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Estimating the costs of intensity-modulated and 3-dimensional conformal radiotherapy in Ontario

J.H.E. Yong MASc,*†‡ T. McGowan MD MBA,§||# R. Redmond-Misner MSc,*†‡ J. Beca MSc,*†‡
P. Warde MCChB BAO,†§** E. Gutierrez MRT(T) BSc,† and J.S. Hoch PhD*†‡††

ABSTRACT

Background Radiotherapy is a common treatment for many cancers, but up-to-date estimates of the costs of radiotherapy are lacking. In the present study, we estimated the unit costs of intensity-modulated radiotherapy (IMRT) and 3-dimensional conformal radiotherapy (3D-CRT) in Ontario.

Methods An activity-based costing model was developed to estimate the costs of IMRT and 3D-CRT in prostate cancer. It included the costs of equipment, staff, and supporting infrastructure. The framework was subsequently adapted to estimate the costs of radiotherapy in breast cancer and head-and-neck cancer. We also tested various scenarios by varying the program maturity and the use of volumetric modulated arc therapy (VMAT) alongside IMRT.

Results From the perspective of the health care system, treating prostate cancer with IMRT and 3D-CRT respectively cost $12,834 and $12,453 per patient. The cost of radiotherapy ranged from $5,270 to $14,155 and was sensitive to analytic perspective, radiation technique, and disease site. Cases of head-and-neck cancer were the most costly, being driven by treatment complexity and fractions per treatment. Although IMRT was more costly than 3D-CRT, its cost will likely decline over time as programs mature and VMAT is incorporated.

Conclusions Our costing model can be modified to estimate the costs of 3D-CRT and IMRT for various disease sites and settings. The results demonstrate the important role of capital costs in studies of radiotherapy cost from a health system perspective, which our model can accommodate. In addition, our study established the need for future analyses of IMRT cost to consider how VMAT affects time consumption.

Key Words Radiotherapy, intensity-modulated radiotherapy, costs, cost analyses, prostate neoplasms, head-and-neck neoplasms, breast neoplasms

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BACKGROUND

Radiotherapy is a common treatment option for many cancers, and accurate estimates of the costs of radiotherapy techniques are essential for program planning. In Canada, 3-dimensional conformal radiotherapy (3D-CRT) had been the most common technique, but intensity-modulated radiotherapy (IMRT), which spares neighbouring tissue while allowing for higher doses of radiation to be delivered to the target, has become more commonly used[1]. Several studies have shown that the toxicity profile is better with IMRT than with 3D-CRT, especially in treating prostate and head-and-neck cancers[2–6]. Comprehensive and up-to-date estimates of the costs of IMRT and 3D-CRT in Canada are needed to assess IMRT's value for money.

Existing radiotherapy cost studies, usually cost-effectiveness analyses (CEAs), use varying sources and methods to obtain cost estimates. A systematic review of such analyses for radiotherapy in prostate cancer found that studies came predominantly from the United States and derived the cost of services from Medicare reimbursement data[7]. That trend persisted in CEAs of IMRT and 3D-CRT published during 2012–2015 that looked at prostate, anal, gynecologic, and head-and-neck cancers[8–12]. However, the included cost components varied and omitted capital costs, with one Australian analysis of IMRT in prostate cancer

Correspondence to: Jeffrey S. Hoch, Pharmacoeconomics Research Unit, Cancer Care Ontario, 620 University Avenue, Toronto, Ontario M5G 2L7.
E-mail: hochj@smh.ca ■ **DOI:** http://dx.doi.org/10.3747/co.23.2998

specifically excluding them based on the recommendations of their national Medical Services Advisory Committee[13]. The integration of components such as gynecologic toxicities[8], concurrent chemotherapy[9], hormonal therapy, and palliative care[10], in addition to no expressed intention for the costing approach to be transferable, demonstrates the challenge of comparability between CEAs. Prior cost calculations were limited to one-time or disease-specific use, and the logic behind that approach is understandable; however, with little information about radiotherapy cost being available, there is a clear need to support comparisons between studies with a uniform way to calculate the cost.

The primary objective of the present study was to estimate the costs of IMRT and 3D-CRT for the treatment of prostate cancer in Canada. The secondary objective was to provide a framework for consistently estimating the costs of IMRT and 3D-CRT for other disease sites or purposes (for example, palliative vs. curative care), because the cost varies with the complexity of planning and delivery. We tested the framework by re-estimating the costs of IMRT and 3D-CRT for breast and head-and-neck cancers.

METHODS

Building on earlier work, we used an activity-based costing (ABC) method to estimate the costs of IMRT and 3D-CRT in prostate cancer, subsequently modifying the model to estimate costs for breast and head-and neck-cancers[14]. Activity-based costing is the preferred method to estimate the costs of radiotherapy, especially when comparing radiation techniques[14–16]. The ABC approach breaks processes down into activities that consume resources to deliver each unit of output. Cost drivers, such as time or patient load, are identified for each resource within each activity. More details about ABC and its importance can be found in earlier papers[14,15,17].

The process diagram[14], unit costs, and activity times were all updated to reflect 2009 practice in Canada. Costs of IMRT and 3D-CRT were estimated for a centre with 3 linear accelerators, treating 1260 patients annually (Appendix A). To avoid capturing the temporarily higher cost associated with the learning curve after implementation, the times required to complete activities were based on the processes of a mature program. The costing was completed in consultation with radiation oncologists, physicists, and radiation therapists. All costs are expressed in 2009 Canadian dollars.

