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Original Article

Radiotherapy underutilisation and its impact on local control and survival in New South Wales, Australia

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ABSTRACT

Background and purpose: This study aimed to identify the actual radiotherapy utilisation rate (A-RUR) in New South Wales (NSW) Australia for 2009–2011 and compare that to the published evidence-based optimal radiotherapy utilisation rate (O-RUR) and to previously reported A-RUR in NSW in 2004–2006. It also aimed to estimate the effect of underutilisation on 5-year local control (LC) and overall survival (OS) and identify factors that predict for underutilisation.

Materials and methods: All cases of registered cancer diagnosed in NSW between 2009 and 2011 were identified from the NSW Central Cancer Registry and linked with data from all radiotherapy departments. The A-RUR was calculated and compared with O-RURs for all cancers. The difference for each indication was used to estimate 5-year OS and LC shortfall. Univariate and multivariate analyses were performed to identify factors that correlated with reduced radiotherapy utilisation.

Results: 110,645 cancer cases were identified. 25% received radiotherapy within one year of diagnosis compared to an estimated optimal rate of 45%. This has marginally improved from previously reported rate of 22% in NSW in 2004–2006. We estimated that 5-year OS and LC were compromised in 1162 and 5062 patients respectively. Factors that predicted for underuse of radiotherapy were older age, male gender, lower socioeconomic status, increasing distance to nearest radiotherapy centre and localised disease.

Conclusion: The identified deficit in radiotherapy use has a significant negative impact on patient outcomes. Strategies to overcome such shortfalls need to be developed to improve radiotherapy use and patient outcomes.

Radiotherapy is an integral part of cancer management with a recognised effective role in curative and palliative settings. It remains however, a globally underutilised treatment [1–5]. Gaps in care can be identified when actual radiotherapy utilisation rate (A-RUR) is compared to optimal radiotherapy utilisation rate (O-RUR), with the latter being derived from evidence-based models of the distribution of treatment indications in a population [6–8]. We estimate that 48% of Australian cancer patients should receive radiotherapy at least once in their lifetime [6]. Previously reported A-RUR from New South Wales (NSW) and Australian Capital Territory (ACT) in 2004–2006 was 25% [9].

In the setting of optimal care, evidence-based radiotherapy has been estimated to result in a 5-year local control (LC) benefit in 10.4% of all cancer patients and 5-year overall survival (OS) benefit in 2.4% [10].

This study aimed to identify A-RUR in NSW Australia and compare this to the estimated O-RUR and to the previously reported A-RUR in NSW in 2004–2006, calculate the impact of radiotherapy underutilisation on LC and OS at the population level and identify patient, treatment, tumour and health service related factors that could impact on radiotherapy use.

Materials and methods

All cancer cases diagnosed in NSW between 1/1/2009 and 31/12/2011 were identified from the NSW Central Cancer Registry. Additional sources of data were obtained from the NSW Clinical Cancer Registry that provided information on disease stage and treatment details, Admitted Patient Data Collection (APDC); Births, Deaths, and Marriages (BDM) as well as data from all public and private radiotherapy departments. Data were linked using unique

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patient identifier created by the Centre for Health Record Linkage (CHeReL) [11]. Ethics approval was obtained from NSW Health Human Research Ethics Committee (Reference HREC/17/CIPHS/2).

A-RUR was calculated for the entire cohort of patients, as well as for each tumour site and, where possible, for different disease stages and/or other groups of indications as per the evidence-based decision trees published by the Collaboration for Cancer Outcomes, Research and Evaluation (CCORE) [6,7].

As the Clinical Cancer Registry does not routinely collect recurrence data, this analysis was limited to the first radiotherapy course within 12 months from diagnosis to represent the treatment of the initial cancer diagnosis without considering recurrence, and therefore the published optimal RTU trees were truncated to exclude re-treatment. The recalculated O-RUR was 44.5% when indications for radiotherapy for recurrent disease were excluded.

Data on radiotherapy use was not available from interstate centres. Patients residing within NSW but who were geographically closer to interstate facilities were excluded from the analysis because the majority of these patients would likely access radiotherapy outside of the NSW centres and inclusion would result in an under-estimate of actual utilisation. These patients were referred to as "cross border patients".

