Quantifying the Potential Benefit of Applying Remote Magnetic Navigation Systems (RMNS) to Abdominal SBRT

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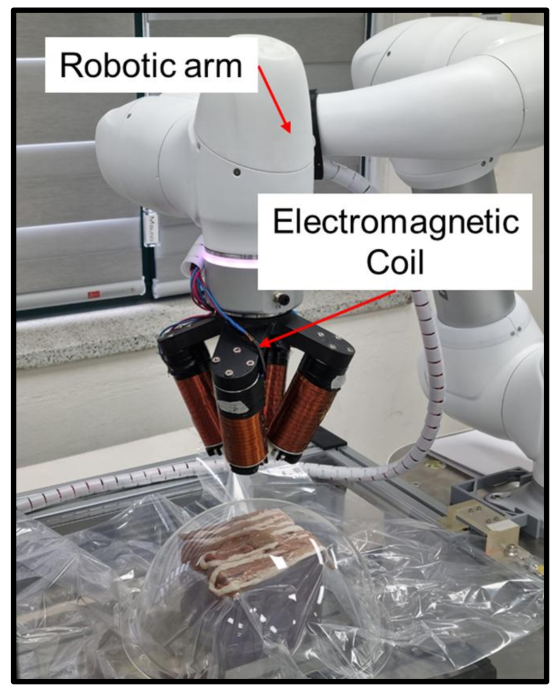
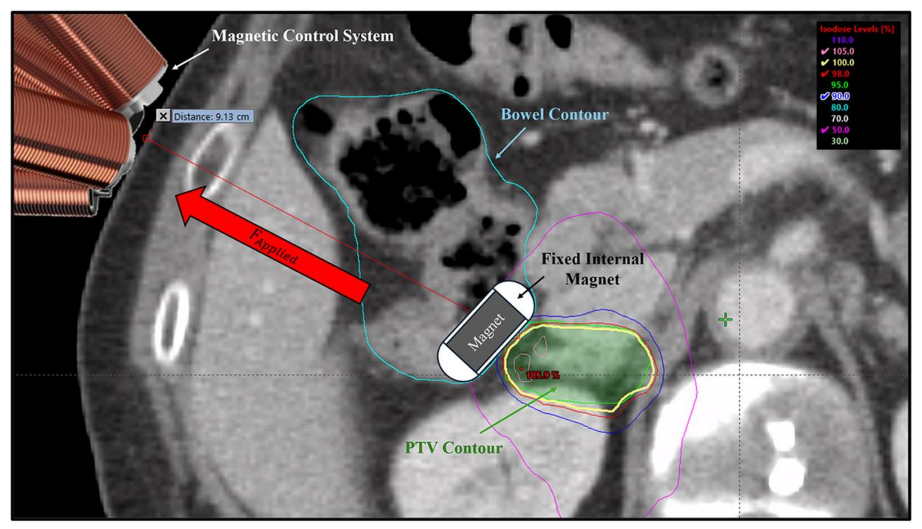
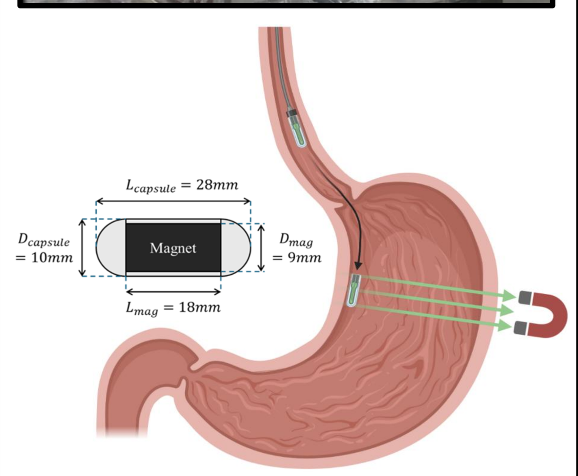
Introduction

- Radiation-induced gastrointestinal (GI) toxicity remains limiting in abdominal SBRT due to proximity between organs-at-risk (OARs) and the planning target volume (PTV).
- Remote magnetic navigation systems (RMNS), originally developed for capsule endoscopy, offer a potential method to manipulate bowel position.







