Techno-Economic Feasibility Analysis of a Fully Mobile Radiation Oncology System Using Monte Carlo Simulation

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abstract

PURPOSE Disparities in radiation oncology (RO) can be attributed to geographic location, socioeconomic status, race, sex, and other societal factors. One potential solution is to implement a fully mobile (FM) RO system to bring radiotherapy to rural areas and reduce barriers to access. We use Monte Carlo simulation to quantify techno-economic feasibility with uncertainty, using two rural Missouri scenarios.

METHODS Recently, a semimobile RO system has been developed by building an o-ring linear accelerator (linac) into a mobile coach that is used for temporary care, months at a time. Transitioning to a more FM-RO system, which changes location within a given day, presents technical challenges including logistics and quality assurance. This simulation includes cancer census in both northern and southeastern Missouri, multiple treatment locations within a given day, and associated expenditures and revenues. A subset of patients with lung, breast, and rectal diseases, treated with five fractions, was simulated in the FM-RO system.

RESULTS The FM-RO can perform all necessary quality assurance tests as suggested in national medical physics guidelines within 1.5 hours, thus demonstrating technological feasibility. In northern and southeastern Missouri, five-fraction simulations' net incomes were, in US dollars (USD), $1.55 ± 0.17 million (approximately 74 patients/year) and $3.65 USD ± 0.25 million (approximately 98 patients/year), respectively. The number of patients seen had the highest correlation with net income as well as the ability to break-even within the simulation. The model does not account for disruptions in care or other commonly used treatment paradigms, which may lead to differences in estimated economic return. Overall, the mobile system achieved a net benefit, even for the most negative simulation scenarios.

CONCLUSION Our simulations suggest technologic success and economic viability for a FM-RO system within rural Missouri and present an interesting solution to address other geographic disparities in access to radiotherapy.

INTRODUCTION

Access to radiotherapy is subject to disparities associated with geographic location, socioeconomic status, age, race, sex, and a variety of other social factors.[1-3] Among these, geographic location, particularly rural locations, can reduce access to care, in part because of travel burdens for multiple, daily visits to a distant facility for extended treatment processes typical of radiotherapy.[4,5] In 2014, Johnson et al[5] showed that rural residents were 1.6 times more likely to have an incompletely staged disease and were less likely to receive indicated radiotherapy compared with urban patients. Potential strategies to limit geographic disparity include building cancer centers in areas of need but can be cost-prohibitive to health care networks. The development of compact linear accelerators (linacs) mounted within a semitrailer may represent

a cheaper and more comprehensive treatment alternative to lessen geographic disparities.[6]

Alliance Oncology (Irvine, CA) has taken initial steps toward this goal by implementing mobile radiation oncology (RO) units within an interim setting. In their system, compact, ring gantry linacs (Halcyon, Varian Medical Systems, Palo Alto, CA) are mounted on tractor trailers and then transported to clinics, where they are parked in a semipermanent concrete shielding structure for clinical use and provide radiation protection.[6] This semipermanent model is intended to provide smaller RO clinics, undergoing planned technology outages (ie, for an upgrade of their existing, permanent linacs), with the ability to maintain treatments. The linac, equipment, and console are all contained within the semitrailer. At locations of interest, additional lead shielding is placed within the semitrailer, which takes roughly 24 working hours. The

CONTEXT

Key Objective
To explore the feasibility of a mobile radiation oncology system in lower resource areas.
Knowledge Generated
This report demonstrates that mobile radiation oncology is both technologically and economically feasible. However, one must consider the patient population and resource limitations before implementation since these factors can affect relative success.
Relevance
These results can generate momentum for expanding radiation oncological use in low-resource areas across the world.

semitrailer is stationary throughout its duration at a single location, which could range from several months to a year. To date, this semimobile linac system has been successfully used for treatment in three locations across the United States.

At present, there has been no comprehensive evaluation of the feasibility of a fully mobile (FM) RO system that could flexibly relocate a compact linac on a weekly or daily basis. Such an increase in the geographic range of a mobile linac could, in theory, increase access to care and reduce travel times for patients.[7-9] The proposed system evaluated here would be supported by a larger medical institution and function as a regional satellite clinic. To limit disparities between the mobile system and a brick-and-mortar facility, the mobile system should be capable of providing state-of-the-art treatment techniques, such as intensity-modulated radiotherapy and stereotactic body radiotherapy (SBRT).

Here, we demonstrate the techno-economic feasibility of a FM RO system design using Monte Carlo simulation to estimate uncertainty and to explore how these uncertainties affect feasibility. For technical capability, logistic testing and quality assurance are investigated. For economic feasibility, we model a mobile linac system-based clinic and workflow within two rural Missouri scenarios.

METHODS

Simulation Scope

We simulate two scenarios, one focused on northern Missouri and the other on southern Missouri (Fig 1), which currently lack regional RO facilities. Each region provides a different cancer patient census, affecting the type and number of patients seen. Within both regions, three distinct locations were selected to create a triangular coverage pattern, in which the mobile RO system could dock to provide treatment and ensure similar travel distances to each docking location. Locations were chosen so travel from surrounding counties was < 1.5 hours. At the beginning of each week, two locations were randomly selected as locations of treatment for the week. Treatment was modeled as occurring at one location in the morning, and then the second in the afternoon. The third location

was not used during week 1. In the following week, the third location was used for treatment in addition to one of the previous two treatment locations. All subsequent weeks in the simulation modeled this care pattern. The procedure for system setup and staffing at each location are included in Data Supplement. Configuration of the system setup is illustrated in Figure 2.

