The effect of spatiotemporal variations in thermal neutron transmission on Yb-169 source re-activation efficiency

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PURPOSE

Commercializing intensity modulated brachytherapy techniques based on partially-shielded intrauterine or interstitial applicators necessitates the cost-effective production of intermediate energy sources. ^{169}Yb is a promising but expensive isotope for this purpose, with 93 keV average γ-ray energy.

Re-activating a single ^{169}Yb source 10+ times in a nuclear reactor was theoretically shown to reduce cost by ~75% relative to conventional single-activation sources. Substantial spatiotemporal variation in isotopic source composition occurs between activations via ^{168}Yb burnup and ^{169}Yb decay, altering neutron transmission and cost per re-activation.

These effects are accounted for to maximize the efficiency of the ^{169}Yb re-activation process.

METHODS

A computational framework to model time-dependent neutron transport, isotope transmutation, and decay was developed.

Thermal neutron flux within each cylindrical sub-volume was calculated using ray-tracing through the spatiotemporal dependent isotopic composition throughout the source, accounting for thermal neutron attenuation along each ray.

Re-activation of a ^{169}Yb source constructed of 82%-enriched $^{168}Yb\text{-}Yb_2O_3$ was modeled, with active dimensions of 0.6 mm diameter, 10.5 mm length, a volume of 3 mm^3, and a density of 8.5 g/cm^3.