Costs were allocated to 5 major activities associated with planning, preparing, and delivering radiotherapy and to the cost of gold seeds (Table I). For each activity, the cost of each resource was derived according to the two main cost drivers: time and patient load.

The process starts with a radiation oncologist consultation (activity 1). In the case of prostate cancer, a radiation oncologist arranges to have gold seeds placed into the prostate. Radiation therapists then place an immobilizer on the patient and use computed tomography (CT) to acquire planning images (activity 2). Next, the radiation oncologist and radiation therapists work together to outline the target volume and to identify at-risk organs to create a treatment plan [dosimetry (activity 3)]. At the quality assurance (QA) stage, a physicist reviews the treatment plan (activity 4). For IMRT, two physics associates create a QA plan and apply the treatment plan to a phantom (a device for measuring delivered dose), collecting and analyzing data to verify the treatment plan. Radiation therapists then deliver treatment, which is accompanied by review visits with a radiation oncologist over the course of radiotherapy (activity 5).

Consistent with the radiation costing literature, we grouped resource items into 3 major cost categories: process costs, clinical infrastructure, and supporting infrastructure[16]. In the base case, to adhere to the Canadian Guidelines for Economic Evaluation[18], we estimated costs from the perspective of the health care system—specifically, the Ontario Ministry of Health and Long-Term Care. To be consistent with the radiation costing literature[14,16], we also estimated costs from the radiation treatment program perspective. The two perspectives differ in that the program costs include neither the capital costs of equipment (acquisition and construction), nor physician fees.

Process Costs

Process costs are the costs directly related to clinical care, which include staff time for patient care and consumables. We obtained the costs of consumables (gold seeds for prostate cancer and immobilizers for each site) from two radiation treatment programs in Ontario.

Costs of the radiation oncologists included physician fees and additional annual funding received from the Ontario Ministry of Health and Long-Term Care[19] (Appendix A). Nursing costs included salary, plus an additional 24% for benefits, obtained from a teaching hospital in Toronto. Costs of the other program staff (therapist, physicist, physics associate, machinist, information system staff, and electronics staff) included salaries and an additional 24% for benefits, which were obtained from Cancer Care Ontario. We estimated staff cost per minute by assuming that staff worked full time (253 days annually and 7.5 hours daily). When estimating staff costs for therapists, physicists, and physics associates, we also included additional management-related costs to reflect management costs not directly attributable to an activity (Appendix A). To allocate therapist costs to treatment preparation and treatment delivery, we also assumed that, for each hour of treatment delivery on the linear accelerator, 2.86 hours of therapist time were required for treatment-related work. That ratio was based on a therapist staffing schedule in a centre with 3 linear accelerators (Appendix A).

Clinical Infrastructure

Clinical infrastructure and equipment costs included the costs of acquisition, construction, and equipment maintenance, plus the personnel cost for operating and conducting routine quality control for equipment ("operating cost"). Based on estimates from Cancer Care Ontario (Appendix A, Table AII), we used the equation that follows to amortize (5% annually) the costs of acquisition, construction, and equipment maintenance over the expected lifespan of each piece of equipment[20]:

$$Annual\ cost = \frac{Total\ cost * interest\ rate}{1 - \frac{1}{(1 + interest\ rate)^{amortization\ period}}}$$

TABLE I Overview of activity-based costing

Activity	Included costs	Cost drivers	
		Time	Patient volume
1. Consultation	Radiation oncologist		X
	Nurse		X
	Gold seed insertion[a]		X
2. CT simulation	Therapist	X	
	CT simulator		X
	Immobilizer		X
	Information system: patient management		X
3. Dosimetry	Therapist	X	
	Planning system	X	
	Radiation oncologist		X
	Information system: patient management		X
4. Physics QA	Physicist		
	Verify treatment plan	X	
	Review data	X	
	Physics associates[b]	X	
	Specialized QA equipment[b]		X
	Planning system		
	Information system: patient management		X
5. Treatment QA and delivery, review visit	Therapist		
	Pre-treatment	X	
	On the unit	X	
	Linear accelerator	X	
	Radiation oncologist (review visit)		X
	Nurse (review visit)		X
	Information system: patient management		X
	Information system: record or verify	X	

[a] Prostate cancer only.
[b] Intensity-modulated radiation therapy only.
CT = computed tomography; QA = quality assurance.

For all equipment, we assumed an annual maintenance cost equal to 10% of the annualized acquisition cost. The unit cost of equipment was calculated based on whether cost was driven by time used or number of patients served (Table II). The calculation assumed that the centre had 3 linear accelerators, 1 treatment planning system, 1 CT simulator, 1 piece of specialized QA equipment (used only for IMRT cases), and 1 information system.

Supporting Infrastructure

The cost of the supporting infrastructure—often called "overhead" or "hotel costs"—included the costs necessary to the day-to-day functioning of the hospital in which the program is housed[16]. It included the costs of hospital administration, building service, security, laundry, medical records, porters, social work, and clerical staff in the radiation treatment program; clinical nutrition; utilities; hospital general registration; and housekeeping. We estimated the costs based on a teaching hospital's budget for fiscal year 2010–2011 and the radiation treatment program's proportion of the hospital's overhead budget (Appendix A, Table AII)[22]. To calculate cost per patient, the total cost of the program was divided by the number of patients seen annually in the program.