Each run of the Monte Carlo simulation included a 5-year life cycle of the mobile system. This assumes that mobile linacs would have shorter life cycles compared with stationary linacs, which typically follow a 10-year depreciation pattern. The simulation was written in Python Tools for Visual Studio (Microsoft, Redmond, WA). Figure 3 illustrates the simulation workflow.

Model Inputs

Shielding requirements/costs are included within the model, and a more in-depth discussion regarding shielding is included in Data Supplement.

Next, we estimated annual patient loads (Fig 3C). Only relevant definitive five-fraction treatment regimens were considered for breast,[10] lung,[11] and rectal[12] disease sites because of the simplicity of scheduling within a given work week. Only weeks with a full 5 working days were considered in our simulation, that is, we would plan to not treat during weeks with holidays. The patient cancer census was gathered from the Cancer Incidence Missouri Information for Community Assessment website from the Missouri Department of Health and Senior Services.[13] This provided the cancer incidence rates and 95% CI per 100,000 population per treatment site in each county of Missouri over the last 20 years. Population census data were gathered from the US Census Bureau Data. The number of patients per year was randomly drawn from a Gaussian distribution with a mean-centered at the yearly rate and the standard deviation derived from the 95% CI for each disease site investigated provided in Table 1. The likelihood of receiving radiotherapy for a given disease stage was extracted from the recent literature (Table 2).[14]

All costs related to the mobile aspect of the system are shown in Table 3. This includes costs of the linac truck (L-truck), clinical truck (C-truck), construction, and
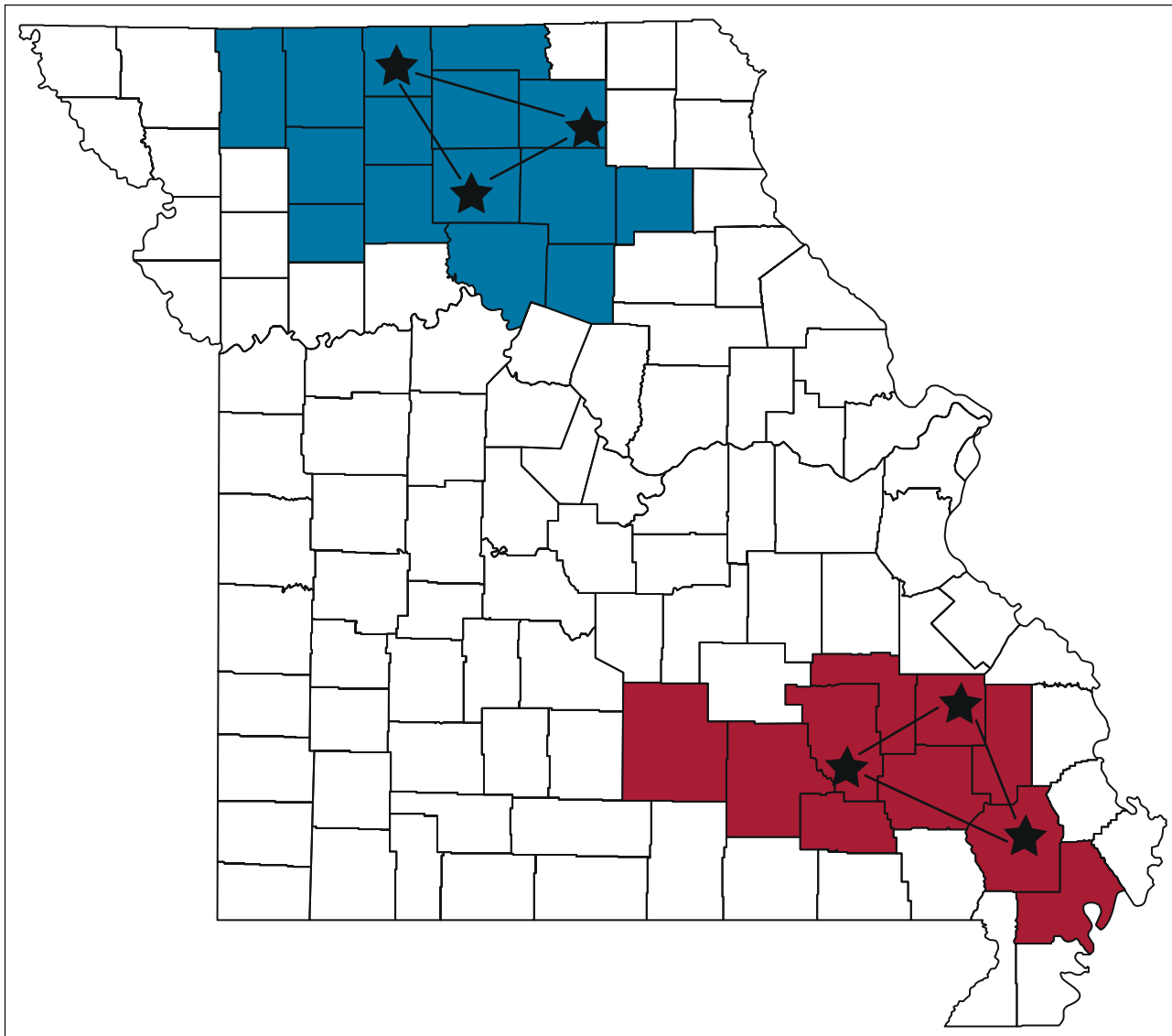
FIG 1. Map of Missouri containing the two separate geographic locations. Shaded in blue is the area that the northern mobile linac would serve while the area shaded in red is the area that the southern mobile linac would serve. Stars represent where the linac would be docked.

