Radiotherapy and Oncology 103 (2012) 123–129

Contents lists available at SciVerse ScienceDirect

Radiotherapy and Oncology

journal homepage: www.thegreenjournal.com

Managing workforce

Managing a national radiation oncologist workforce: A workforce planning model

Teri Stuckless [a], Michael Milosevic [b], Catherine de Metz [c], Matthew Parliament [d], Brent Tompkins [a], Michael Brundage [c,e,*]

[a] Division of Radiation Oncology, Cancer Care Program, NL; [b] Princess Margaret Hospital and Department of Radiation Oncology, University of Toronto; [c] Department of Radiation Oncology, Cancer Center of Southeastern Ontario, Kingston; [d] Radiation Oncology, University of Alberta; [e] Queen's Cancer Research Institute, Kingston, Canada

ARTICLE INFO

Article history:
Received 17 May 2011
Received in revised form 28 October 2011
Accepted 23 December 2011
Available online 31 January 2012

Keywords:
Radiation oncology
Human resources

ABSTRACT

Purpose: The specialty of radiation oncology has experienced significant workforce planning challenges in many countries. Our purpose was to develop and validate a workforce-planning model that would forecast the balance between supply of, and demand for, radiation oncologists in Canada over a minimum 10-year time frame, to identify the model parameters that most influenced this balance, and to suggest how this model may be applicable to other countries.
Methods: A forward calculation model was created and populated with data obtained from national sources. Validation was confirmed using a historical prospective approach.
Results: Under baseline assumptions, the model predicts a short-term surplus of RO trainees followed by a projected deficit in 2020. Sensitivity analyses showed that access to radiotherapy (proportion of incident cases referred), individual RO workload, average age of retirement and resident training intake most influenced balance of supply and demand. Within plausible ranges of these parameters, substantial shortages or excess of graduates is possible, underscoring the need for ongoing monitoring.
Conclusions: Workforce planning in radiation oncology is possible using a projection calculation model based on current system characteristics and modifiable parameters that influence projections. The workload projections should inform policy decision making regarding growth of the specialty and training program resident intake required to meet oncology health services needs. The methods used are applicable to workforce planning for radiation oncology in other countries and for other comparable medical specialties.

Radiotherapy has a critical role in the curative and palliative management of patients with cancer, and radiation health services require specific infrastructure and highly trained personnel. In Canada, delivery of radiation services is highly centralized, owing to the Cody Commission (1931) report [1] and related recommendations [2]. Hence, there exists a finite number of domestic radiotherapy-capable centers, and a corresponding limited number of domestic employment opportunities for new trainees in radiation oncology. Human resource planning is required to avoid under- or over-training of qualified specialists.

Much of the literature on physician manpower planning in Canada has focused on the overall needs of the health care system, particularly in primary care [3–9]. A 2008 survey of 27 specialist organizations, however, illustrated that 20 (74%) could not quantify the then-existent shortage of relevant physician specialists [10]. Work to fill this knowledge gap was required.

The Canadian Association of Radiation Oncology (CARO) Manpower and Standards Committee is the group that has been charged with the task of "evaluating staffing and workload across the country and estimating the future state of affairs as a guide to determining domestic training needs" in this specialty area [11]. Building on previous surveys performed in Canada [12] and in other countries [13–16]. Radiation oncologist (RO) division heads across Canada are now surveyed annually with regard to five-year workforce projections at their respective centers. These data provide clear information with regard to the current workforce, but do not reliably predict human resources requirements over the longer time frame required to plan training, recruitment, and government investment in specialty positions.

The goal of this research was to develop and validate a workforce projection model for radiation oncology that could be used for planning over a 10-year period. In so doing, we sought to identify the variables that most influenced the balance between supply and demand. Modeling of workforce requirements in radiation oncology has not been undertaken previously in Canada. While there had been general physician manpower modeling efforts

* Corresponding author. Address: Cancer Care and Epidemiology, Queen's Cancer Research Institute, 10 Stuart Street, Level 2, Kingston, Ontario, Canada K7L 3N6.
E-mail address: michael.brundage@krcc.on.ca (M. Brundage).