A-RUR was calculated using the following equation:

$$A-RUR = \frac{number\ of\ patients\ receiving\ radiotherapy\ for\ an\ indication}{total\ population\ with\ the\ attribute} \times 100\%$$

Estimates of O-RUR for each branch were calculated based on the truncated trees and based on the epidemiological data of the current study cohort and therefore the optimal rates calculated in this study differ slightly from the optimal rates in the published trees. The relative shortfall in radiotherapy utilisation (RTU) was then calculated using the following equation:

$$Shortfall\ in\ RTU = \frac{Optimal\ RUR - actual\ RUR}{optimal\ RUR}$$

Previously reported A-RUR in NSW and ACT in 2004–2006 was recalculated (for the overall cohort as well as for all individual tumour sites) to exclude ACT patients and those who received radiotherapy beyond 1 year of diagnosis to allow comparison with the current data.

Patient, tumour and treatment related factors that could affect radiotherapy use were analysed using univariate and multivariate analyses. These factors included age, gender, degree of disease spread (local, regional or distant), country of birth (Australia versus overseas), socioeconomic status (SES) using Index of Relative Socioeconomic Disadvantage 2011 (IRSD 2011) [12], remoteness of residence and distance of residence to closest treatment centre. The latter was obtained by geocoding patient's residence and that of nearest treatment facility to calculate the road distance [13].

CCORE has also published optimal utilisation trees that incorporated trial evidence for LC and OS at each branch in order to estimate LC and OS benefits for an optimally treated cancer population [10]. These trees were used to calculate the LC and OS detriment due to radiotherapy underutilisation. Where there was no standard-of-practice alternative treatment to radiotherapy, this indication for radiotherapy was called "irreplaceable benefit". In cases where alternative treatments could be equally used, such as surgery for early prostate cancer, then this was defined as replaceable benefit. For the purpose of this study, replaceable benefits were not calculated. Therefore the survival and local control losses estimated are conservative estimates.

The following formula was used to calculate the loss of benefit:

$$Loss\ of\ benefit = proportional\ benefit\ (LC\ or\ OS)\ x\ shortfall\ x\ number\ of\ patients\ with\ the\ attribute.$$

Results

118,626 cancer cases were diagnosed in NSW during the study period. After exclusion of cross-border patients (n = 7981 (6.7%)), 110,645 cases were included in the analysis. The median age was 67 years and 43% of patients were females, 41% were born in Australia, 82% were living within 50 km from the nearest radiotherapy facility and 71% were in major cities (Supplementary File 1).

The overall 1-year A-RUR was 25% compared to the estimated O-RUR of 44.5%. Table 1 details the actual and optimal RTU rates by tumour site and for the overall cohort. Underutilisation was observed in almost all tumour sites but the greatest relative deficit was seen in breast (61% A-RUR versus 86% O-RUR) followed by prostate (23% versus 52%), lung (41% versus 73%), lymphoma (22% versus 65%) and head and neck cancers (51% versus 70%) (Fig. 1).

The recalculated A-RUR from NSW data in 2004–2006 (after excluding ACT patients and those who received radiotherapy beyond 1 year of diagnosis) was 22%. Therefore the current A-RUR of 25% represented a small increase in the overall A-RUR. When compared by tumour site, there has been an increase in A-RURs for all cancers except for oesophagus, testis, bladder and lymphoma (Fig. 2).

Over the 3-year study period, we estimated that this "missed" radiotherapy potentially compromised survival in 1162 patients (an average annual excess death of 387 patients per year) and compromised the local control in 5062 patients (an average LC loss of 1687 cases per year). When analysed by tumour site (Table 1) the greatest estimated OS shortfall in person number was seen in lymphoma (209 people) followed by head and neck (193), lung (164), prostate (124) and breast (87) cancers, whereas shortfall in LC was mostly impacted by radiotherapy underutilisation in prostate (1398 people) followed by breast (583), lymphoma (353), head and neck (333), and lung cancers (327).

On univariate and multivariate analyses, the factors that were significantly associated with radiotherapy underutilisation were: older age, male gender, localised disease, Australian country of birth, living in most disadvantaged and regional areas and increasing distance to the nearest radiotherapy facility (Table 2).

Fig. 3 demonstrates effect of age on A-RUR. For tumours such as lymphoma, there is reduction in A-RUR after 29 years of age and that reduction continues into later age. In breast and rectal cancers the drop starts from 70 years of age and from 60 years in brain and lung cancers.