operations. Because of uncertainty surrounding the cost of the L-truck, C-truck, and construction on the basis of vendor and design, uniform distributions were used to approximate costs. Cost-per-mile variables were estimated from the operational costs of trucking in the literature.[15] Data Supplement summarizes the expenditure data within the system in Data Supplement. When traveling from one location to the next, beta distributions were applied to the time traveled/setup time and maintenance to introduce longer outlier times and maintenance costs.

Reimbursement from both Centers for Medicare & Medicaid Services recently proposed the RO alternative payment model and fee-for-service private insurance were included to better understand differences in payment models.[16-18] At the end of

each year, the total cost of operation was subtracted from the total earnings to estimate a net income.

Sensitivity analyses reporting the percent change in cost between using minimum and maximum values for each parameter were conducted to identify factors with high potential influence. For patient populations, two standard deviations from the mean were used as the extremes. All other extremes were either extracted from the literature,[15,19] defined system constraints, or from vendor quotes (Table 4). In addition, a variety of simulations were performed within northern and southern Missouri to determine break-even scenarios for the system in each geographic location. This included iterating the number of patients, from zero patients to each disease site's average and

FIG 2. System configuration. The linac truck (L-Truck) contains the linac, whereas the clinical truck (C-Truck) contains both the treatment console and clinic room. The black star represents possible locations of radiation survey measurements.
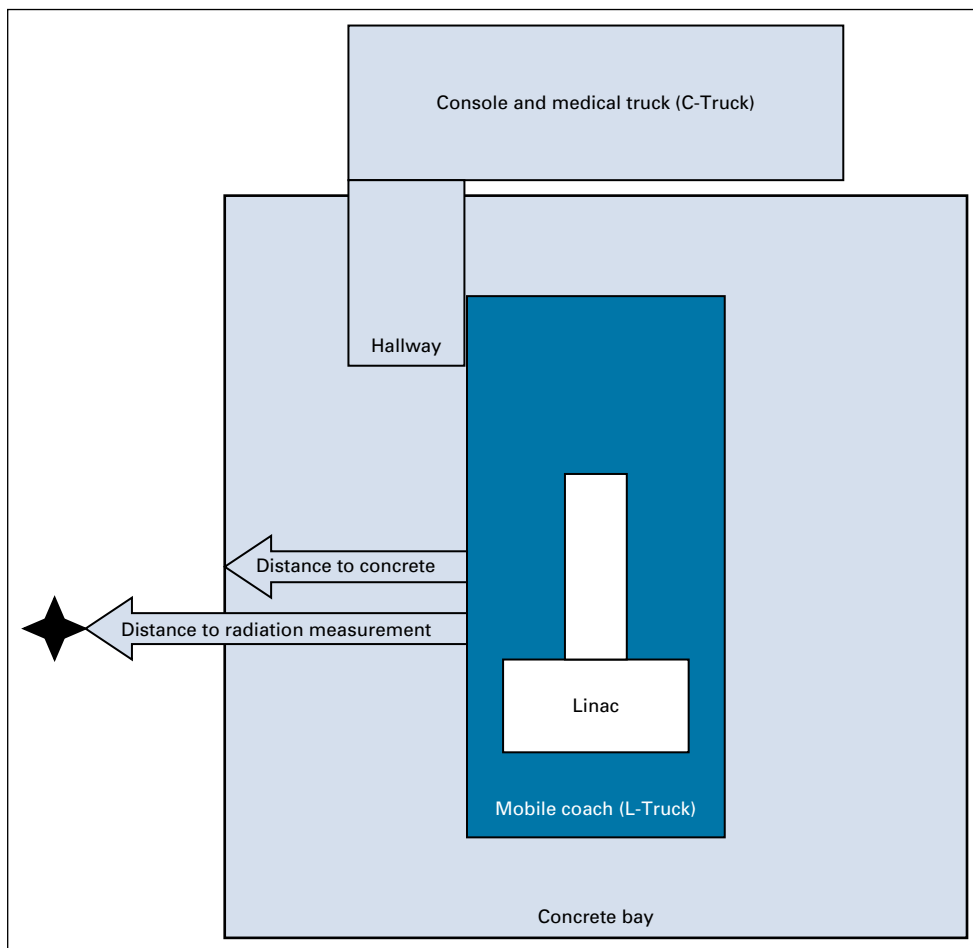
insurance types: 25% private insurance to 75% private insurance, reporting the resulting system profit.

