A Framework for Designing Glass Vessels Used in Water Calorimetry

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INTRODUCTION

- Water calorimeters determine absolute dose to water at a point by accurately measuring radiation induced temperature rise[1]
- To minimize the presence of impurities in water that can cause additional heat loss/gain, the point of measurement is surrounded with a glass vessel filled with pure water[2,3]
- The heat transfer correction (k_{ht}) accounts for additional heat loss/gain at the point of measurement due to heat transfer mechanisms such as conduction/convection
- The glass vessel also impacts k_{ht} because it heats up differently than the surrounding water given its much lower specific heat capacity relative to water
- k_{ht} is determined using Finite Element Method analysis by simulating the ideal case with no heat transfer effects occurring, and a realistic case with heat transfer effects occurring
- When performing water calorimetry with electron beams, sharp dose gradients can lead to complex temperature distributions within the vessel
- Parallel-plate vessels have been successfully used in photon and electron beams[4] (Figure 1)

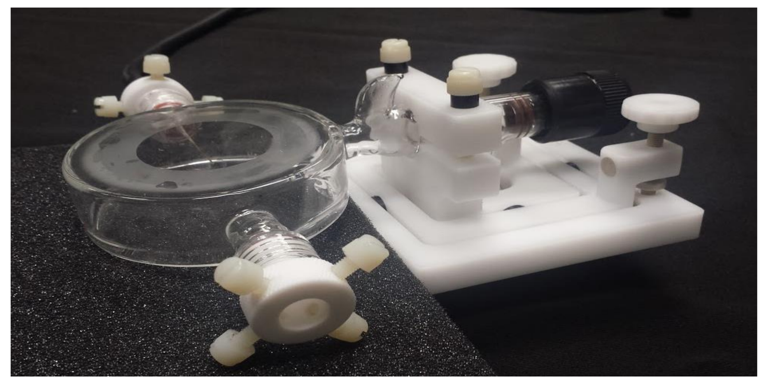

Figure 1 – Parallel-plate glass vessel

AIMS

- To develop a FEM framework that can be used to systemically guide the process of vessel design
- To apply the framework to parallel plate vessels that have been successfully used in electron beams

METHODS

- FEM software COMSOL Multiphysics v5.6a was used in this study
- The calorimeter vessel/thermistors were modeled using a 3D-quarter geometry (Figure 2) where the vessel was simulated inside a water phantom
- FEM studies were performed to evaluate the sensitivity of k_{ht} on different boundary conditions (fixed temperature/thermal insulation) and phantom x/y dimensions
- A framework was developed where in the first stage the effect of vessel radius and height on k_{ht} are independently analyzed
- In the second stage a parametric sweep studying k_{ht} for different combinations of vessel upstream/downstream thickness and vessel position is performed (Figure 3)
- The framework was applied to 6 MeV and 18 MeV beams. For all energies, the thermistors were placed at d_{ref} as outlined by AAPM's TG-51 and addendum[5,6]
- Optimal vessel parameters were obtained for both energies where an optimal vessel resulted in k_{ht} varying less than 0.1 % as a function of position

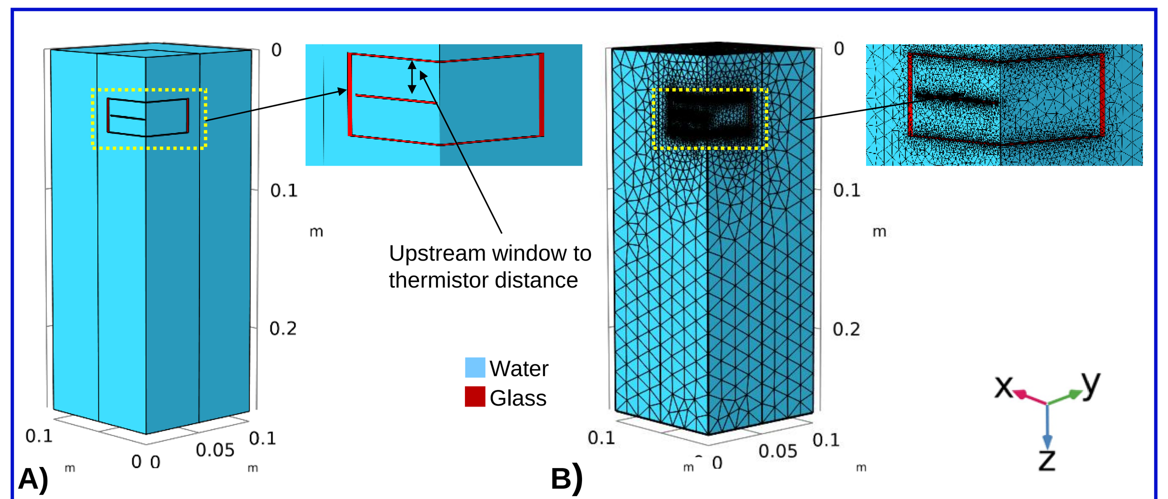

Figure 2 – The calorimeter was modeled in COMSOL using 3D-quarter geometry (A). The vessel and thermistor can be seen in yellow in the cut view. The actual point of measurement is at the very tip of the thermistor. The meshing used can be seen in (B).