Activity Time

Activity time—the amount of time consumed by an activity—drove the cost of some resources. We estimated the average treatment delivery time (minutes per fraction) for prostate cancer from the historical treatment time for more than 5000 fractions delivered at a centre that had been using IMRT for more than 3 years. At that centre, image-guided radiotherapy was used alongside IMRT, a process that improves the accuracy of treatment by using imaging for guidance. The IMRT treatment time therefore included the additional time associated with image-guided radiotherapy. From the historical data, the average treatment delivery time per fraction was the same for both techniques

TABLE II Unit costs of capital equipment, 2009 Canadian dollars

Equipment	Annual cost ($)				Metrics		Unit cost ($)	
	Acquisition and construction	Maintenance	Operating	Total	Operating hours per year (*n*)	Patients per year (*n*)	Per hour	Per patient
Linear accelerator	471,312	40,097	417,317[a]	928,725	2174[b]		427	
Incremental cost to support linear accelerator (IMRT)	—		55,361	55,361	2174[b]		25	
Treatment planning system	415,755	41,575		457,330	2560[c]		181	
CT simulator	300,267	23,097		323,365		1260		257
Information system: patient management	271,172	27,117	58,900[d]	357,190		1260		283
Information system: record or verify	237,392	23,739	58,900[d]	320,031	6522		49	
Specialized QA equipment	32,914	3,291		36,205		630[e]		57

[a] Operating 3 linear accelerators requires an electronics staff, machinist, physicist, and physics associate.
[b] Each linear accelerator and information system was assumed to be used 9.25 hours daily for 235 days annually.
[c] Each case was assumed to need, on average, 2 hours on the treatment planning system (1260 cases/year × 2 hours/case).
[d] The information system that supports 3 linear accelerators required 1 information systems staff member for its operation. Maintenance of the patient management component was assumed to required 0.5 full-time equivalents; the remaining time was dedicated to the record or verify component. The latter component is used to verify doses, ensure accurate dose delivery, and minimize accidental exposure[21].
[e] Half the cases in a centre were assumed to be IMRT cases, which were the only ones to require specialized QA equipment.
IMRT = intensity-modulated radiation therapy; CT = computed tomography; QA = quality assurance.

(15 minutes per fraction). Assuming that treatment for each prostate cancer patient requires 39 fractions, the average treatment delivery time was 585 minutes.

Pre-treatment preparation time was estimated based on a survey of 8 radiation oncologists and radiation therapists in Ontario about the typical time required for CT simulation and dosimetry. The average time was the same for IMRT and 3D-CRT, with 2 therapists being required to perform the CT simulation, each spending 30 minutes on average. The Physics Professional Advisory Committee conducted a survey of physicists in Ontario to estimate the additional time needed by physicists and physics associates to conduct QA for IMRT compared with 3D-CRT. Each respondent sketched a flow diagram representing the physics QA process and the time required for each step.

To capture the total work time of radiation therapists, we estimated a ratio of radiation therapist work time to treatment time from the radiation therapist work schedule at the centre. Compared with 3D-CRT, IMRT required 56% more direct clinical support from physicists and 1.5 hours of support from physics associates.

Estimating Costs for Other Disease Sites

We adapted the costing model to estimate the costs of IMRT and 3D-CRT for head-and-neck cancer and breast cancer by changing the activity time estimates, the number of fractions per patient, and the number of review visits per patient (Appendix A, Table AIII). The disease-site estimates were based on experience at a teaching hospital in Ontario that had fully implemented IMRT since 2006.

Sensitivity Analysis

To address uncertainty about the cost estimates, we tested various scenarios in which one or more variables were modified to evaluate the effect on the cost of IMRT compared with 3D-CRT. Scenarios tested the effects of longer dosimetry time for IMRT, longer QA for IMRT, and the use of volumetric modulated arc therapy (VMAT) alongside IMRT, among others. In prostate cancer, VMAT has been found to improve and speed up conventional IMRT[23]. Based on more than 1000 fractions of prostate cancer treatment delivered at a hospital in the Greater Toronto Area, we estimated the average treatment delivery time with VMAT to be 10 minutes per fraction rather than the 15 minutes per fraction estimated for 3D-CRT or for IMRT without VMAT.

RESULTS

In prostate cancer, IMRT was more costly than 3D-CRT ($12,834 vs. $12,453 per patient; incremental cost: $381) because IMRT required more resources for dosimetry and physics QA (Table III). From the health system perspective, 39% of the cost of IMRT was attributed to process, 45% to clinical infrastructure, and 16% to supporting infrastructure. The costs of IMRT and 3D-CRT were lower from the program perspective ($7,802 and $7,588; incremental cost: $213), which omitted physician fees and the capital costs of equipment. The results of the sensitivity analyses showed how the cost and incremental cost of IMRT varied with activity time, cost of the linear accelerator, and the number of patients receiving IMRT treatment in a centre (Table IV). Compared with 3D-CRT, IMRT with the addition of VMAT created cost savings in prostate cancer. In a scenario of IMRT in the initial phase of IMRT implementation, the cost of IMRT rose to as much as $19,113 per patient because of the additional time required when staff are learning the technique.