RESULTS

Technological Implementation

Table 5 illustrates a combination of daily, monthly, multileaf collimator, and imaging tests along with their tolerances that are described in Task Group-142 (TG-142) as well as the corollary tests performed during the Machine Performance Check (MPC).[20-22] Additionally, a secondary quality assurance (QA) device, such as the Sun Nuclear ArcCheck (Sun Nuclear Corporation, Melbourne, FL) with a Winston-Lutz attached end piece, is included denoting whether or not the device could perform the TG-142 test.
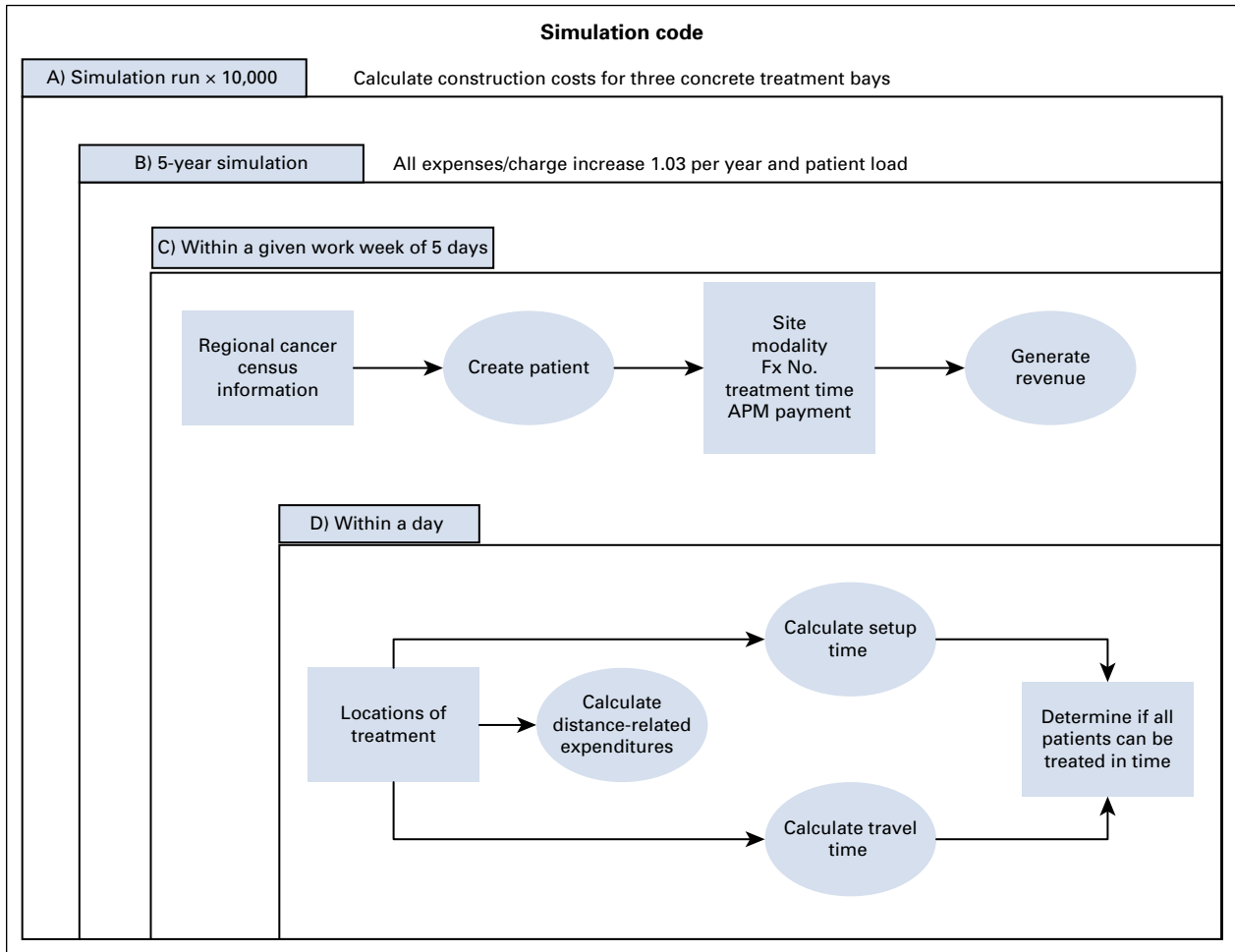
In total, MPC and a secondary QA delivery system can be performed in less than 30 minutes. When considering setup time and QA beam delivery, the total time from arrival to treatment ready would be 2.5 hours for the worst-case scenario such as delays in docking or trouble with connections. When done twice, that equals 5 hours of non-treatment time with 1 hour of travel time during the work day. Despite only leaving 4 hours for treatment, previous studies reported that imaging and treatment times on the Halcyon unit for both breast and gynecologic patients can be performed in under 5 minutes, respectively.[23,24] Considering patient setup time, imaging, treatment, and patient exit, most standard fractionation patients can complete treatment in around 10 minutes and SBRT style dosing can be finished in 20 minutes. With 4 hours for treatment, upward of 12 patients can be treated depending on the modality and site, which is greater than the number of patients seen in a given day during simulation.

Economic Feasibility

Figure 4 illustrates results for simulations run in both northern and southern Missouri. In the northern region, the average annual revenue was \$1.55E6 in US dollars (USD) ± \$1.65E5 USD. The average number of patients seen was 74.6 ± 0.0 patients. In the southern region, the average annual revenue was higher at \$3.65E6 USD ± \$2.46E5 USD. The average number of patients seen was also higher in the southern region at 98.6 ± 0.1. In both simulations, there were no simulations where annual profits were negative. Additionally, there were no scenarios where patient treatment had to be postponed due to traffic patterns or delays in machine setup.