0167-8140/$ - see front matter © 2012 Elsevier Ireland Ltd. All rights reserved.
doi:10.1016/j.radonc.2011.12.025

[17], we required a model specific to the needs of radiation oncology. Furthermore, we sought to develop a model that was not only applicable to the Canadian health-care system, but could be modified for use elsewhere. We chose to develop our model on the basis of the work done by the Australian Medical Workforce Advisory Committee, who used a thorough description of the existing radiation oncology workforce to project 10-year human resources needs (based on growth of the population and on predicted cancer incidence rates) [13]. Our goal was to ensure that policy makers had sufficient information to plan for the appropriate availability of radiation oncologists to meet the health care needs of cancer patients, and to adjust residency training program capacity and/or professional recruitment strategies to avoid mismatches between graduate radiation oncologists and employment opportunities.

Brief historical perspective

Throughout the 1980's and early 1990's Canadian ROs experienced high workloads secondary to increasing demands for radiotherapy services without a concomitant increase in physical treatment capacity and personnel [18]. The shortfall in resources contributed to increasingly limited access to radiation services; the proportion of cancer patients referred for radiotherapy fell from 45% in 1971 to 35% in 1984–1986 [19] (both below the target of 50%, based on current best estimates) [20]. Work hours were monopolized by patient care, thus curtailing specialty-specific research and teaching activities [21].

The workforce gradually expanded through an increase both in recruitment of foreign-trained ROs and in domestic trainees. New radiotherapy technology, increasing indications for radiotherapy, an attractive lifestyle and wide employment opportunities roused the interest of graduating medical students. Despite these increases, as late as 1995, professional leaders remained pessimistic that staffing needs could be met [22]. Ironically, within two years, expanded residency programs, coupled with a lack of new staff positions in most provinces, resulted in trainees fearing unemployment [18,23]. Some residents transferred out and program directors were questioned regarding poor planning practices. Ultimately, the problem was recognized as a deficit of funded staff positions, since workload remained much higher than the recommended professional caseload [17].

One critical consequence of these and other events on Canadian RO workforce planning was the impact they had on residents' willingness to train in radiation oncology. As illustrated in Fig. S1 (see on-line supplementary data), there exists a clear relationship between manpower predictions and subsequent supply of ROs that is due to the influence of these projections on medical graduates' decisions to enter a radiation oncology program conditional on perceived employment opportunities. For example, one year after a deficit of ROs was forecast in 1994, over 135 residents were in training programs. In contrast, when a surplus of ROs was forecast in 1996, trainees dropped to less than 70 in number. These data highlight the need for both robust predictions of workforce requirements and a stronger linkage of these predictions to policy decisions in residency training and cancer control governance. This paper focuses on the former requirement.

Methods

Model development

The framework used to develop the workforce modeling equations is illustrated in Fig. 1. The right side depicts the factors that determine the number of radiation oncologists' full-time equivalents available for employment (supply or FTEs), while the left side illustrates factors affecting the number of radiation oncology positions required for appropriate service (demand or FTPs). The key factors that influence supply and demand are listed in Table 1. To obtain trend information, the model is seeded with data five years prior to the projection baseline. Thereafter, the model is recalculated annually by adjusting supply and demand according to the relationships shown in Fig. 2.

The incremental annual change in the supply of ROs is determined by adding new staff (career initiation sub-equation) and simultaneously removing some existing staff (career change and career termination sub-equations). Baseline values for the parameters utilized in the model are listed in Table 1. The number of ROs is multiplied by a "work intensity factor" to estimate the number of FTEs, because some RO positions will be part-time equivalents, either for reasons of life style (e.g., parents of young children) or significant non-clinical aspects of a position (e.g., administration).

The demand for radiation oncologists is estimated by calculating the number of new patient referrals to radiation oncology, and dividing this by the ratio of new patient consults (NPC) seen per FTE [19,21]. Further, NPC rates are influenced by existing forecasted cancer incident case rates and by potential changes in the proportion of incident cases referred to radiation oncology. Hence, "demand" is defined as the *required* number of radiation oncology full-time positions given a set RO average workload; it does not refer to the *actual* number of existing positions.

We refer to *discordance* as the difference between the number of required radiation oncology FTPs and the coincident number of radiation oncologist FTEs predicted by the model at any given year. Thus, *discordance* = (*demand*) − (*supply*) = Predicted required FTPs − Predicted FTEs.