Of the three disease sites, breast cancer was the least expensive and head-and-neck cancer was the most expensive because of differences in treatment complexity

TABLE III Cost, from a health system perspective, of treatment with 3-dimensional conformal radiation therapy (3D-CRT) and intensity-modulated radiation therapy (IMRT) for prostate cancer, 2009 Canadian dollars

Activity	Resource	Hourly rate ($)	Hours (*n*)		Cost ($)			
			3D-CRT	IMRT	Per patient		Per patient per activity	
					3D-CRT	IMRT	3D-CRT	IMRT
Consultation								
	Radiation oncologist				179	179	292	292
	Nurse				113	113		
Gold seed insertion								
	Gold seed				117	117	117	117
CT simulation								
	Radiation therapist	84	2×0.5	2×0.5	84	84	426	426
	CT simulator				257	257		
	Immobilizer				14	14		
	Information system: patient management				71	71		
Dosimetry								
	Radiation therapist	84	2.5	2.5	210	210	1,487	1,623
	Planning system	181	2.5	2.5	454	454		
	Radiation oncologist				752	888		
	Information system: patient management				71	71		
Physics QA								
	Physicist		0.35	0.55	41	64	176	421
	Physics associate	86		0.75		129		
	Specialized QA equipment					57		
	Planning system	181	0.35	0.55	64	99		
	Information system: patient management				71	71		
Treatment preparation and delivery, and review visits								
	Radiation therapist (pre-treatment)	84	3.08[a]	3.08[a]	259	259	7,973	7,973
	Radiation therapist (treatment delivery)	84	0.25×39×2.86[b]	0.25×39×2.86[b]	2,347	2,347		
	Linear accelerator	427	0.25×39[c]	0.25×39[c]	4,166	4,166		
	Information system: patient management				71	71		
	Information system: record or verify	49	0.25×39[c]	0.25×39[c]	478	478		
	Review visits per patient (both protocols)							
	Radiation oncologist		7		540	540		
	Nurse				113	113		
Supporting infrastructure							1,982	1,982
TOTAL COST							12,453	12,834

a Calculated from the radiation therapist work schedule at a radiation treatment program.
b This value represents the ratio of work-hour to treatment-hour, calculated from the radiation therapist work schedule at a radiation treatment program.
c That is, 15 minutes per fraction for a total of 39 fractions per patient.
CT = computed tomography; QA = quality assurance.

and fractions per treatment (Tables V and VI). For all 3 disease sites, IMRT cost more than 3D-CRT, with the incremental cost ranging from $57 to $1,619. That finding remained true when sensitivity analyses were applied to the breast cancer and head-and-neck cancer models (Table VII). The largest cost differences were seen in head-and-neck cancer, because delivery took longer with IMRT than with 3D-CRT (20 minutes vs. 17 minutes per fraction; approximately 100 minutes more per patient). Again, the cost difference between techniques was larger from the health system perspective than from the program perspective. Treatment delivery was the most costly activity regardless of disease site.

DISCUSSION

We estimated radiotherapy costs of $5,270–$14,155 per patient in prostate, breast, and head-and-neck cancers in Ontario. Compared with 3D-CRT, IMRT cost $57–$1,619 more

TABLE IV Sensitivity analysis results for the costs of treatment with intensity-modulated radiation therapy (IMRT) in prostate cancer

Scenario	Time (hours) for ...			Cost for IMRT (2009 CA$)	
	Dosimetry	QA	Treatment	Total	Incremental
Base case	2.50	0.5	9.75	12,834	381
Longer dosimetry time for IMRT	3.75			13,166	713
Longer QA time for IMRT		2.0		13,269	816
Longer dosimetry and QA time for IMRT	3.75	2.0		13,601	1,148
Adding VMAT to the process[a]			6.50	10,679	–1,773
Initial implementation of IMRT[b]	6.00	4.0	13.00	16,720	4,268
25% higher cost of linear accelerator				13,875	381
75% of cases using IMRT[c]				12,815	362

[a] Shorter treatment delivery time for IMRT (5 min less per fraction) and additional costs for VMAT (module cost for linear accelerator and VMAT license cost for treatment planning system).
[b] Calculated as 6 hours of dosimetry, 4 hours of physics QA, and 5 additional minutes per fraction in treatment delivery.
[c] The base-case assumption was that 50% of cases used IMRT (the remaining cases were assumed to use 3-dimensional conformal radiation therapy). The unit cost of specialized QA equipment is therefore affected because it is divided by the number of IMRT cases performed annually.
QA = quality assurance; VMAT = volumetric modulated arc therapy.

TABLE V Cost, from a health system perspective, of treatment with intensity-modulated radiation therapy (IMRT) and 3-dimensional conformal radiation therapy (3D-CRT) for head-and-neck and breast cancer, 2009 Canadian dollars

Activity	Cost by cancer site ($)					
	Head and neck			Breast		
	IMRT	3D-CRT	Incremental	IMRT	3D-CRT	Incremental
Consultation	292	292	—	292	292	—
Gold seed insertion			—			—
CT simulation	574	574	—	426	426	—
Dosimetry	1,623	1,487	136	1,357	1,222	136
Physics QA	491	220	271	203	146	57
Treatment preparation and delivery, and review visits	9,193	7,980	1,213	4,592	4,592	—
Supporting infrastructure	1,982	1,982	—	1,982	1,982	—
TOTAL	14,155	12,536	1,619	8,853	8,659	193

CT = computed tomography; QA = quality assurance.

per patient for the disease sites considered. The costs varied depending on the analytical perspective, the radiation technique, and the disease site. In addition to the resources included in the program perspective, the health system perspective encompassed physician fees and the capital costs of equipment. The distribution of costs in the three major categories (process, clinical infrastructure, and supporting infrastructure) varied depending on the perspective.