In the southern Missouri sensitivity analysis, the number of lung patients had the highest impact on a change in overall

Simulation code

A) Simulation run × 10,000   Calculate construction costs for three concrete treatment bays

B) 5-year simulation   All expenses/charge increase 1.03 per year and patient load

C) Within a given work week of 5 days

Regional cancer census information → Create patient → Site modality Fx No. treatment time APM payment → Generate revenue

D) Within a day

Locations of treatment → Calculate distance-related expenditures

Calculate setup time

Calculate travel time

Determine if all patients can be treated in time

FIG 3. The simulation workflow for a mobile radiation oncology system illustrating the sublevel iterations needed to run the Monte Carlo system. Fx, number of fractions; APM, alternative payment model.

cost to the system, followed by insurance type, number of breast patients, and number of rectum patients. The concrete position, C-truck, and fluctuation in operational costs had the lowest impact on change in overall costs to the system. Detailed results are summarized in Table 4.

Results of break-even analyses for both northern and southern Missouri are shown in Figure 5. Increasing the number of patients treated results in increased profit. Additionally, increased private insurance populations also increase the profit. This figure also illustrates how the number of patients or the ratio of insurance type differs for

different locations, which affects potential economic viability.

DISCUSSION

In this study, we estimated the techno-economic feasibility of a fully mobile RO system. On the basis of a thorough quality assurance overview and a timing analysis of setup and treatment times, we have demonstrated that it is possible to adequately verify safe treatment delivery while also having enough time to treat patients. Economically, the simulations performed demonstrate financial viability of a

TABLE 1. Breast, Lung, and Rectal Cancer Incidence Rates in Both Northern and Southern Missouri

	Breast		Lung		Rectum	
Variable	Northern	Southern	Northern	Southern	Northern	Southern
Rate	79.02	84.83	73.04	131.63	11.25	20.89
Lower 95% CI	74.13	78.67	68.56	123.94	9.51	17.94
Upper 95% CI	83.92	91.00	77.51	139.31	13.22	24.18

TABLE 2. Likelihood That an Individual Would Receive Radiotherapy for the Various Disease Sites Investigated in This Study

Site	Staging	Staging, %	Receiving RT, %
Breast	1-2	77	49
Lung	1-2	25	31
Rectum	2-4	65	100

Abbreviation: RT, radiotherapy.

TABLE 3. Costs Relating to the Mobile Unit

Item	Lower Bound	Upper Bound	Unit
Linac truck	3,000,000	5,000,000	$
Clinical truck	400,000	500,000	$
Truck maintenance	0.124	0.171	$/mi
Truck gas	0.336	0.645	$/mi
Truck insurance	0.059	0.084	$/mi
Permits and licenses	0.019	0.040	$/mi
Tires	0.035	0.044	$/mi
Concrete construction	850	2,994	$/yd^3

NOTE. Each item has lower and upper bounds of the uniform distribution.

Abbreviation: $,US dollars.

fully mobile RO system, generating positive profits in every year of simulation.

Most health care facilities will have both power and internet connections; however, health care facilities may not be present in areas of interest and should be heavily considered before implementation. Health care planners might have to look at other non-health care–related locations with both power and internet if needed to provide this crucial service. Availability of staffing and transportation infrastructure must also be considered during planning. There are resources available to help optimize the location of a health care facility that can be applied in project planning.[25-29] Since the machine is built into the truck, accepted, and commissioned all before the first treatment, during setup, only connections, level adjustments, and a

series of constancy checks are needed to demonstrate that the machine meets baseline performance standards set at the time of commissioning. Not incorporating the lead into the L-truck requires the need for a C-truck for safety issues, which introduces higher logistical and risk concerns but will help increase the temporal mobility of the system and reach a larger patient population

Over time, the linac may incur more wear from repeated setup and travel damages. Because of this concern, the linac would be tested more rigorously at a higher frequency compared with linacs at standard brick and mortar facilities. Both the MPC and secondary QA check would provide detailed constancy trends of the L-linac over time to potentially identify when preventative maintenance is needed. The low patient volume and decreased treatment times could in theory improve the flexibility of when maintenance occurs or when patients are scheduled if needed.

To base our simulations closer to reality, the simulations are rooted in the cancer census data in both northern and southern Missouri. It is inappropriate to assume that there will be an acceptable patient load with the use of the system without modeling its implementation. We also see how patient make-ups including both disease and insurance type affects break-even points. With that said, our model was limited by only considering five fractions or less lung, breast, and rectal cases at first which is a small portion of the RO patient population as a whole. Extending past five fraction treatments or to palliative treatment courses introduces additional scheduling and human interaction/compliance issues, which could be an area of future research.