- We propose the use of a RMNS with an internal magnetic capsule to physically displace the GI tract from the PTV; similar in placement to the Bravo™ pH system

Aims of This Work

1. **Applicability:** Review clinical SBRT cases to quantify how often RMNS intervention would be useful and to identify specifically promising prior SBRT cases
2. **Efficacy:** Apply biomechanical modeling to estimate the achievable bowel displacement and dose reduction that could be applied via use of a RMNS in realistic clinical scenarios

Methods

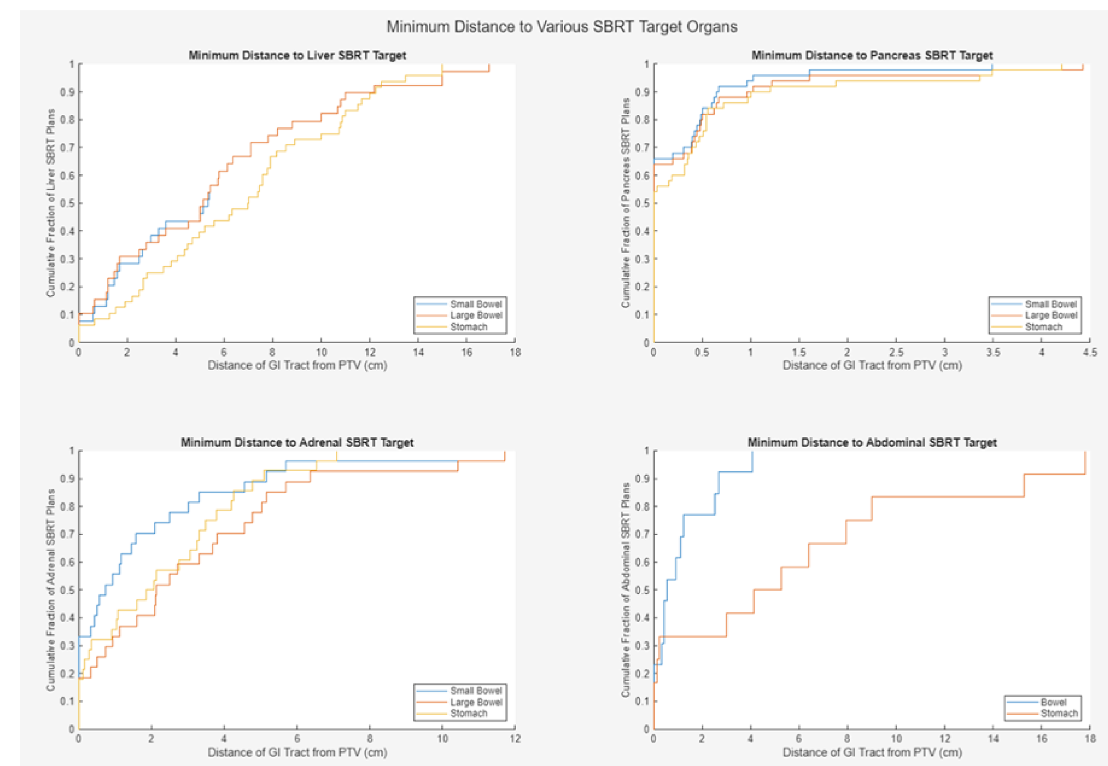
Aim 1:

- Retrospective abdominal SBRT case review (liver, pancreas, adrenal, abdomen)
- Measured GI to PTV distance and dose metrics such as max dose, mean dose, D1cc, D0.5cc
- Cases refined by physician review to identify ideal candidates for in-depth analysis