Sources of data

The sources of data used in the model are also listed in Table 1. Radiation oncology resident data were collected from the Canadian Post-MD Education Registry (CAPER) (1989–2005), the Canadian Residency Matching Service (CaRMS) (1995–2005) and the CARO Manpower Survey (MPS) (2004–2009). The CMA Masterfile (1996–2005), CIHI (1990–2004), CARO MPS (1999–2009) and the National Physician Survey 2004 provided data regarding the number of practicing radiation oncologists in the country. Cancer incidence data were taken from Canadian Cancer Statistics and the Canadian Cancer Registry. The validity of the data was checked by evaluating the consistency between data sources wherever possible. If different sources of data yielded discordant data, the more directly acquired data (CARO manpower survey) were utilized in the model.

Workload data (2004 onward) were gathered with the CARO Manpower Survey. Department heads and training program directors complete an annual questionnaire regarding current and projected staffing and trainees (residents and fellows where relevant) in their individual departments. Response rates for the past five years have ranged from 94% to 100%. These data allow descriptions of the workforce across the parameters most likely to influence workforce projections (see, for example, Fig. S2 in on-line material that predicts retirement statistics based on national age demographics).

Sensitivity analysis

The model was seeded with point estimates of parameter values based on 2000–2005 trends. We assigned a plausible range of values to each parameter, based on these trends and on the literature review (Table 1). Changes in workload were made on a graduated basis over five years and sustained thereafter.

Model validation

The model was reviewed by the CARO Manpower and Standards Committee and found to have face validity (each

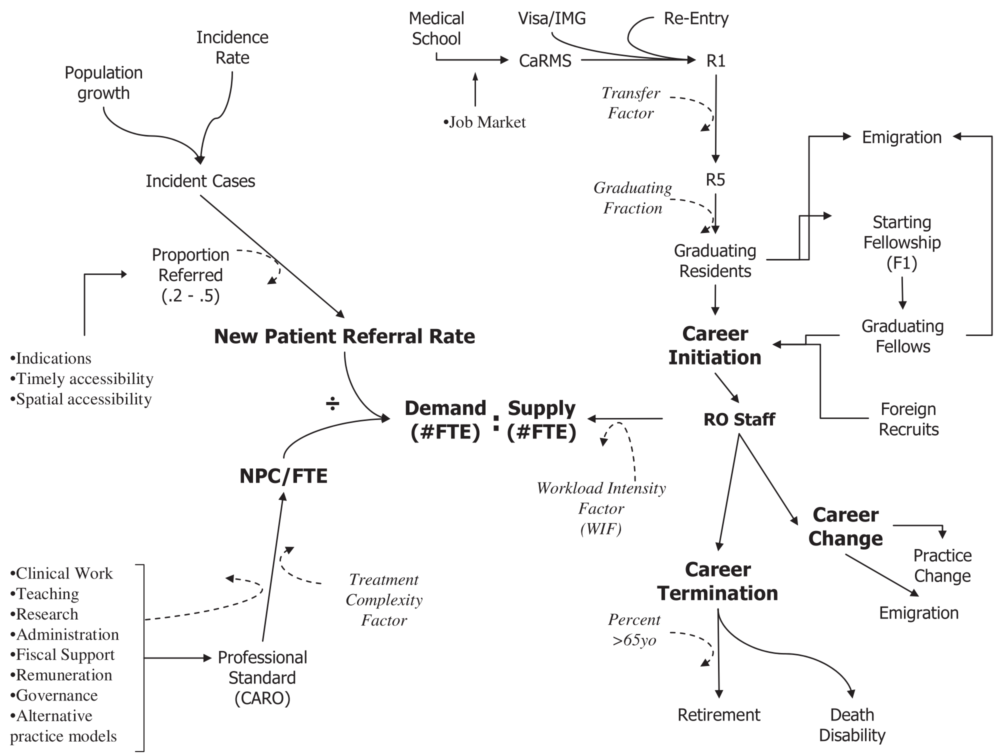

Fig. 1. The forward calculation model parameters are illustrated for both demand and supply calculations. Dotted lines refer to modifying factors.

Table 1
Key variables used in workforce projection model.