TABLE 4. Parameters Used Within the Sensitivity Analysis Along With Its Standard Value and Range

Parameter	Standard Value	Min, Step, Max	Change Cost, %
Patients with lung cancer	36	11.7, 2.6, 60.6	69.30
Insurance type	30%	10%, 2.105%, 50%	−39.8
Patients with breast cancer	45	14.5, 3.2, 74.8	34.2
Patients with rectal cancer	20	6.9, 1.4, 32.5	16.2
Linac truck	$4,000,000	$3,000,000, $105,263, $5,000,000	−6.3
Shielding cost	$1,922/yd^3	$800/yd^3, $115.8/yd^3, $3,000/yd^3	−2.7
Dose measurement X1	9.05 m	2.8 m, 0.658 m, 15.3 m	2.8
Dose measurement X2	9.05 m	2.8 m, 0.658 m, 15.3 m	
Dose measurement Y1	10.95 m	6.6 m, 0.458 m, 15.3 m	
Dose measurement Y2	14.05 m	12.8 m, 0.132 m, 15.3 m	
Concrete position X1	8.75 m	2.5 m, 0.658 m, 15 m	0.8
Concrete position X2	8.75 m	2.5 m, 0.658 m, 15 m	
Concrete position Y1	10.65 m	6.3 m, 0.458 m, 15 m	
Concrete position Y2	13.75 m	12.5 m, 0.132 m, 15 m	
Clinical truck	$450,000	$400,000, $5,263, $500,000	−0.5
Operational costs	1	0.97, 0.003, 1.03	0.6

NOTE. The results of the linear regression analysis are given within this table, along with the index of standardized sensitivity and the impact on total cost.

Abbreviation: $, US dollars.

TABLE 5. Tests Defined in TG-142 and Associated Tolerances Defined in TG-142 and the MPC Tolerances

Tests to Be Performed

Test	TG-142 Tol.	MPC Tol.	External QA
Daily			
X-ray output constancy	3%	4%	Yes
Laser localization	1 mm	2 mm	Yes
Collimator size indicator	1 mm	1 mm	Yes
Door interlock	Functional	NA	NA
Audio-visual monitors	Functional	NA	NA
Beam-on indicator	Functional	NA	NA
Monthly			
X-ray output constancy	2%	4%	Yes
Backup monitor chamber	2%	10%	No
Typical dose rate output	NA	NA	NA
Photon beam profile constancy	1%	2%	Yes
Gantry angle indicators	1.0°	0.5°	Yes
Collimator angle indicators	1.0°	0.5°	Yes
Collimator walkout	1 mm	0.5°	Yes
Treatment couch indicators	1 mm	0.5 mm (short) and 1.0 mm (long)	Yes
Localizing lasers	1 mm	2 mm	Yes
MLC			
Weekly qualitative test	Visual	0.9 mm (prox) and 0.8 mm (dist)	Yes
Monthly MLC position v radiation	2 mm	0.55 mm (prox) and 0.6 mm (dist)	Yes
Imaging			
Imaging v treatment isocenter coincidence	1 mm	0.9 mm	Yes
Position/reposition	1 mm	0.5 mm (short) and 1.0 mm (long)	Yes

NOTE. The external QA column denotes whether those tests can be performed on that device.

Abbreviations: MLC, multi-leaf collimator; NA, not available; QA, quality assurance; TG-142, Task Group-142.

In the sensitivity analysis, patient and insurance type are the largest drivers for impact on total profit considering those variables control profit. Patients with lung disease are the greatest drivers due in part to the higher reimbursement return on investment for SBRT and the sheer number of patients needing treatment in southern Missouri. This is also shown in the break-even analysis for both northern and southern Missouri where patients with breast and lung diseases had a much higher impact on profit and could be economically viable without any rectal patients. This would not be the case in northern Missouri, demonstrating that placing a mobile system in an area of interest will not automatically guarantee a viable system. One must perform this type of analysis before the implementation of a FM RO system in the geographic area of interest as part of the planning phase. Ignoring patient flow patterns and the current standard of care in these regions is a limitation of this work that is being addressed in future modeling studies.

There is still significant uncertainty in the parameter values, which is why we estimated distribution of outcomes using Monte Carlo simulation. When considering that the

semimobile linac solution has only been physically moved three times, the data are sparse in terms of experience to inform the technical challenges that our proposed solution would provide. However, our investigation did look at mobile mammography and positron emission tomography/computed tomography to understand the mobile impact on maintenance and additional costs, which were introduced into our simulation. For other variables that were not known for certain, such as the cost of the L-truck or construction costs, a uniform distribution was implemented within the model, meaning that all scenarios were equally likely to occur. This approach captures the greater range of uncertainties within the system for investigation. Despite this conservative approach, our simulations suggest this is an economically viable system.