Aim 2:

- Developed two analytical models to predict GI OAR displacement
  - Springs in Series (Euler-Bernoulli Beam Theory)
  - Springs in Parallel (Abdominal Cavity Constraints)
- Applied models to RMNS and magnetic capsule system via OAR shift
- Evaluated dosimetric impact for representative cases (n = 10)
- Exploratory FEA of GI deformation in FEBio

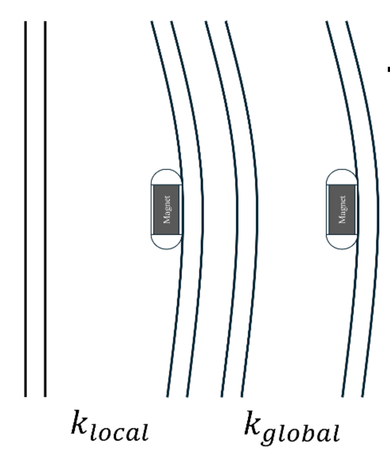
Results



Applicability Analysis:

- OAR within 2 cm of PTV in **99/142** cases
- Physician review reduced applicable cases to **28/142**:
  - Pancreatic head cases not feasible due to immobile duodenum
  - Only left sided liver lesions deemed feasible
  - Potentially feasible at additional sites not yet explored

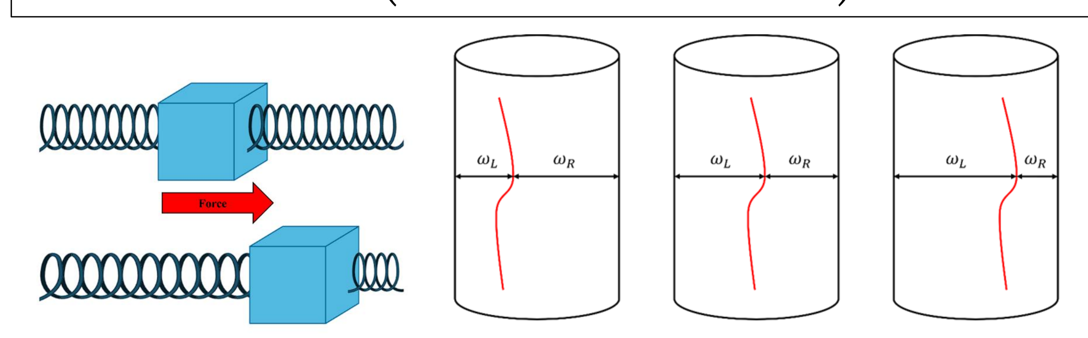
Mathematical Models of OAR Displacement (δ):



Model 1 assumes global and local displacement are governed by two spring forces acting in series.

$$k_{local}(\delta) = \frac{2E_0}{t_0}\left(1 + \alpha_{local}\frac{\delta_{local}}{t_0}\right) r_{cap} l_{cap} \cdot \frac{\left[\cos^{-1}\left(1 - \frac{\delta_{local}}{r_{cap}}\right)\right]^2}{\cos^{-1}\left(1 - \frac{\eta t_0}{r_{cap}}\right)}$$

$$k_{global}(\delta) = \frac{C\pi E_0}{4}\left(1 + \alpha_{global}\frac{R_{bend}\delta_{global}}{L^2}\right)\left(4R_{bend}^3 t_0 + 4R_{bend} t_0^3\right) \cdot \left[1 + \beta\left(\frac{\delta_{global}}{L}\right)^2\right]$$