Domain	Parameter	Description	Base assumption	Range evaluated in sensitivity analysis
Demand	Incident cases	Rate of incident cases *(Canadian Cancer Statistics)*	Data as published, Growth 1.3% an.	Not applicable
	Proportion referred	Proportion of incident cases referred to radiation oncology (ref Delaney, Mackillop) *(CARO MPS and CCS)*	0.40	0.3–0.5
	NPC/FTE	Ratio of NPC per FTE based on workload factors that modify the standard professional workload *(CARO MPS)*	285	200–315
Supply (career initiation)	Resident graduates taking RO positions	Number of residents successfully completing training and entering workforce	Calculated annually from survey data	Not applicable
	RO fellows taking RO positions	Estimated number of RO fellows entering workforce on fellowship completion	Calculated annually from survey data	Not applicable
	Residents/fellows emigrating	Proportion of RO residents and fellows leaving the country at completion of training (estimated based on trends during seeding period) *(CAPER)*	0.12	0–0.15
	Resident transfer factor	Proportion of RO residents transferring into other training programs (estimated based on trends during seeding period).	0.9	Not applicable
	Foreign recruits	Estimated number of RO positions filled by neither RO residents nor fellows *(CMA)*	3	1–5
	Work intensity	Estimated proportion of RO positions that will be FTE (e.g., due to part-time or administrative positions) based on survey data	0.875	0.80–0.95
Supply (career change or termination)	RO emigration	Estimated number of ROs leaving practice in Canada for positions elsewhere *(CMA)*	5	2–9
	RO practice change	Estimated number of ROs changing practice to other specialty	0	N/A
	Death/Disability	Estimated number of ROs unable to practice	1	N/A
	Retirement	Estimated number of retirees from workforce *(CMA and CARO MPS)*	Calculated annually from survey data, retirement age 65	Retirement age 60–65

committee member independently reviewed the model and comments were collated by the writing committee). Construct validity was confirmed by comparison with other workforce planning models published in the literature. A 'historical prospective' test of predictive validity was carried out by seeding the model with data from 1990–1996 to project the balance of RO supply and demand predicted for 10 years hence (2007). The projected workforce balance and the number of predicted RO FTE positions were then compared with actual data collected throughout that timeframe.

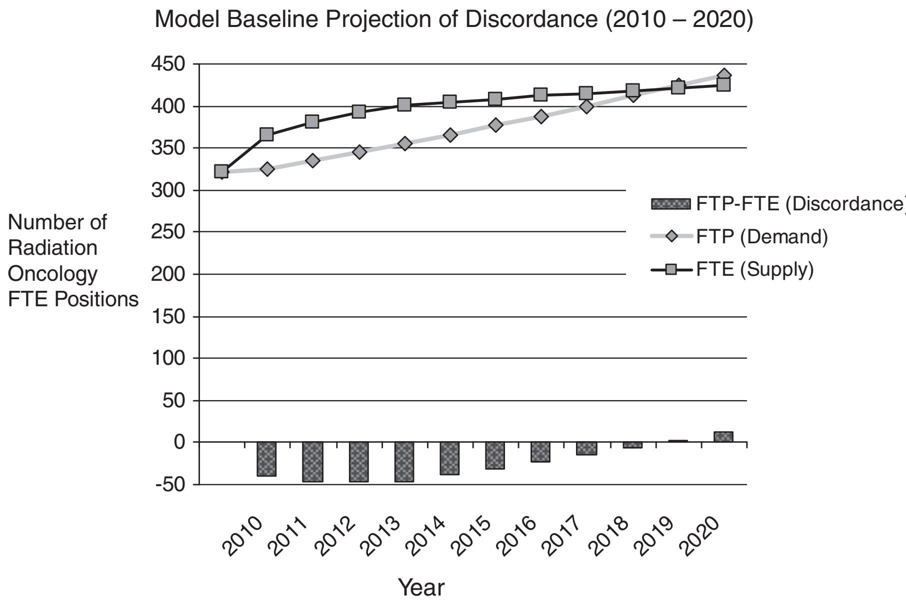

Fig. 2. Model calculations using baseline parameter estimates. Negative vertical bars represent a surplus of graduates; positive bars represent a deficit compared to projected workforce requirements.

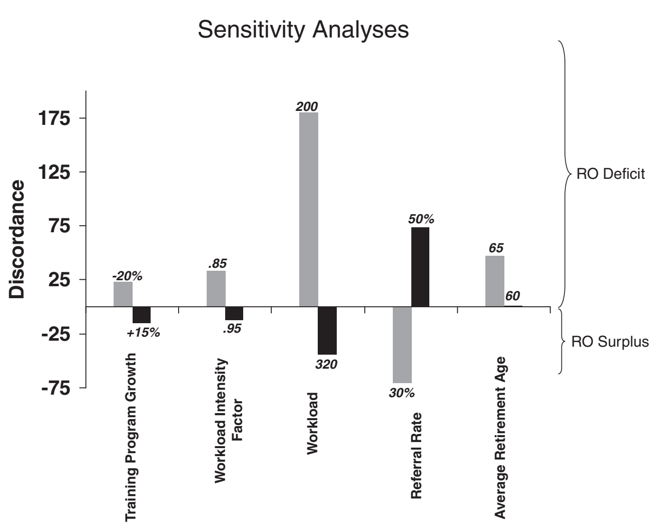

Fig. 3. Five factors most influencing discordance between supply and demand. Numbers at the bar ends refer to extremes of the range of plausible values used in the sensitivity calculations.

