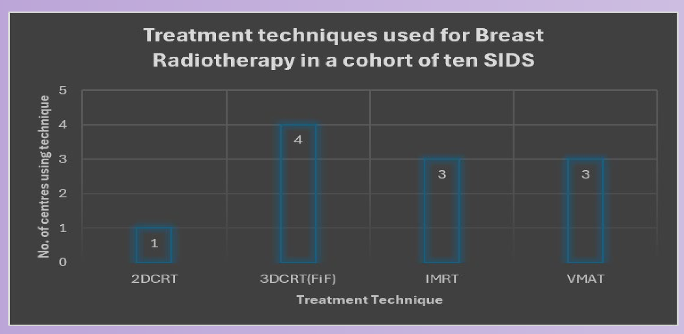


Chart 1: Bar graphs showing the variability in left breast and regional lymph node irradiation across ten SIDS radiotherapy facilities

2. Comparison of commercial-based phantoms

- **SMALL** Volume attachments (350-750cc)
- **Standard density** 50% glandular and 50% adipose
- **NO** direct Regional Lymph node assessment

Figure 4: CIRS IMRT Thorax Phantom with breast attachments

Figure 5: Alderson Radiation Therapy (ART) Phantom

Figures 6 and 7: CIRS Atom Phantom

Aims:

- Development of a **clinically significant** anthropomorphic phantom for end-to-end dosimetry audit to best **characterize** the radiotherapy implementation in SIDS
- Anthropomorphic breast phantoms will allow review of new techniques (e.g. FAST FORWARD Boost), TPS beam models, and commissioning of new radiotherapy machines

HOW? –Methodology for phantom creation

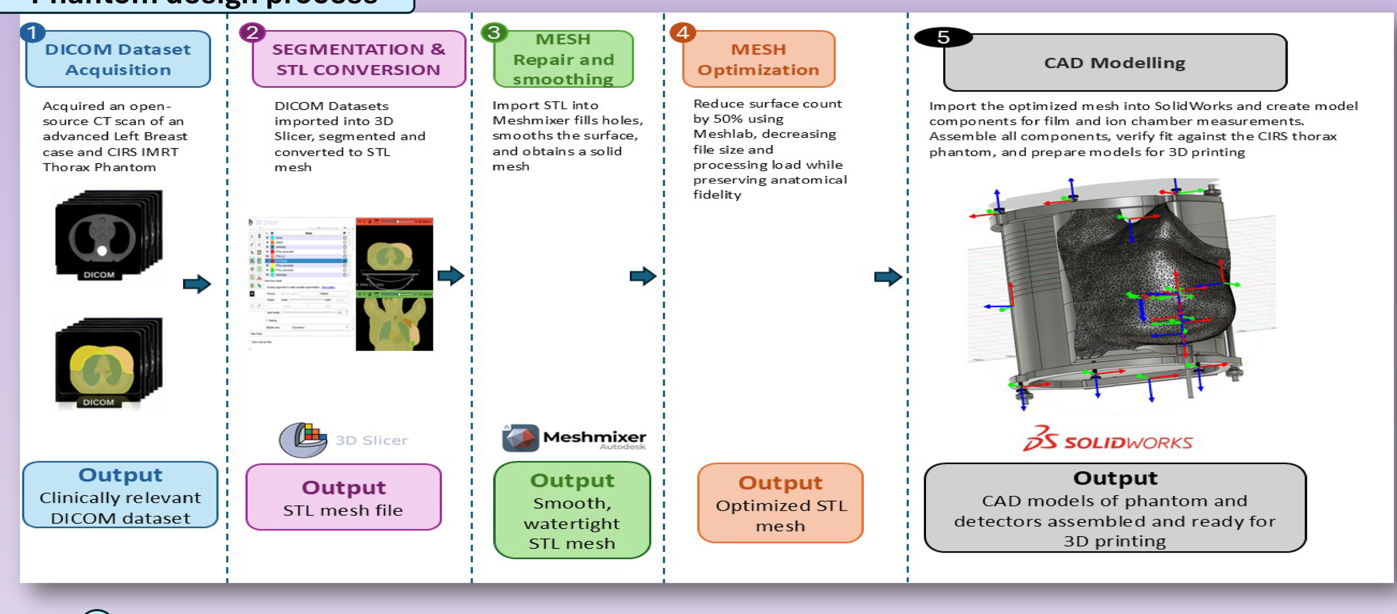
1 DICOM Selection

- 5-year retrospective cohort analysis of Left Breast Ca in SIDS
- Literature Review of Left Breast Ca clinical characteristics
- Clinically relevant target and structure geometries
- → Open source DICOM dataset selection