The cost distribution from the program perspective was within the range reported in the literature[16,17], although the included resources varied between the studies. In the start-up scenario, the incremental cost of IMRT increased by a factor of about 11 ($4,268 rather than the $381 estimated for a mature program), which highlights the importance of evaluation timing. In most CEAS, cost estimates based on a mature program are more appropriate, because it takes less than 1 year for a centre to become familiar with the technique[24].

Applying the costing model to head-and-neck cancer, radiotherapy was more costly than prostate cancer because head-and-neck cancer requires more time for QA and treatment delivery. That observation is consistent with findings in earlier studies of IMRT[25–28]. Of all activities, treatment delivery was the most costly—an observation that accords with findings reported in an ABC study of IMRT in Europe[27]. Although our centre reported longer treatment times for IMRT than for 3D-CRT in head-and-neck cancer, two other studies showed shorter treatment times with IMRT in head-and-neck cancer[26,28]. It is possible that those studies did not count as many time components of treatment or that their process was different. For example, use of the VMAT technique for a similar IMRT plan would save 3 minutes per fraction (of 8 minutes allocated for delivery) in head-and-neck cancer.

Our study is the first to estimate the costs of 3D-CRT and IMRT in Canada for multiple disease sites. To estimate

TABLE VI Cost, from a radiation treatment program perspective, of treatment with intensity-modulated radiation therapy (IMRT) and 3-dimensional conformal radiation therapy (3D-CRT) for prostate, head-and-neck, and breast cancers, 2009 Canadian dollars

Activity	Cost by cancer site ($)								
	Prostate			Head and neck			Breast		
	IMRT	3D-CRT	Incremental	IMRT	3D-CRT	Incremental	IMRT	3D-CRT	Incremental
Consultation	113	113	—	113	113	—	113	113	—
Gold seed insertion	117	117	—			—			—
CT simulation	133	133	—	281	281	—	133	133	—
Dosimetry	268	268	—	268	268	—	168	168	—
Physics QA	277	64	213	309	84	224	108	51	57
Treatment preparation and delivery, and review visits	4,910	4,910	—	5,799	5,015	785	2,823	2,823	—
Supporting infrastructure	1,982	1,982	—	1,982	1,982	—	1,982	1,982	—
TOTAL	7,802	7,588	213	8,753	7,744	1,009	5,328	5,270	57

CT = computed tomography; QA = quality assurance.

the costs of radiotherapy, we used the ABC method, which is considered the best method for this purpose[14–16], and the process that we mapped was aligned with the literature[26,30]. By changing activity times, the number of fractions per patient, and the number of review visits per patient, the costing model developed in the present study can be adapted to estimate the costs of IMRT and 3D-CRT in other disease sites.

In prostate cancer, IMRT became cost-saving when delivered using VMAT, which reduces treatment time by 5 minutes per fraction. A recent timing study comparing IMRT with 3D-CRT in prostate cancer showed that IMRT can be delivered slightly more quickly than 3D-CRT, suggesting that our analysis might have overestimated the incremental cost of IMRT in prostate cancer[27]. Treatment delivery is less complex and thus less costly in prostate cancer compared with head-and-neck cancer, although it requires 39 fractions rather than the 35 required in head-and-neck cancer. That observation suggests that estimating radiotherapy costs for other disease sites requires more than just an estimate of cost per fraction, because a more complex treatment takes more resources (time and effort) to plan regardless of dose (number of fractions). In other words, a treatment given in fewer fractions can cost more because it is more complex. We have used the cost estimates from this model to inform other CEAs of IMRT[31,32].

Our study shows that the capital cost of equipment is a big component of radiotherapy cost and a major source of cost differences by technique and by payer perspective. Although economic evaluation guidelines recommend that analyses be conducted from a health system perspective[18], most published studies estimate radiotherapy costs from a program perspective, which omits capital costs[16]. That omission affects the results of the CEAs, because the costs of and the cost difference between the techniques are both underestimated.

Our cost estimates were derived from two centres in Ontario; further validation might therefore be required for generalizability to other centres with different configurations, because radiotherapy costs depend on patient volume and other process factors[33]. Our costing framework can be modified to reflect those differences, as well as differences in unit cost and workflow found in other jurisdictions. For example, if physicists play a larger role in conducting QA in some centres, that difference could be reflected by changing the activity time for physicists in the costing model.

CONCLUSIONS

Although 3D-CRT has been the standard of care for many patients receiving radiotherapy, IMRT is increasingly considered for indications that require an escalated dose of radiation. We developed an ABC model that estimates the costs of 3D-CRT and IMRT in prostate cancer and subsequently adapted it to breast cancer and head-and-neck cancer. The cost of radiotherapy varied by disease site largely because of differences in treatment complexity, which affected the planning and QA processes and the number of fractions per treatment. Our costing model can be modified to estimate the costs of 3D-CRT and IMRT for various disease sites and settings by varying the planning and treatment times and the number of fractions per treatment.