Results

Fig. 2 shows the baseline model projections of workforce size and concordance with workforce supply. Assuming training program size remains constant (26 residents per year nationally), and the variable base-rates in Table 1, the model projects a surplus of radiation oncologists over the next 8 years, peaking at 47 in 2012. By 2020, there would be a deficit of 13 RO positions.

Fig. 3 illustrates the findings of the one-way sensitivity analyses on each model variable, and reveals that the five most influential factors affecting discordance at 10 years (2020) are training program growth, workload intensity factor (FTE conversion per RO), workload per FTE, referral rate and average retirement age. When each factor was modified within its respective plausible range, referral rate and workload had the greatest impact on projections of discordance. A rapid exodus of 20% of trainees in the current R1 and R2 cohorts, accompanied by a sustained 20% decrease (from current total trainees) in training program size, resulted in a deficit of 43 ROs by 2020.

Given the importance of workload and referral rates in determining the degree of workforce concordance, we undertook a two-way sensitivity analysis of these parameters; the results of this analysis are shown in Fig. 4. As illustrated, a variety of combinations of referral rate and RO workload would result in no discordance between supply and demand of ROs in 2020 (all other variables being held constant at the baseline values). For example, were the referral rate to increase to 45% of incident cases, workload would have to increase to over 315 new patients consultations per FTE in order to remain in balance with current resident training program capacity.

In a validation using a historical data cohort followed prospectively, data regarding the number of practicing ROs, RO and resident emigration and immigration rates, resident training numbers, retirements, referral rates and cancer incidence rates were collected for 1990–1996. The model was seeded with these data and the RO FTP:FTE discordance was projected from 1997 to 2007. The results are shown in Fig. S3. Ten years hence to seeding the model, it projected a supply of 357 RO FTEs and demand for 363 required FTPs for 2007 (panel A), consistent with the actual number of RO FTEs at that time point, thus validating the model. In contrast, Panel B illustrates the same 10 year projection along with actual observed manpower data collected from the same time period; the latter showed a temporary deficit of positions followed by a ‘catch-up’ period. The deficit was due to an unpredicted exodus of residents out of training programs beginning in the early 90’s where the first-year trainee cohort went from a peak of 26 trainees in 1993 down to 4 trainees in 1997.

Discussion

Physician workforce planning in radiation oncology is critical for ensuring that the RO workforce has sufficient capacity to meet patient care needs while also ensuring that resident training does not substantially exceed or fall short of employment opportunities (given the restrictions on where and under what conditions radiation oncologists are able to work). Beyond the general challenges in physician workforce planning (such as the long lead-time for