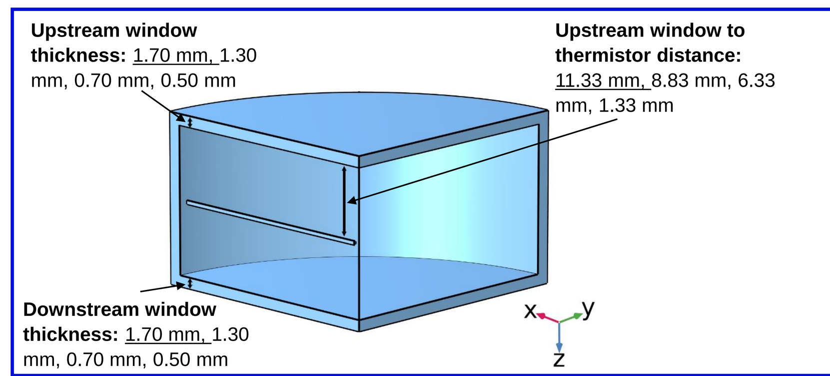

Figure 3 – Simulated vessel in 3D-quarter geometry used in FEM model with parameters varied during sweep. Underlined parameters are dimensions shown in the figure.

RESULTS

- FEM analysis showed a 0.1 % difference in k_{ht} between thermal insulation/fixed temperature boundary conditions
- k_{ht} varied by less than 0.01 % as x/y dimensions were decreased from 15 cm to 6 cm
- A phantom with x/y dimensions of 10 cm was used as it reduced computational time (due to fewer elements in the FEM Model)
- Walls of a water calorimeter are often held at 4 ℃, as such the fixed temperature boundary condition was applied

- Figure 4A and 4B display the effect of the radius and height of a parallel plate vessel on k_{ht} under 6 and 18 MeV electron beams
- k_{ht} stabilized when the radius and height were greater than 20 mm and 15 mm respectively
- The optimal radius and height for the parametric sweep were selected to be 39.50 mm and 22.66 mm

- Figure 5 shows the results obtained for the 18 Mev parametric sweeps
- k_{ht} varied by as much as 25 % as the vessel's upstream window approached the measurement point
- When d_{ref} was within 8 mm of the upstream window, the dimensions of the downstream window played no effect on k_{ht}
- However, when d_{ref} was more than 8 mm from the upstream window, variations in k_{ht} due to the downstream window became noticeable
- Similar trends were seen for the 6 MeV beam

- Five vessel parameter configurations for a 6 MeV beam and three for an 18 MeV beam resulted in k_{ht} varying by less than 0.1 % when d_{ref} was more than 8 mm away from the upstream window (Figure 5)
- One set of parameters (upstream thickness = 0.70 mm and downstream thickness = 0.50 mm) appeared in both energies and as such was taken as optimal