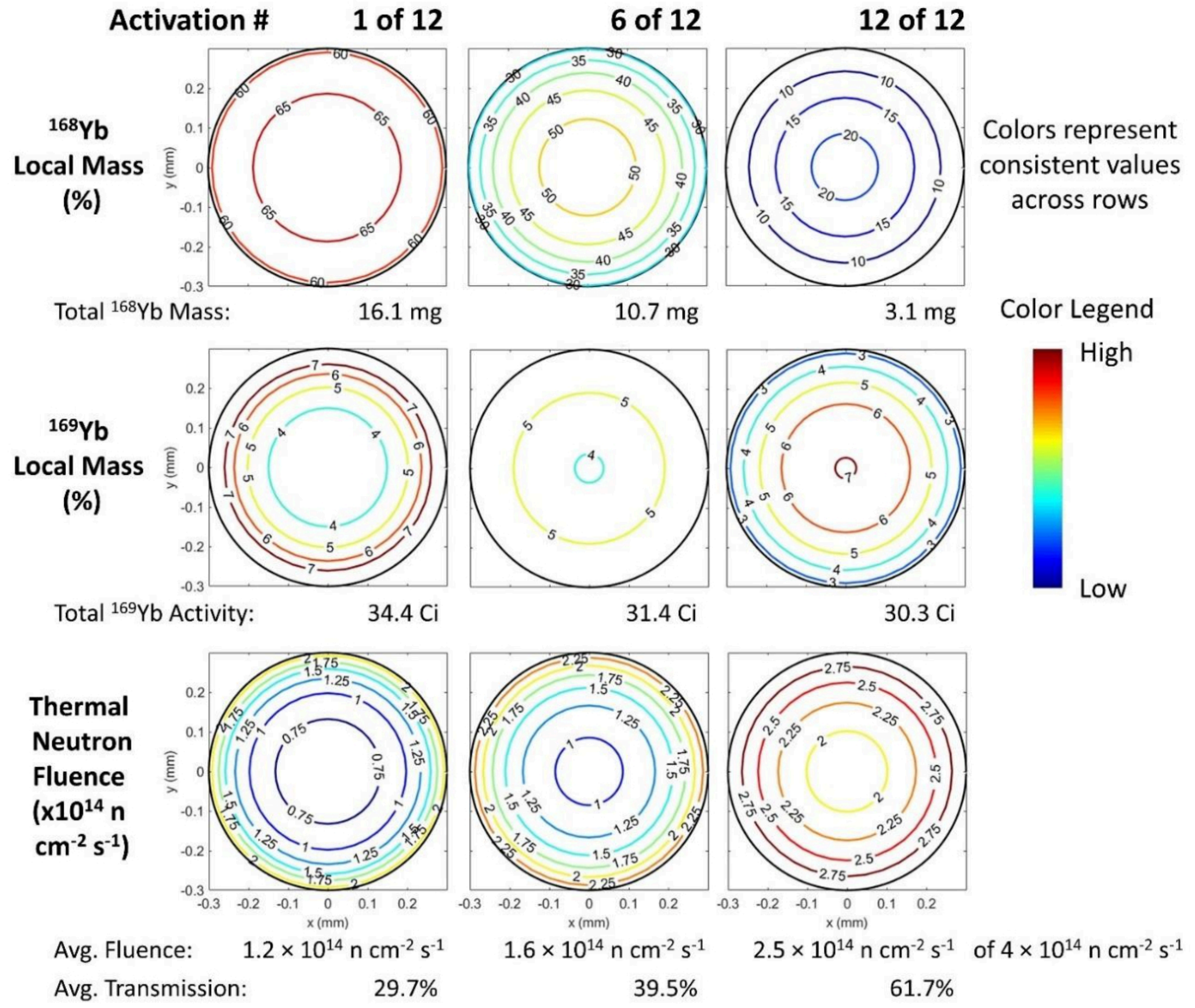
RESULTS

Cost has impeded the clinical implementation of ^{169}Yb. ^{169}Yb is generated by irradiating an expensive precursor material containing ^{168}Yb, such as 82% enriched $^{168}Yb\text{-}Yb_2O_3$ (~$692/mg, 25 mg needed per source), with thermal neutrons in a nuclear reactor. Re-activating the ^{169}Yb sources 10+ times could result in major cost savings (~75%) relative to conventional single-activation sources.

Re-activating sealed sources is not standard practice and successfully doing so accurately estimating the length of time to place the source into a thermal neutron flux for each re-activation.

The re-activation time is dependent upon the average thermal neutron fluence inside the source, and ^{168}Yb and ^{169}Yb have very high thermal neutron absorption cross sections, making the thermal neutron transmission in the source and therefore the neutron fluence time-dependent. 3-D spatiotemporal modeling of re-activated ^{169}Yb sources is unexplored but relevant when estimating the cost of the approach. We developed a novel computational framework to calculate the spatiotemporal dependence of isotopic composition that accounts for isotope transmutation, decay, and thermal neutron transmission over the entire live cycle of a ^{169}Yb source (10+ activations).

Axial cross sections of the 0.6 mm diameter, 10.5 mm long ^{169}Yb source are shown in Figure 1 at varying stages throughout the re-activation process. Twelve total re-activations were modeled. Average thermal neutron transmission throughout the active source more than doubled between the first activation and the eleventh (final) re-activation, increasing from 29.7% to 61.7%. The new model predicts a 32% reduction in the reactor-time needed per clinic-year of ^{169}Yb activity produced at a reactor flux of 4×10^{14} n cm^{-2}s^{-1} relative to a model that does not account for spatiotemporal changes in thermal neutron transmission.



Axial cross-sections through the geometric center of the 0.6 mm diameter × 10.5 mm long active ^{169}Yb source for 3 different activations (1, 6, and 12 of 12, by column) indicating (top row) ^{168}Yb and (middle row) ^{169}Yb distribution as percentages of local mass and (bottom row) thermal neutron fluence given a reactor fluence of 4 × 10^{14} n cm^{-2} s^{-1}. The ^{168}Yb distribution (top row) is most concentrated at the active source core throughout all activations, ^{169}Yb distribution (second row) is most concentrated at the active source edge for activation 1 of 12, relatively flat by activation 6 of 12, and concentrated at the core by activation 12 of 12.

CONCLUSIONS

Accounting for spatiotemporal changes in thermal neutron attenuation within a re-activatable ^{169}Yb source demonstrates a 32% reduction in reactor time per clinic-year needed to generate the ^{169}Yb sources.

This finding increases the feasibility of the ^{169}Yb approach to enabling intensity modulated brachytherapy approaches such as rotating shield brachytherapy or direction-modulated brachytherapy.

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Conflict of Interest: RTF is the President of pxAlpha, LLC, which is developing an RSBT delivery system.