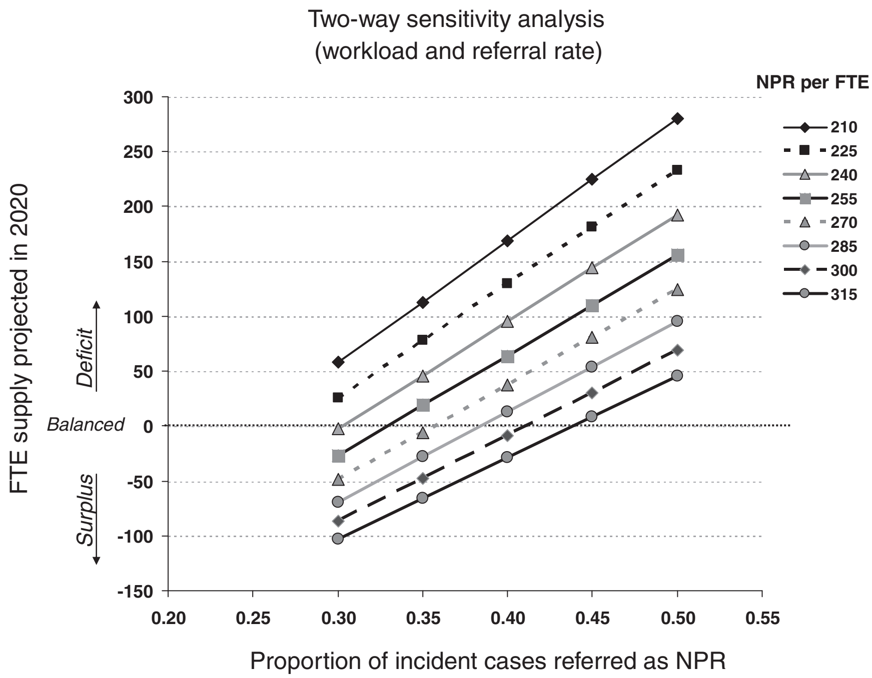

Fig. 4. A two-way sensitivity analysis illustrating concurrent effects of estimates of workload (new patient referrals (NPR) per FTE radiation oncologist) and access to care (proportion of incident cases referred to RO). The horizontal dotted line indicates combinations of these parameters that result in balance of supply and demand in 2020.

training, regional disparities, alternate remuneration strategies, dependence on government support for salaried positions and facilities, and implementation delays), there are additional challenges more specific to radiation oncology workforce planning such as predicted growth in cancer incidence, potential changes in indications for radiotherapy, potential changes in complexity of workload with the increased use of new technologies, and the lack of predictability in residency enrollment (in turn, a complex function of how attractive the specialty is seen to be by medical graduates). This workforce planning model can predict RO workforce needs, and the sensitivity of these predictions to a variety of key influencing factors highlights the need for careful, coordinated workforce planning.

The model has several strengths. Baseline estimates are taken from a robust data-set (an annually repeated survey of RO departments with virtual complete response rates) which shows convergence with other sources of staffing data. Many of the parameters such as cancer incidence projections and age demographics are also quite robust, and the model estimates themselves are based on transparent integration of factors that influence supply and demand. The model can thus generate robust estimates of supply and demand at the national level over a longer time frame suitable for workforce planning.

The model complements components of the ESTRO QUARTS project [24] that evaluated radiotherapy infrastructure and staffing requirements within the EU, including more broad aspects of infrastructure such as linear accelerator throughput and other aspects of radiotherapy delivery which were beyond the scope of the present modeling. "Work Package 1" of the QUARTS project – an overview of national guidelines for infrastructure and staffing of radiotherapy [25], focused specifically on workforce planning in several European countries, by summarizing existing national guidelines where available (about 40% of those nations surveyed). The methods also took into account between-country differences in cancer incidence and evidence-based estimates of infrastructure needs. The authors suggested estimates of radiation oncology human resources planning based on a ratio of ROs to annual patient load, but also noted that specific guidelines varied substantially between EU countries, and between the EU, Australia and Canada. The model developed herein could complement RO workforce planning in other nations using these global estimates; for example, by explicitly modeling plausible ranges of future human resources needs 10 years hence based on manipulation of several different parameter assumptions including predicted changing cancer incidence rates, referral rates, complexities and patterns of practice, among others.

The model is not without limitations, however with regard to selection of the basic model design, we elected to employ a "utilization-based" approach [26] rather than the alternatives such as complex simulation approaches, [17] econometric approaches that incorporate costs explicitly, [26] or more complex "demand-based" approaches that build from a zero-base the quantity and types of services that are felt to be needed. [26] Although the utilization-based approach has been criticized as risking propagation of the status quo without re-evaluation, [26] we believe the approach is the most realistic and efficient way to forecast trends in a centralized system where practice patterns are already well established.

As with all workforce models, projections are also somewhat limited by the required simplifying assumptions. Clearly radiation oncology practice is not without complexities in both health care delivery and non-patient care activities. For example, implementation of advances in treatment technology (e.g., IMRT, SBRT, and complex brachytherapy) is becoming commonplace, and the next decade could well see changing demands on RO professional time based on these changes, or could see increased use of other healthcare professionals (e.g., advanced practice radiation therapists) in roles currently performed by ROs. The model allows explicit incorporation of how such changes in caseload complexity, or alternative patterns of practice, would be reflected as adjustments to the ratio of new cases per FTE. These adjustments, however, require appropriate data to inform the best-estimate of the magnitude of the specific correction factors required by the model. Such data will likely be forthcoming, as briefly addressed for IMRT, for example, by Das et al., [27] or for introducing new technologies such as proton therapy by Pommier et al. [28] Other simplifying assumptions include the provision for fellowship training (a consistent proportion of residents deferring entry into the workforce based on current patterns, Table 1) and a consistent proportion of foreign-trained ROs entering the workforce (Table 1). We point out that the sensitivity analyses address the impact of these assumptions on the model projections.