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TABLE VII Sensitivity analysis results for the costs of treatment with intensity-modulated radiation therapy (IMRT) in prostate, head-and-neck, and breast cancer

Scenario	Time for ...									Cost for IMRT (2009 CA$)					
	Dosimetry (hours)			QA (minutes)			Treatment (minutes)			Prostate		Head and neck		Breast	
	Prostate	HN	Breast	Prostate	HN	Breast	Prostate	HN	Breast	Total	Incremental	Total	Incremental	Total	Incremental
Base case															
IMRT	2.5	2.5	1.5	33	47	15	15	20	15	14,520	1,019	16,085	2,447	9,787	537
CRT	2.5	2.5	1.5	21	30	15	15	17	15						
Long dosimetry time (IMRT)															
IMRT	3.75	3.75	2.25							15,151	1,650	16,716	3,078	10,165	916
Longer QA time (IMRT)															
IMRT				120	120	60				15,303	1,802	16,742	3,104	10,190	941
Longer dosimetry and QA time (IMRT)															
IMRT	3.75	3.75	2.25	120	120	60				15,934	2,433	17,373	3,735	10,569	1,320
VMAT[a]															
IMRT							10	17	12	12,077	–1,424	14,949	1,311	9,060	–189
CRT							15	17	15						
Initial implementation of IMRT[b]															
IMRT	6	6	6	240	240	240	20	25	20	20,389	6,888	21,963	8,325	13,417	4,168
CRT	2.5	2.5	1.5	21	30	15	15	17	15						

[a] Shorter treatment delivery time for IMRT (5 minutes less for prostate cancer, 3 minutes less for head-and-neck and breast cancers), and VMAT module cost added to linear accelerator and VMAT license cost to treatment planning system.

[b] Calculated as 6 hours of dosimetry, 4 hours of physics QA, and 5 additional minutes per fraction in treatment delivery.

HN = head-and-neck cancer; QA = quality assurance; CRT = conformal radiation therapy; VMAT = volumetric modulated arc therapy.

CONFLICT OF INTEREST DISCLOSURES

We have read and understood *Current Oncology*'s policy on disclosing conflicts of interest, and we declare that we have none.

AUTHOR AFFILIATIONS

*St. Michael's Hospital, †Cancer Care Ontario, and ‡Canadian Centre for Applied Research in Cancer Control, Toronto, ON; §Department of Radiation Oncology, Faculty of Medicine, University of Toronto, Toronto, ON; ||The Cancer Centre Bahamas, Nassau, Bahamas; #The Cancer Centre Eastern Caribbean, St. John's, Antigua; **Princess Margaret Hospital, and ††Institute of Health Policy, Management and Evaluation, University of Toronto, Toronto, ON.