2 Material Selection

- Literature Review of relevant CT number for large breast morphologies
- Literature Review of anthropomorphic phantom development in radiotherapy
- → Characterization of six 3D printed thermoplastics
- → Material selection for 3D printing

3 Phantom design process



4 Phantom validation

- Visual inspection → CT Scan → RT Plan Creation → RT Plan Delivery and analysis
- CT Scan → HU analysis; Air Gap Analysis
- Repeated for three (3) CIRS Thorax phantoms

WHAT are the findings? –Results

1 DICOM Selection

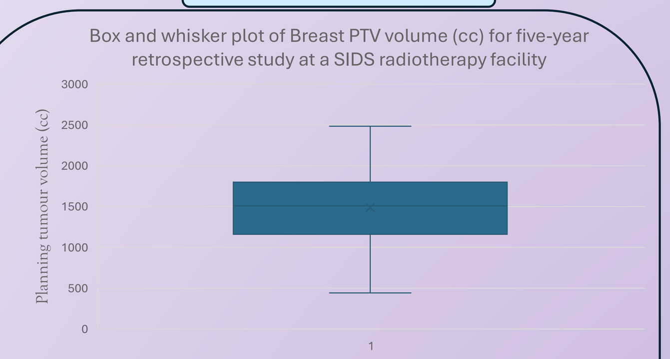
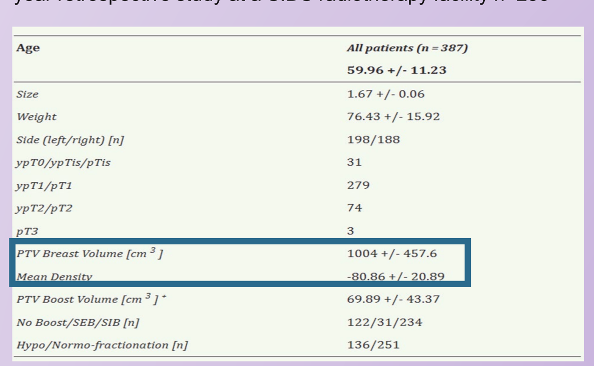


Chart 2: Box and whisker plot of Breast PTV volume (cc) for five-year retrospective study at a SIDS radiotherapy facility n=256



Age	All patients (n = 387)
	59.96 +/- 11.23
Size	1.67 +/- 0.06
Weight	76.43 +/- 15.92
Side (left/right) [n]	198/188
ypT0/ypTis/pTis	31
ypT1/pT1	279
ypT2/pT2	74
pT3	3
PTV Breast Volume [cm^3]	1004 +/- 457.6
Mean Density	-80.86 +/- 20.89
PTV Boost Volume [cm^3] +	69.89 +/- 43.37
No Boost/SEB/SIB [n]	122/31/234
Hypo/Normo-fractionation [n]	136/251

Figure 8: PTV Breast volume (cc) mean and mean density findings for study of n =387 reported by Sonnhoff et al. Radiation Oncology Vol 21:51, 2026

2 Material Selection

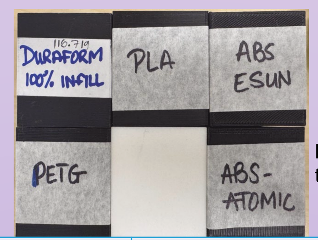


Figure 9: Six 3D printed thermoplastics at 100% infill

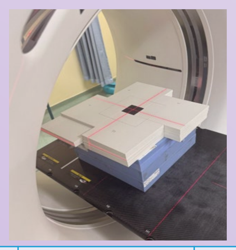


Figure 10: Jig for CT and dosimetry assessment of 3D printed cubes

Thermoplastic Material	Manufacturer	Elemental Composition	Mass density (vendor provided)	Mass density (measured)	CT Number (Mean HU [SD])	Relative electron density (theoretical)	Relative electron density (measured)	Type of 3D printing
Duraform PA	3D Systems	$[(CH_2)_{11}C(O)NH]_n$	1.00	0.936	-113.801 [14.061]	-	-	SLS- Selective Laser Sintering
PLA- Polyactic Acid	SUNLU	$(C_3H_4O_2)_n$	1.24	1.157	113.574 [19.063]	1.029 [0.972-1.143]	1.0889	FDM- Fused Deposition Modeling
PETG- Polyethylene Terephthalate Glycol	OVERTURE	$(C_{10}H_8O_4)_n$	1.27	1.212	93.866 [23.67]	1.07985 [1.0795-1.2700]	1.0939	
ABS- Acrylonitrile Butadiene Styrene	ATOMIC	$C_{15}H_{17}N$	1.04	0.986	-25.932 [9.685]	0.913 [0.862-1.014]	0.988	
	ESUN		1.06	1.012	-11.16 [12.997]	0.913 [0.862-1.014]	1.010	
	ARGYLE		1.05	0.798	-200 [35.792]	0.913 [0.862-1.014]	0.7997	