There are several important implications for the model projections. As noted earlier, access to radiotherapy services can fall under periods of workforce shortage [19]. In Canada, there is recent health-services research evidence that utilization of radiation remains sub-optimal, [20,29–31] as has been seen in other countries [15,16,32–36]. Our findings illustrate that utilization rates – increases in the proportion of cases referred – have the greatest magnitude of impact on RO workforce requirements. Since cancer incidence rates are also projected to increase with growth and aging of the Canadian population, the two phenomena combine to project a marked increase in case load and, hence, on workload demand. In addition, a recent evaluation of the US radiation oncology workforce [37] has predicted a deficit of ROs, raising concern about a potential shortage of specialists beyond Canada. Hence, resident specialty training must be adjusted to be commensurate with expected availability of positions, and physical resources must be created to see and treat increased numbers of patients. Since both residency training and cancer clinic physical resources require long time lines, lack of coordination of implementing policy in one of these areas threatens the other. Moreover, governance of residency training (positions are funded by Ministries of Education and allocated by Provincial University Deans) is quite distinct from governance of radiation oncology positions, and an expansion or contraction of trainee spots must be negotiated between training program directors and deans. These complexities further emphasize the need for data that will inform the respective policies of these governing agencies. Finally, the present modeling exercise could also be modified and applied to other relevant disciplines such as medical physicists, and radiation technology as has been done, for example, in Australia [38] and the USA [38].

Conclusions

Valid workforce planning in radiation oncology can be effectively undertaken. Increasing cancer incidence and increasing utilization rates predict greater caseload demand that must be met by adjusting intake and retention of radiation oncology trainees. Discordance between supply and demand may lead to a repeating cycle of high individual workloads and lack of resident enrollment. Information provided by workload projections should inform such policy decisions.

Conflict of interest

None declared.

Funding acknowledgements

Dr. Brundage is supported as a Senior Research Chair of Cancer Care Ontario.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.radonc.2011.12.025.