REFERENCES

1. Cancer Quality Council of Ontario (CQCO). Radiation Therapy Evidence-based Series [Web page]. Toronto, ON: CQCO; 2010. [Available at: https://www.cancercare.on.ca/cms/One.aspx?portalId=289784&pageId=10445; cited 18 December 2015]
2. Al-Mamgani A, Heemsbergen D, Peeters T, Lebesque JV. Role of intensity-modulated radiotherapy in reducing toxicity in dose escalation for localized prostate cancer. *Int J Radiat Oncol Biol Phys* 2009;73:685–91.
3. Braam PM, Terchaard CH, Roesink JM, Raaijmakers CP. Intensity-modulated radiotherapy significantly reduces xerostomia compared with conventional radiotherapy. *Int J Radiat Oncol Biol Phys* 2006;66:975–80.
4. Kam MK, Leung SF, Zee B, *et al.* Prospective randomized study of intensity-modulated radiotherapy on salivary gland function in early-stage nasopharyngeal carcinoma patients. *J Clin Oncol* 2007;25:4873–9.
5. Zelefsky MJ, Levin EJ, Hunt M, *et al.* Incidence of late rectal and urinary toxicities after three-dimensional conformal radiotherapy and intensity-modulated radiotherapy for localized prostate cancer. *Int J Radiat Oncol Biol Phys* 2008;70:1124–9.
6. Nutting CM, Morden JP, Harrington KJ, *et al.* on behalf of the PARSPORT trial management group. Parotid-sparing intensity modulated versus conventional radiotherapy in head and neck cancer (PARSPORT): a phase 3 multicentre randomised controlled trial. *Lancet Oncol* 2011;12:127–36.
7. Amin NP, Sher DJ, Konski AA. Systematic review of the cost effectiveness of radiation therapy for prostate cancer from 2003 to 2013. *Appl Health Econ Health Policy* 2014;12:391–408.
8. Chen A, Kim J, Boucher K, *et al.* Toxicity and cost-effectiveness analysis of intensity modulated radiation therapy versus 3-dimensional conformal radiation therapy for postoperative treatment of gynecologic cancers. *Gynecol Oncol* 2015;136:521–8.
9. Hodges C, Beg MS, Das P, Meyer J. Cost-effectiveness analysis of intensity modulated radiation therapy versus 3-dimensional conformal radiation therapy for anal cancer. *Int J Radiat Oncol Biol Phys* 2014;89:773–83.
10. Hummel SR, Stevenson MD, Simpson EL, Staffurth J. A model of the cost-effectiveness of intensity-modulated radiotherapy in comparison with three-dimensional conformal radiotherapy for the treatment of localised prostate cancer. *Clin Oncol (R Coll Radiol)* 2012;24:e159–67.
11. Kohler E, Sheets NC, Wheeler SB, Nutting C, Hall E, Chera BA. Two-year and lifetime cost-effectiveness of intensity modulated radiation therapy versus 3-dimensional conformal radiation therapy for head-and-neck cancer. *Int J Radiat Oncol Biol Phys* 2013;87:683–9.
12. Sheets NC, Wheeler SB, Kohler RE, Fried DV, Brown PM, Chera BS. Costs of care in a matched pair comparison of intensity-modulated radiation therapy (IMRT) versus conventional radiation therapy (CRT) for the treatment of head and neck cancer. *Am J Clin Oncol* 2014;37:539–44.
13. Carter HE, Martin A, Schofield D, *et al.* A decision model to estimate the cost-effectiveness of intensity modulated radiation therapy (IMRT) compared to three dimensional conformal radiation therapy (3DCRT) in patients receiving radiotherapy to the prostate bed. *Radiother Oncol* 2014;112:187–193.
14. Poon I, Pintilie M, Potvin M, McGowan T. The changing costs of radiation treatment for early prostate cancer in Ontario: a comparison between conventional and conformal external beam radiotherapy. *Can J Urol* 2004;11:2125–32.
15. Lievens Y, van den Bogaert W, Kesteloot K. Activity-based costing: a practical model for cost calculation in radiotherapy. *Int J Radiat Oncol Biol Phys* 2003;57:522–35.
16. Ploquin NP, Dunscombe PB. The cost of radiation therapy. *Radiother Oncol* 2008;86:217–23.
17. Lievens Y, Slotman BJ. Radiotherapy cost-calculation and its impact on capacity planning. *Expert Rev Pharmacoecon Outcomes Res* 2003;3:497–507.
18. Canadian Agency for Drugs and Technologies in Health (CADTH). *Guidelines for the Economic Evaluation of Health Technologies: Canada*. 3rd ed. Ottawa, ON: CADTH; 2006. [Available online at: https://www.cadth.ca/media/pdf/186_EconomicGuidelines_e.pdf; cited 18 December 2015]
19. Ontario Ministry of Health and Long-Term Care (MOHLTC). *Ontario Health Insurance (OHIP) Schedule of Benefits for Physician Services.* Toronto, ON: MOHLTC; 2009.
20. Drummond MF, Sculpher MJ, Torrance G, O'Brien B, Stoddart G. *Methods for the Economic Evaluation of Health Care Programmes*. 3rd ed. Oxford, UK: Oxford University Press; 2005.
21. International Atomic Energy Agency (IAEA). *Record and Verify Systems for Radiation Treatment of Cancer: Acceptance Testing, Commissioning and Quality Control*. Vienna, Austria: IAEA; 2013.
22. Wodinsky HB, Jenkin RD. The cost of radiation treatment at an Ontario regional cancer centre. *CMAJ* 1987;137:906–9.
23. Warde P, Murphy T. Measuring the cost of palliative radiotherapy. *Can J Oncol* 1996;6(suppl 1):90–4.
24. Fogarty GB, Ng D, Liu G, Haydu LE, Bhandari N. Volumetric modulated arc therapy is superior to conventional intensity modulated radiotherapy—a comparison among prostate cancer patients treated in an Australian centre. *Radiat Oncol* 2011;6:108.
25. Clark CH, Mubata CD, Meehan CA, *et al.* IMRT clinical implementation: prostate and pelvic node irradiation using Helios and a 120-leaf multileaf collimator. *J Appl Clin Med Phys* 2002;3:273–84.
26. Miles EA, Clark CH, Urbano MT, *et al.* The impact of introducing intensity modulated radiotherapy into routine clinical practice. *Radiother Oncol* 2005;77:241–6.
27. Van de Werf E, Lievens Y, Verstraete J, Pauwels K, van den Bogaert W. Time and motion study of radiotherapy delivery: economic burden of increased quality assurance and IMRT. *Radiother Oncol* 2009;93:137–40.
28. Williams MV, Hoole AC, Dean JC, *et al.* IMRT can be faster to deliver than conformal radiotherapy. *Radiother Oncol* 2010;95:257–8.
29. Van de Werf E, Verstaete J, Lievens Y. The cost of radiotherapy in a decade of technology evolution. *Radiother Oncol* 2012;102:148–53.
30. Thomas SJ, Vinall A, Poynter A, Routsis D. A multicentre timing study of intensity-modulated radiotherapy planning and delivery. *Clin Oncol (R Coll Radiol)* 2010;22:658–65.
31. Yong JH, Beca J, McGowan T, Bremner KE, Warde P, Hoch JS. Cost-effectiveness of intensity-modulated radiotherapy in prostate cancer. *Clin Oncol (R Coll Radiol)* 2012;23:521–31.
32. Yong J, Beca J, O'Sullivan B, *et al.* Cost-effectiveness of intensity-modulated radiotherapy in oropharyngeal cancer. *Clin Oncol (R Coll Radiol)* 2012;24:532–8.
33. Dunscombe P, Roberts G, Walker J. The cost of radiotherapy as a function of facility size and hours of operation. *Br J Radiol* 1999;72:598–603.

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APPENDIX A: SUPPLEMENTARY METHODS

Size of Radiation Therapy Program

The size of the program in the base-case analysis is similar to the program at Southlake Regional Health Centre, which, at the time of the study, had 3 linear accelerators and used IMRT for half their patients.