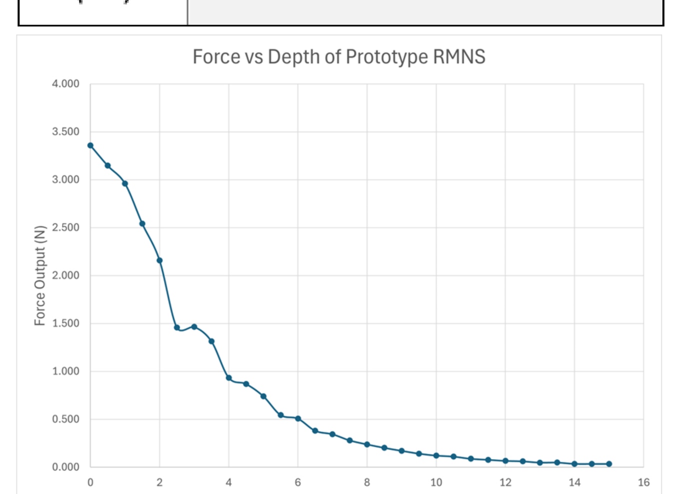


Model 2 treats the GI tract as rigid within a body cavity of uniform Young's Modulus, exerting parallel spring forces.

$$k_{total} = \frac{\left[E_0 + (E_{max} - E_0)\left(1 - e^{\frac{-\beta\delta}{\omega_L}}\right)\right] L_{bowel} R_{outer}\pi}{\omega_L - \delta} + \frac{E_0 L_{bowel} R_{outer}\pi}{\omega_R + \delta}$$

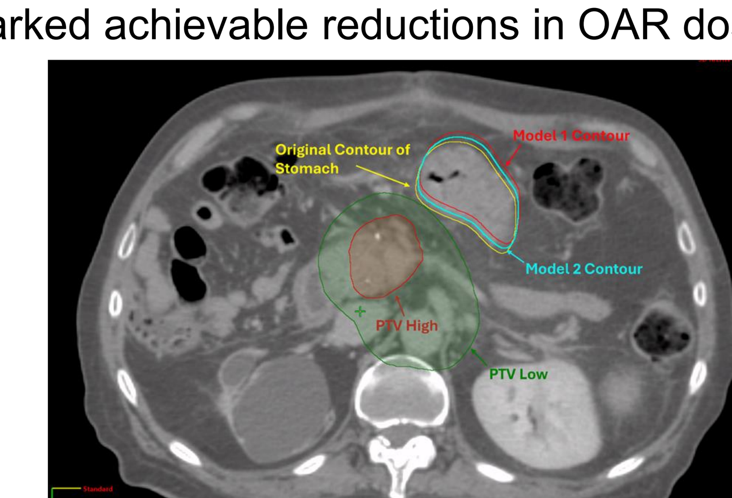
Metric	Model 1 Mean ± SD	Model 2 Mean ± SD
Displacement (mm)	4.9 ±1.8	2.2 ± 0.8

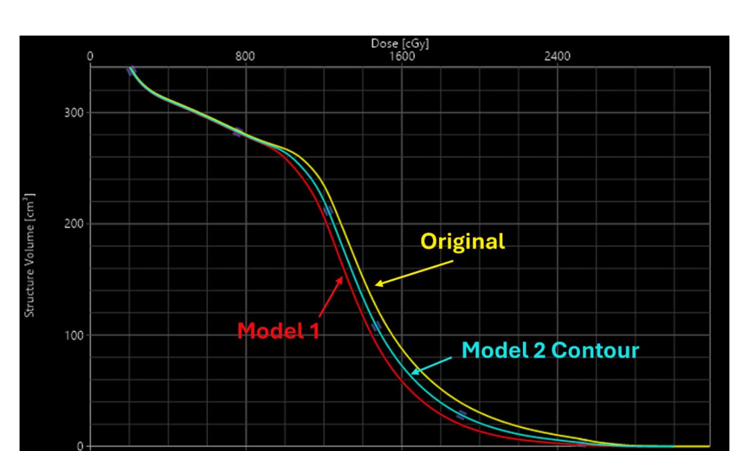
Model 1 predicts greater displacements for known applied forces in 10 representative cases.



Dosimetric Impact Analysis:

Shifting treatment plans by modeled displacements suggests marked achievable reductions in OAR dose.