Ultimately, there are three types of delays that may influence patient care and system profitability, conditions that affect (1) the patient and mobile system equally, (2) the mobile system, and (3) the patient. These types of delays are not fully modeled in the present simulation and may lead to an overestimation of effectiveness. Conditions that
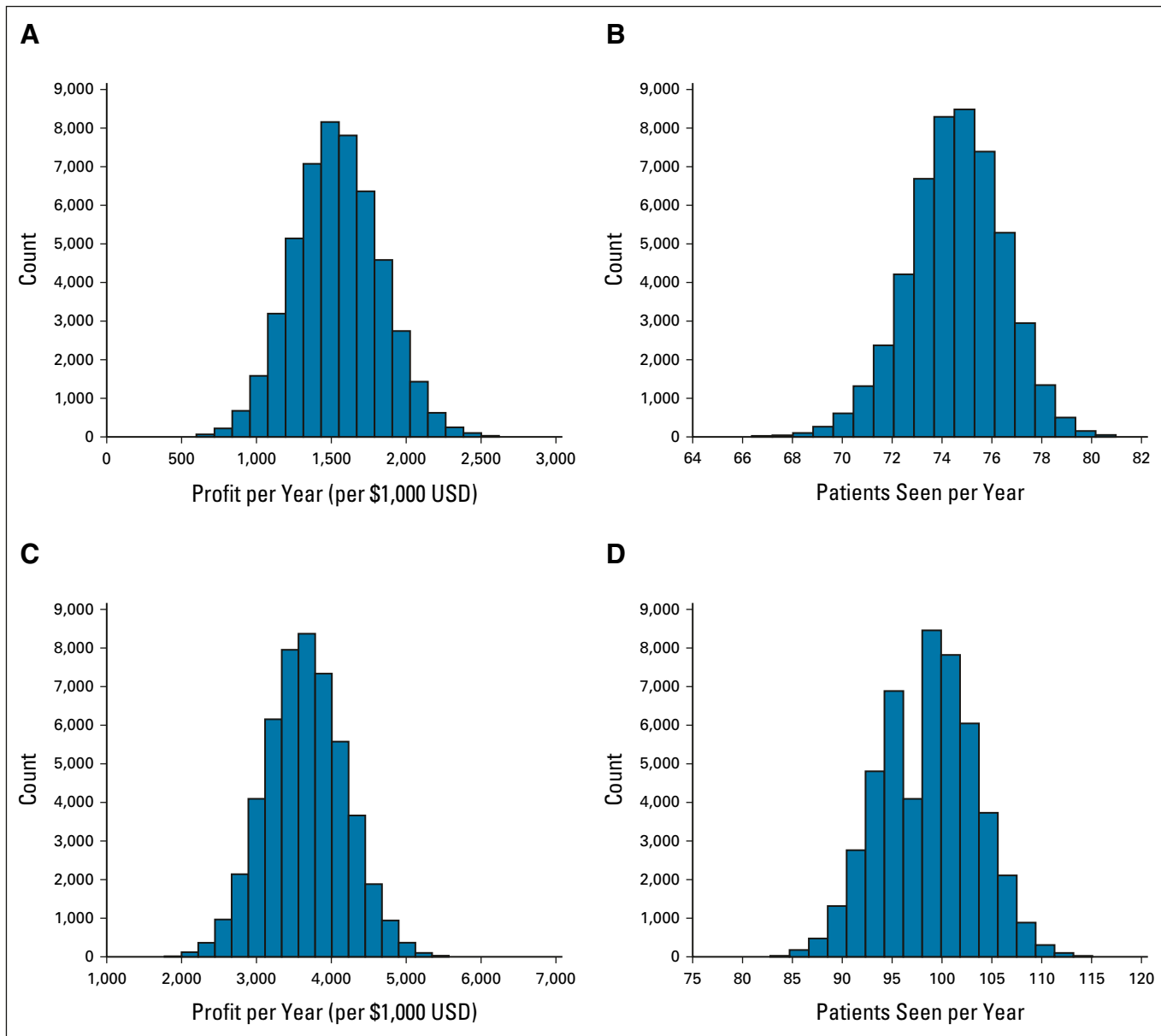
FIG 4. Plots of simulations results for both northern and southern Missouri: (A) a histogram showing northern Missouri average annual profit, (B) a histogram of the average number of patients seen per year in northern Missouri, (C) a histogram showing southern Missouri average annual profit, and (D) a histogram of the average number of patients seen per year in southern Missouri. $, US dollars.

affect both the patient and mobile systems equally, such as weather, are likely to lead to unavoidable delays in care. For example, if the mobile system cannot travel to the patient because of a snowstorm, the patient is likely also unable to travel to a brick-and-mortar facility. We expect this to represent a small number of cases and not influence a comparison between mobile and brick-and-mortar facilities. Conditions that affect the mobile system, such as traffic or emergency maintenance, are a key concern for this analysis. The present analysis uses Beta distributions to include the uncertainty of high impact, low likelihood events. If the L-linac is down for maintenance or the mobile system faces other difficulties such as a traffic accident or C-truck maintenance, the mobile

system could stay at the two current locations for the following week to prevent these patients from having to travel to a separate location, further away. Conditions that affect the patient, such as a missed appointment, would have to be resolved by the patient. For example, if a patient were to miss the treatment, the patient may have to travel to a separate location the following week if the system does not travel back to the patient's location the following week.