Process Costs

Radiation Oncologist Cost

Radiation oncologists in Ontario receive an annual base salary plus fees for each visit (McGowan T. Personal communication, 2009). To allocate the base funding to patient visits, we assumed that each radiation oncologist saw, on average, 275 patients annually. Every prostate cancer patient made 9 visits to radiation oncologists: 1 consultation visit (fee code A345), 1 dosimetry visit (fee code X312 or X313), and 7 review visits (fee code A348). The base funding cost for the radiation oncologist per visit was therefore $46.57 ($115,260 / 275 / 9). That cost was included in each radiation oncologist visit, in addition to the cost obtained from the physician fee schedule ("fee for service").

Nursing Cost

We the estimated nursing cost per patient by assuming that

- each nurse supported two radiation oncologists,
- each radiation oncologist saw 275 patients per year, and
- nursing time was split evenly between the consultation and review visits.

The estimated nursing cost per patient was $225.73. Nursing salary was estimated from the maximum job rate in a radiation treatment program.

Management-Related Costs

In addition to computed tomography (CT) simulation, dosimetry, pre-treatment preparation, and treatment delivery, therapists often have other responsibilities such as training, management, and so on. To estimate the costs related to management or training, we assumed that a centre with 3 linear accelerators had 27 full-time equivalent (FTE) therapists (9 FTEs per linear accelerator). Of the 27 FTEs, 9 FTEs were required for CT simulation and dosimetry, 12 were required for treatment preparation and delivery, and the remaining 6 FTEs were for other activities ("management-related"), representing approximately an additional 29% of a FTE.

For physicists and physics associates, we assumed an additional 20% of a FTE for management-related costs.

Estimating Treatment-Related Time for Therapists

To allocate the cost of the therapist to pre-treatment preparation and treatment delivery, we assumed that 4 therapists staffed a treatment unit for each linear accelerator and that each work shift was 8 hours (total work-hours: 4 × 8 = 32). Of the 32 available work-hours, 5.5 hours were assumed to be required for pre-treatment preparation, and therapists were assumed to spend the remaining 26.5 hours on treatment delivery. Assuming that each linear accelerator operated for 235 days and treated 420 patients annually, the preparation time per patient was 3.08 hours (5.5 hours × 235 days / 420 patients).

During treatment delivery, therapists often spend time on more than just operating the linear accelerator. For each hour of treatment delivery on the linear accelerator, 2.86 hours of therapist time was required for treatment-related work (26.5 hours × 235 days / 2174 linear accelerator operating hours).

Clinical Infrastructure

Table AI sets out the costs allocated for acquisition and construction of capital equipment.

TABLE AI Acquisition and construction cost of capital equipment, 2009 Canadian dollars

Item	Cost ($)		Expected lifespan (years)
	Acquisition	Construction	
Linear accelerator	2,850,000	500,000	9
Treatment planning system with IMRT capability[a]	1,800,000	—	5
CT simulator	1,000,000	300,000	5
Information system	2,201,818	—	5
Specialized QA equipment for IMRT	142,500	—	5

[a] A system that can support 3 linear accelerators.
IMRT = intensity-modulated radiation therapy; CT = computed tomography; QA = quality assurance.

Supporting Infrastructure

Table AII presents the proportions of various hospital infrastructure costs allocated to a radiation therapy program.

TABLE AII Proportion of supporting infrastructure cost[a] for a radiation treatment (RT) program

Cost centre	RT proportion (%)
Hospital administration	15.5
Building service	10.0
Security	10.0
Laundry	10.0
Medical records	26.0
Porters	60.0
Social work	20.0
Clerical (RT)	100.0
Clinical nutrition	50.0
Utilities	10.0
Clerical (registration)	10.0
Housekeeping	10.0

[a] Radiation treatment cost / hospital cost.

Estimating Costs for Other Disease Sites

Table AIII presents the activity time estimates that were used for the other disease sites analyzed.

TABLE AIII Activity time estimates, fractions, and review visits per patient, by disease site

Activity	Resource	Disease site					
		Prostate		Head and neck		Breast	
		3D-CRT	IMRT	3D-CRT	IMRT	3D-CRT	IMRT
Gold seed insertion	Gold seed	Yes	Yes	Yes	Yes	No	No
CT simulation[a]	Radiation therapist	2×0.5	2×0.5	2×0.75	2×0.75	2×0.5	2×0.5
Dosimetry (hours)	Radiation therapist	2.5	2.5	2.5	2.5	1.5	1.5
	Planning system	2.5	2.5	2.5	2.5	1.5	1.5
Physics QA (hours)	Physicist	0.35	0.55	0.50	0.78	0.25	0.25
	Physics associate		1.50		1.50		
	Planning system	0.35	0.55	0.50	0.78	0.25	0.25
Treatment preparation and delivery	Radiation therapist (treatment delivery)[b]	0.25×39×2.86	0.25×39×2.86	0.50×35×2.86	0.42×35×2.86	0.25×21×2.86	0.25×21×2.86
	Linear accelerator[c]	0.25×39	0.25×39	0.50×35	0.42×35	0.25×21	0.25×21
	Information system (record or verify)[c]	0.25×39	0.25×39	0.50×35	0.42×35	0.25×21	0.25×21
Review visits (*n*)	Radiation oncologist and nurse	7		5	5		

[a] Sessions × hours.
[b] Hours × fractions × patients.
[c] Hours × fractions.
3D-CRT = 3-dimensional conformal radiation therapy; IMRT = intensity-modulated radiation therapy; CT = computed tomography; QA = quality assurance.