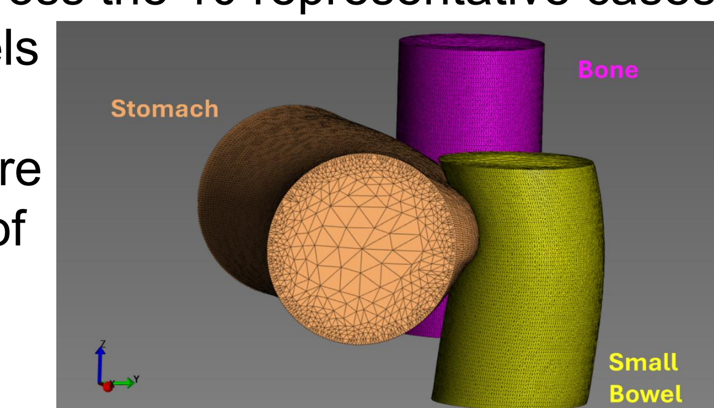


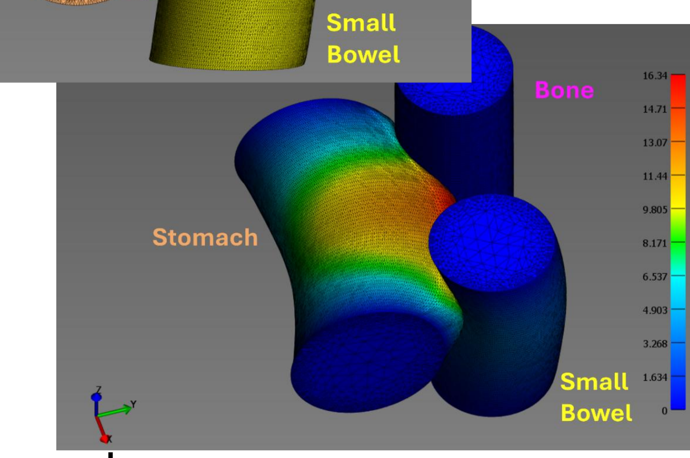


Metric	Model 1 Mean ± SD	Model 2 Mean ± SD
Max Dose Reduction (%Rx)	8.79 ± 7.11	3.82 ± 3.19
Mean Dose Reduction (%Rx)	1.20 ± 0.93	0.54 ± 0.53
D1cc Reduction (%Rx)	6.84 ± 5.22	3.26 ± 3.30
D0.5cc Reduction (%Rx)	7.48 ± 6.65	3.70 ± 4.05

Discussion and Conclusions

- 70% of abdominal SBRT cases reviewed would benefit from a method which physically increases separation between the PTV and OARs
- 28.3% of cases initially reviewed were deemed good candidates for RMNS displacement of OARs based on physician recommendation
- Model 1 predicts larger displacements and dose reductions, but until more rigorous testing is done, the more conservative model is recommended for evaluating efficacy of the proposed method
- Even at changes of less than 1cm, significant falloff of dose can be seen across the 10 representative cases (>10% for 5)
- Analytical models are helpful, but don't fully capture the complexity of the abdomen
- Finite Element Analysis simulations were explored as a quantitative, more realistic solution





- Limitations:
  - Small patient sample surveyed
  - Clinical placement of RMNS
  - Simplified geometry explored via FEA
  - Lack of stable simulations during FEA

Main Takeaways

- There exists a need for physical separation of the GI Tract away from the PTV during abdominal SBRT due to numerous toxicity issues
- RMNS have the capability to slightly displace OAR and thus markedly reduce dose to GI OAR
- Placement of magnetic capsule would not interrupt treatment chain or significantly disrupt patient life
- Finite Element analysis proves a promising pathway for continued exploration into patient-specific modeling

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Duke Cancer Institute ICARL MEDICAL PHYSICS GRADUATE PROGRAM