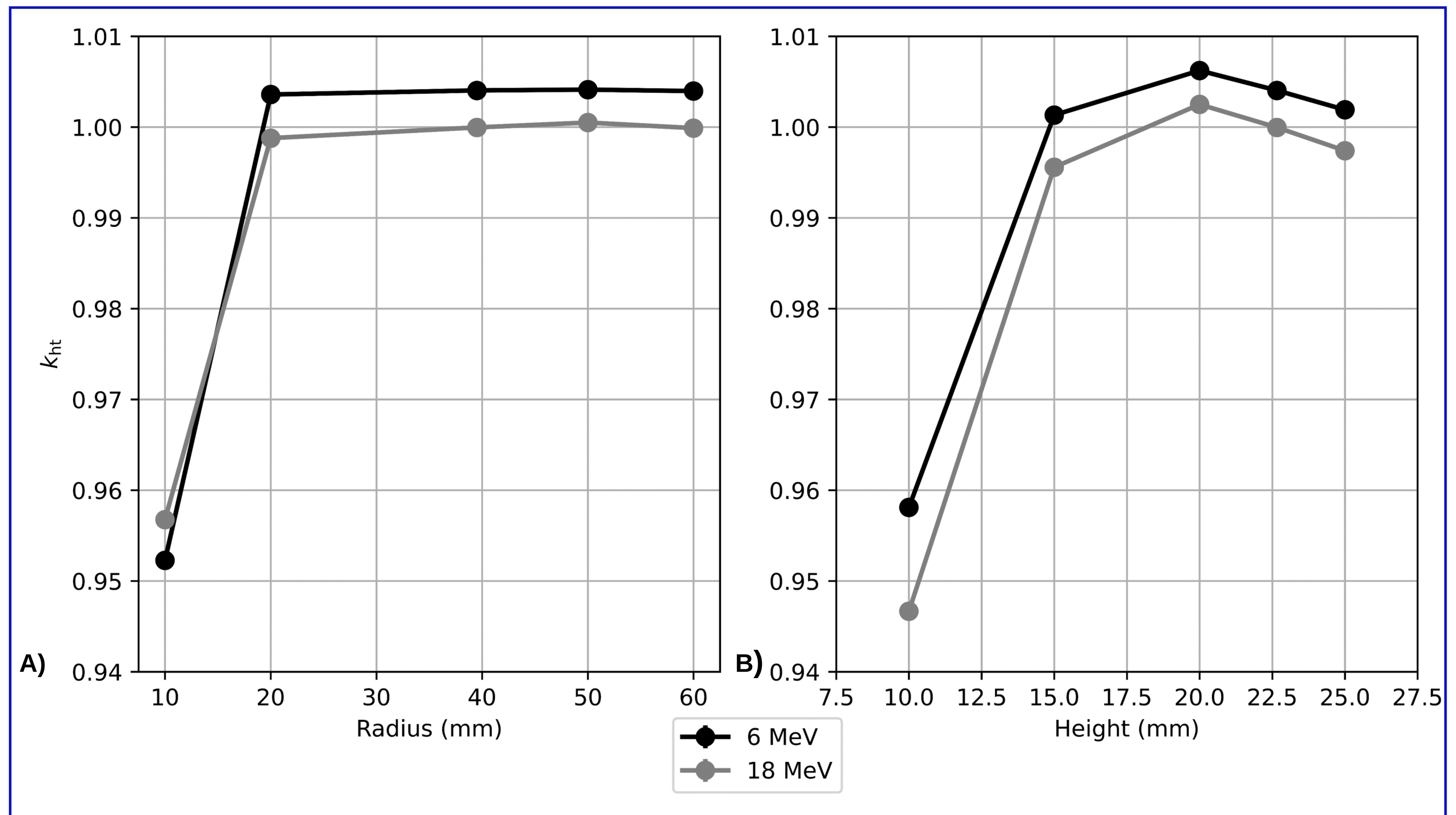

Figure 4 – k_{ht} as a function of vessel A) radius, and B) Height for 6 and 18 MeV electron beams