In a recent study of 427 patients receiving five fractions or less, only 3.7% of those patients missed two fractions or more,[1] which may translate to a small percentage of our simulated patients missing treatments. When a patient misses the treatment, some may wait for at least a week or
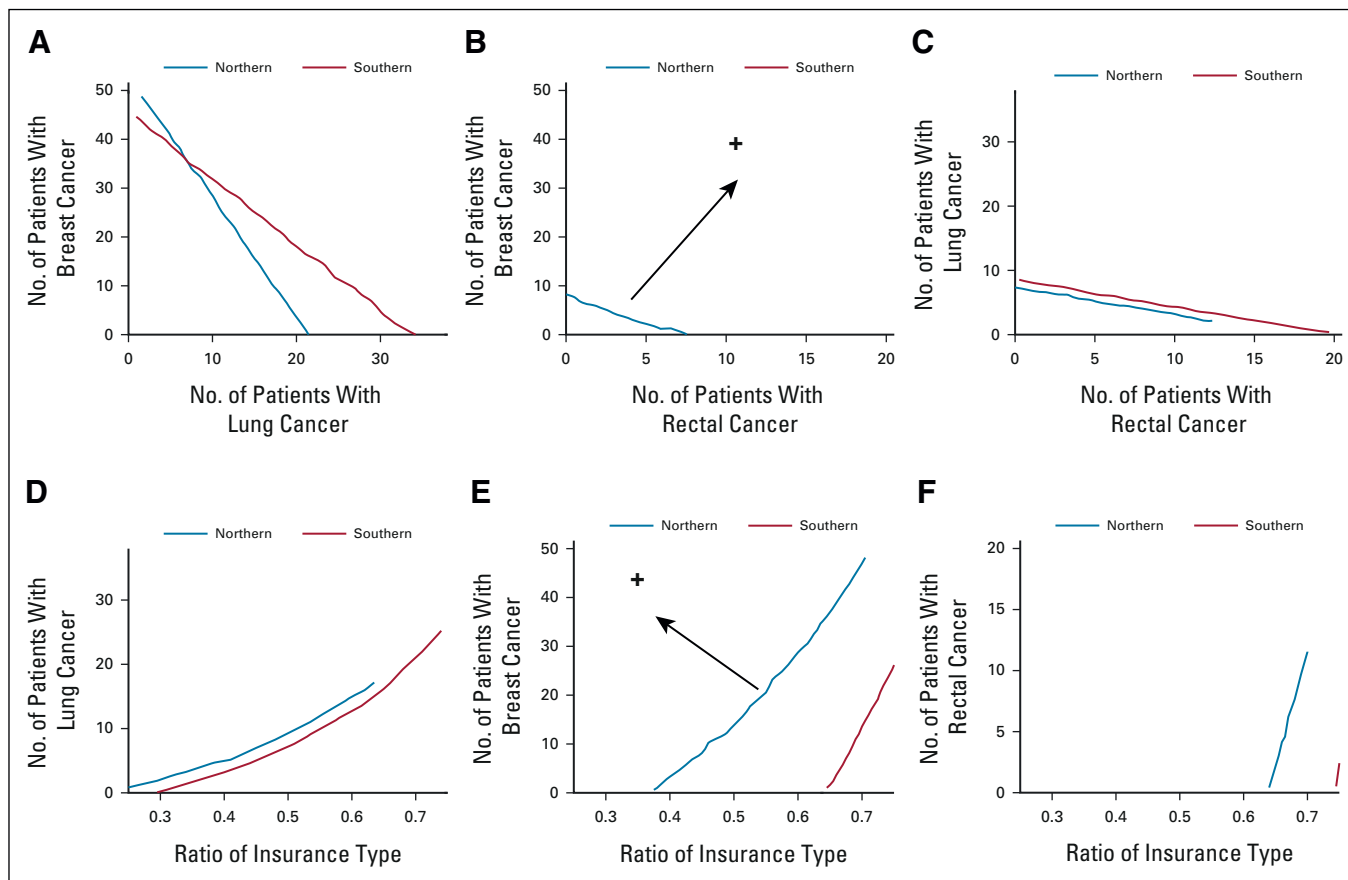
FIG 5. Break-even analyses for all six scenarios investigated: (A) breast versus lung, (B) breast versus rectum, (C) lung versus rectum, (D) lung versus insurance, (E) breast versus insurance, and (F) rectum versus insurance. In the top row, the area point to the top right indicates increasing income. In the bottom row, the arrow pointing to the top left indicates the direction of increasing income. Each line within the graph represents the line at which a positive profit is made based on varied parameter on the *x*- and *y*-axes. An insurance ratio of 0.25 means that the clinical makeup for the patient population would be 25% private insurers and 75% Medicare/Medicaid-based.

two for the mobile system to return to their location if they are not willing to travel to a separate location. Patients may also not finish their treatment because of the mobile system moving to another location because they are lost to follow up. This would have both a negative financial and health outcome to the system and patient, respectively. With this in mind, our model is most likely overestimating the overall success on average but our estimated uncertainties capture the extremes of the mobile system that still demonstrate an overall net benefit.

There are also other patient-related clinical care decisions that affect the success of the overall system. For example, simulation and resimulation may prove to be challenging with only a cone-beam computed tomography imager. However, recent research on the use of diagnostic imaging for planning and simulation-free techniques could be appropriately used to improve the efficiency of the system.[30-32] For treatment monitoring, telehealth and remote symptom monitoring applications could be used to aid in managing the patients' health during treatment.[33,34] Although, the effectiveness may be limited by patient access to internet service or willingness to participate in telemedicine.

To date, this novel fully mobile approach to RO has not been discussed in the literature. Fully mobile RO is now a possibility within the field and would have substantial impacts not only on rural health care but also within developing countries. The fully mobile system could adjust to regional demands of cancer treatment and provide a more cost-effective approach to the delivery of care. Our work is important in that we are simulating the life-cycle of a fully mobile RO system rooted in cancer census specific to the area of interest, which is the driver of economic viability for such a system. Our future work will be to model the health care infrastructure in rural Missouri to understand how the deployment of a fully mobile RO system would affect infrastructure, decision making, and health care in the region.

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