References

[1] Cody HJ. Report of the Royal Commission on the Use of Radium and X-Rays in the Treatment of the Sick. Toronto: King's Printer, The Royal Commission. 1932. Ref Type: Report.
[2] Hayter CR. Historical origins of current problems in cancer control. Can Med Assoc J 1998;158:1735–40.
[3] Barer ML, Stoddart GL. Toward integrated medical resource policies for Canada: 1. Background, process and perceived problems. Can Med Assoc J 1992;146:347–51.
[4] Barer ML, Stoddart GL. Toward integrated medical resource policies for Canada: 12. Looking back, looking forward. Can Med Assoc J 1993;148: 29–32.
[5] Borrie MJ, Dalziel W, Fisher R, Molloy W. Puxty J Physician supply: future tense. Can Med Assoc J 2003;169:752–3.
[6] Buske L. Newtons an overview of Canadian Physician Work Force databases. Can Med Assoc J 1997;5:56–60.
[7] Dawes CR. Physician supply: future tense. Can Med Assoc J 2003;169:749–50.
[8] Evans RG. Same old wine: right and wrong on physician supply. Can Med Assoc J 1998;158:757–9.
[9] Kondro W. Canada's physician density remains stagnant. Can Med Assoc J 2006;175:465.
[10] Howell E. Physician, count thyself. Can Med Assoc J 2008;178:381–4.
[11] http://www.caro-acro.ca/Committees_and_Programs/CARO_Committees.htm. CARO web site. 2010.
[12] Podgorsak EB. Radiotherapy services in Canada: equipment and staff workloads. Current Oncol 1998;5:208–15.
[13] AMWAC Report - Specialist Medical Workforce Planning in Australia – A Guide to the Planning Process Used by the Australian Medical Workforce Advisory Committee, Sydney. 2003.
[14] The Royal College of Radiologists Clinical Oncology UK Workforce Census 2009. London: The Royal College of Radiologists.
[15] Expert Working Group on Radiation Oncology Services. The Development of Radiation Oncology Services in Ireland. 2003.
[16] Numasaki H, Teshima T, Shibuya H, et al. National structure of radiation oncology in Japan with special reference to designated cancer care hospitals. Int J Clin Oncol 2009;14:237–44.
[17] Denton FT, Gafni A. Spencer BG Physician supply in Ontario: further observations on SHARP and the SHARP projections. Can Med Assoc J 1995;152:1389–91.
[18] Sullivan P. For first time unemployment line awaits group of new Canadian specialists. Can Med Assoc J 1997;156:1739–41.
[19] Cummings BJ. Principles of radiation oncology training and manpower requirements in Canada. Int J Radiat Oncol Biol Phys 1992;24:833–5.
[20] Mackillop WJ. Health services research in radiation oncology. In: Gunderson LL, Tepper JE, editors. Clinical Radiation Oncology. Churchill Livingstone: Philadelphia; 2007. p. 215–37.
[21] Froud PJ. Radiation oncology in Canada: the increasing manpower crisis. Can Med Assoc J 1985;132:351–7.
[22] Thorne S. Staffing shortfall plagues radiation oncology. CMAJ: Canadian Medical Association Journal 1995;152:398–9.
[23] Kamra J. Worried residents watch and wait. CMAJ: Canadian Medical Association Journal 1997;157:253.
[24] Bentzen SM, Heeren G, Cottier B, et al. Towards evidence-based guidelines for radiotherapy infrastructure and staffing needs in Europe: the ESTRO QUARTS project. Radiother Oncol 2005;75:355–65.
[25] Slotman BJ, Cottier B, Bentzen SM, Heeren G, Lievens Y. Van den BW Overview of national guidelines for infrastructure and staffing of radiotherapy. ESTRO-QUARTS: work package 1. Radiother Oncol 2005;75:349–54.
[26] O'Brien-Pallas L, Baumann A, Donner G, Murphy GT, Lochhaas-Gerlach J, Luba M. Forecasting models for human resources in health care. J Adv Nurs 2001;33:120–9.
[27] Das IJ, Moskvin V, Johnstone PA. Analysis of treatment planning time among systems and planners for intensity-modulated radiation therapy. Journal of the American College of Radiology 2009;6:514–7.
[28] Pommier P, Lievens Y, Feschet F, et al. Simulating demand for innovative radiotherapies: an illustrative model based on carbon ion and proton radiotherapy. Radiother Oncol 2010;96:243–9.
[29] Foroudi F, Tyldesley S, Walker H, Mackillop WJ. An evidence-based estimate of appropriate radiotherapy utilization rate for breast cancer. Int J Radiat Oncol Biol Phys 2002;53:1240–53.
[30] Mackillop WJ, Groome PA, Zhang-Solomons J, et al. Does a centralized radiotherapy system provide adequate access to care? J Clin Oncol 1997;15:1261–71.
[31] Tyldesley S, Boyd C, Schulze K, Walker H. Mackillop WJ Estimating the need for radiotherapy for lung cancer: an evidence-based, epidemiologic approach. Int J Radiat Oncol Biol Phys 2001;49:973–85.
[32] Vinod SK, Simonella L, Goldsbury D, Delaney GP, Armstrong B. O'Connell DL Underutilization of radiotherapy for lung cancer in New South Wales, Australia. Cancer 2010;116:686–94.
[33] Delaney G, Jacob S. Barton M Estimating the optimal radiotherapy utilization for carcinoma of the central nervous system, thyroid carcinoma, and carcinoma of unknown primary origin from evidence-based clinical guidelines. Cancer 2006;106:453–65.
[34] Delaney G, Jacob S. Barton M Estimating the optimal external-beam radiotherapy utilization rate for genitourinary malignancies. Cancer 2005;103:462–73.
[35] Ruggieri-Pignon S, Pignon T, Marty M, Rodde-Dunet MH, Destembert B. Fritsch B Infrastructure of radiation oncology in France. a large survey of evolution of external beam radiotherapy practice. Int J Radiat Oncol Biol Phys 2005;61:507–16.

[36] Teshima T, Numasaki H, Shibuya H, et al. Japanese structure survey of radiation oncology in 2007 based on institutional stratification of patterns of care study. Int J Radiat Oncol Biol Phys 2010;78:1483–93.
[37] Smith BD, Haffty BG, Wilson LD, Smith GL, Patel AN. Buchholz TA The future of radiation oncology in the United States from 2010 to 2020: will supply keep pace with demand? J Clin Oncol 2010;28:5160–5.
[38] Round WH. A 2009 survey of the Australasian clinical medical physics and biomedical engineering workforce. Australas Phys Eng Sci Med 2010;33:153–62.