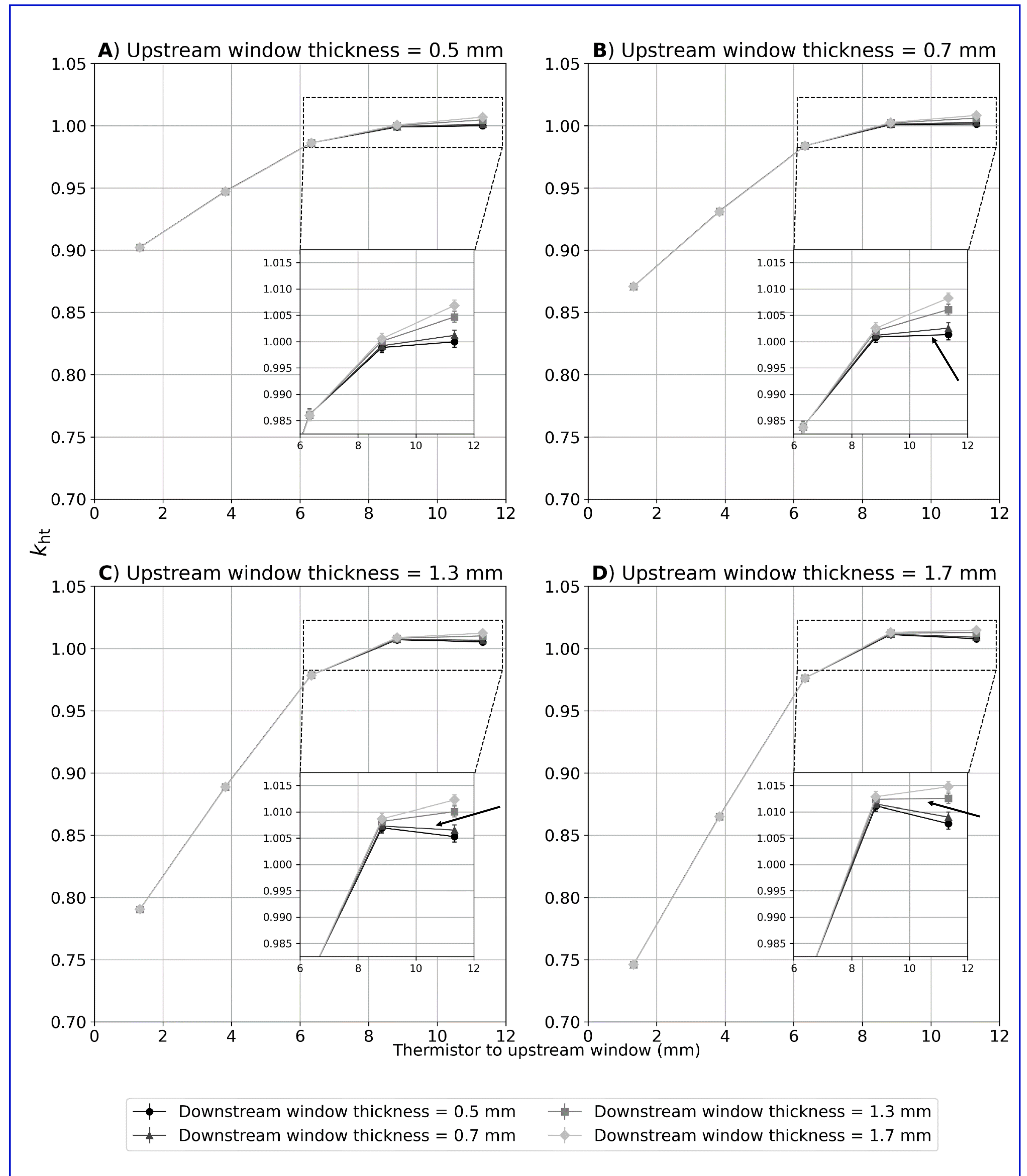

Figure 5 – k_{ht} for an 18 MeV electron beam with upstream window thickness A) 0.50 mm, B) 0.70 mm, C) 1.30 mm, D) 1.7 mm. The shape/shading represents the downstream window thickness. Arrows point to locations where k_{ht} changes by less than 0.1 % and as such are considered optimal

CONCLUSIONS

- A FEM framework was developed to aid in vessel design and applied to clinical electron beams
- A smaller model can be used to study k_{ht} leading to reduced computational time
- Our results showed that for electron beams a parallel plate vessel should have a radius and height greater than 20 mm and 15 mm respectively
- For 6 and 18 MeV beams, when d_{ref} was less than 8 mm away from the upstream window of the vessel k_{ht} deviated significantly as a function of position, this is minimized beyond 8 mm
- The ideal vessel for these beams had a radius of 39.50 mm, a height of 22.66 mm, an upstream thickness of 0.70 mm, and a downstream thickness of 0.50 mm.

- This study demonstrates that optimal vessel dimensions and designs that are different from traditional systems may be identified using our proposed FEM analysis framework
- Future work is focused on conducting FEM analysis for novel techniques such as ultra-high dose rate, and protons

REFERENCES

1. McEwen M. Primary standards of air kerma for 60Co and x-rays and absorbed dose in photon and electron beams. In: Rogers DWO, Cygler JE, eds. *Clinical Dosimetry Measurements in Radiotherapy*. Madison, WI: Medical Physics Publishing; 2009
2. Domen SR. A sealed water calorimeter for measuring absorbed dose. *J Res Natl Inst Stand Technol*. 1994;99(2):121. doi:10.6028/jres.099.012
3. Klassen N V., Ross CK. Water calorimetry: The heat defect. *J Res Natl Inst Stand Technol*. 1997;102(1):63-74. doi:10.6028/jres.102.006
4. Renaud J, Sarfehnia A, Marchant K, McEwen M, Ross C, Seuntjens J. Direct measurement of electron beam quality conversion factors using water calorimetry. Med Phys. 2015;42(11):6357-6368. doi:10.1118/1.4931970
5. Almond PR, Biggs PJ, Coursey BM, et al. AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams. *Med Phys*. 1999;26(9):1847-1870. doi:10.1118/1.598691
6. McEwen M, Dewerd L, Ibbott G, et al. Addendum to the AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon beams. *Med Phys*. 2014;41(4):1-20. doi:10.1118/1.4866223

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