Table 1: Comparison of six 3D printed thermoplastics to determine best suit for left breast and regional lymph node phantom

3 Phantom design process

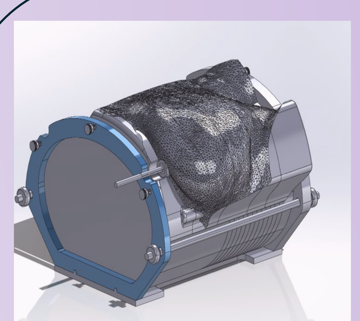


Figure 11: CAD Assembly of phantom on top of CIRS IMRT Thorax Phantom

Figure 12: CT Scan Setup of **BRENDA**- Breast and Regional Lymph Node End-to-End Dosimetry Assessor

Part Number	Print Time	Material used (g)
1	25 HR 41 MIN	760.23
2	27 HR 5 MIN	802.31
3	13 HR 45 MIN	402.76
4	21 HR 5 MIN	616.42
5	17 HR 15 MIN	501.23
Total	104 HR 51 min	3,082.95 (g)

Table 2: Print time and material used for 3D printed phantom

4 Phantom validation

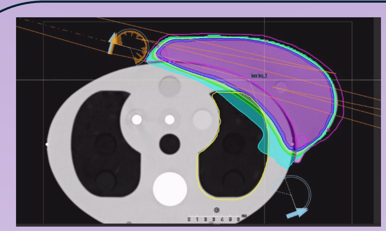
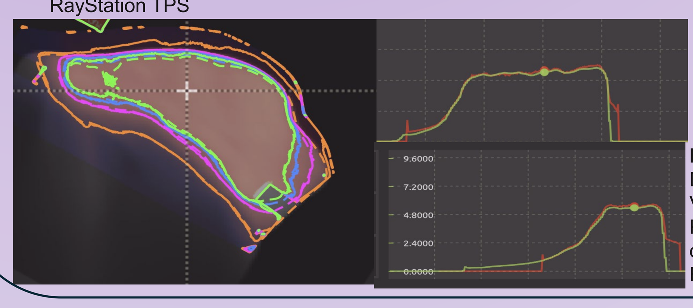


Figure 13: Phantom Validation VMAT Treatment Plan on RayStation TPS

Organ Assessed	Gamma passing rate (%) (3%,3mm, 10% threshold)	Gamma passing rate (%)(3%, 2mm, 10% threshold)
CTVn(L1-L3)	99.1	96.6
CTVp_breast	98.5	97
CTVp_tumourbed	98.8	98.1

Table 2: Gamma Passing rate (%) based on AAPM TG 218 protocol analyzed using film dosimetry and Radiochromic.com



Figures 14, 15 and 16: Film Dosimetry Analysis of Breast Volume showing Measured vs Planned Isodose Lines and doses- analyzed using Radiochromic.com

Discussion

- Patient population of SIDS often compounds obesity with advanced disease with average breast volumes of 1489 cc (SD 214cc) and average CT number of -87 HU, indicating a high presence of fat within breast tissue
- Traditional commercial phantoms do not represent these populations in target and structure geometry
- 3D printing has been shown to be robust enough for phantom manufacture in radiotherapy, and PLA provides a wide range for the construction of various normal tissues
- This work represents a clinically significant anthropomorphic left breast and regional lymph node phantom that fits snuggly (largest airgap < 3mm) over the CIRS IMRT Thorax Phantom and utilizes planes of reference for ion chamber and film dose correlation.
- for end-to-end dosimetry audits
- Good gamma analysis (minimum 96.6%) using film dosimetry and ion chamber results was achieved, verifying the feasibility of the detectors for use in this phantom
- The designed phantom can aid in the assessment of the implementation of breast radiotherapy in SIDs, including dose escalation (FAST FORWARD)
- This work also provides proof of concept for the modification of commercial phantoms using 3D printed parts

Conclusion

- Anthropomorphic phantom development utilizing a hybrid approach (3D printed part onto a commercial phantom) is feasible and produces clinically relevant structures for SIDS
- To our knowledge, this is the first clinically optimized left breast phantom that assesses four planning tumour volumes (Breast CTV, CTV_Tumour bed, Axillary Lymph Nodes (Levels 1-3), and Supraclavicular lymph nodes (Level 4) using both film and ion chamber
- PLA has been established as a good fit for 3D printed phantoms due to its wide HU range, manipulated by varying % infill
- This work can be further adopted by other centers of clinical trials for the testing of novel breast treatment deliveries e.g. ULTRA-FAST Trial

References

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