Table 3 shows the effect of travel distance to nearest radiotherapy facility and compares this to NSW data from 2004 to 2006 [7]. Accessibility has improved with 82% of patients in the current data living within 50 km of the nearest radiotherapy facility, compared to 78% in 2004–2006. A drop in RTU is noted with distances greater than 50 km.

Discussion

It is important to identify the A-RUR to assess patient accessibility and determine the required future capacity of radiotherapy services. This study identified a significant overall underuse of radiotherapy within one year of diagnosis with a rate of 25% compared to the estimated O-RUR of 44.5%. There was a small improvement from the A-RUR of 22% in NSW five years prior.

A-RURs reported in other jurisdictions vary, but NSW 2009–2011 compares unfavourably with reported rates in other high income countries such as Belgium (37%) [14], Sweden (43%) [15], Ontario, Canada (39%) [16] and USA (31%) [1]. It is important to point out that some of these figures include re-treatments and/or

Table 1
Actual and Optimal radiotherapy utilisation rates in NSW 2009–2011 and estimated 5-year LC and OS shortfall due to radiotherapy underutilisation.

Tumour Site	Population with the attribute	Proportion of patients with attribute	Given RT within 1-year	Not given RT within 1-year	Actual RTU	Optimal RTU	Estimated 5-year OS benefit for RT (%)	Estimated OS Shortfall in person (N)	Estimated 5-year LC benefit for RT (%)	Estimated LC Shortfall in person (N)
Head and Neck	3848	3.5%	1974	1874	51.3%	70.4%	18.5%	193	31.9%	333
Oesophagus**	1215	1.1%	589	626	48.5%	69.7%	2.0%	7	6.0%	22
Stomach	1918	1.7%	356	1562	18.6%	27.3%	1.1%	6	1.8%	11
Pancreas	2696	2.4%	197	2499	7.3%	45.3%	0.0%	–	0.0%	–
Colon	9906	9.0%	334	9572	3.4%	0.5%	0.0%	–	0.0%	–
Rectum**	3628	3.3%	1307	2321	36.0%	55.4%	4.0%	51	13.0%	165
Liver	1640	1.5%	61	1579	3.7%	0.0%	0.0%	–	0.0%	–
Gall Bladder	292	0.3%	19	273	6.5%	16.5%	0.0%	–	0.0%	–
Lung	9927	9.0%	4039	5888	40.7%	72.6%	3.8%	164	7.5%	327
Melanoma	10,769	9.7%	478	10,291	4.4%	14.9%	0.0%	–	3.5%	265
Breast	13,311	12.0%	8095	5216	60.8%	86.4%	2.2%	87	14.8%	583
Vulva	283	0.3%	73	210	25.8%	35.2%	8.4%	6	9.9%	7
Vagina	70	0.1%	41	29	58.6%	93.0%	–	–	–	–
Cervix*	745	0.7%	347	398	46.6%	70.1%	13.0%	32	28.0%	70
Uterus	2096	1.9%	501	1595	23.9%	35.8%	2.3%	16	5.2%	36
Ovary	1250	1.1%	46	1204	3.7%	3.6%	0.0%	–	0.0%	–
Prostate*	19,816	17.9%	4460	15,356	22.5%	52.2%	1.1%	124	12.4%	1398
Testis	659	0.6%	74	585	11.2%	5.6%	8.6%	–	9.3%	–
Kidney	2858	2.6%	249	2609	8.7%	7.3%	0.0%	–	0.0%	–
Bladder	2282	2.1%	412	1870	18.1%	23.2%	3.0%	15	5.1%	26
Brain	1433	1.3%	873	560	60.9%	78.2%	4.5%	14	9.0%	28
Thyroid	2519	2.3%	101	2418	4.0%	2.2%	0.8%	–	1.1%	–
Unknown	2808	2.5%	531	2277	18.9%	61.3%	0.0%	–	0.0%	–
Lymphoma	4773	4.3%	1037	3736	21.7%	65.2%	6.6%	209	11.1%	353
Leukaemia	2809	2.5%	161	2648	5.7%	3.9%	0.5%	–	0.4%	–
Multiple Myeloma	1376	1.2%	348	1028	25.3%	40.6%	1.0%	5	2.0%	10
Other Cancers	5718	5.2%	1018	4700	17.8%	18.5%	3.0%	6	9.0%	19
Total	110,645	100.0%	27,721	82,924	25.1%	44.4%	2.4%	1162	10.5%	5062
Annual								387		1687

* Irreplaceable RT benefit.
** Concurrent chemo-radiotherapy benefit.

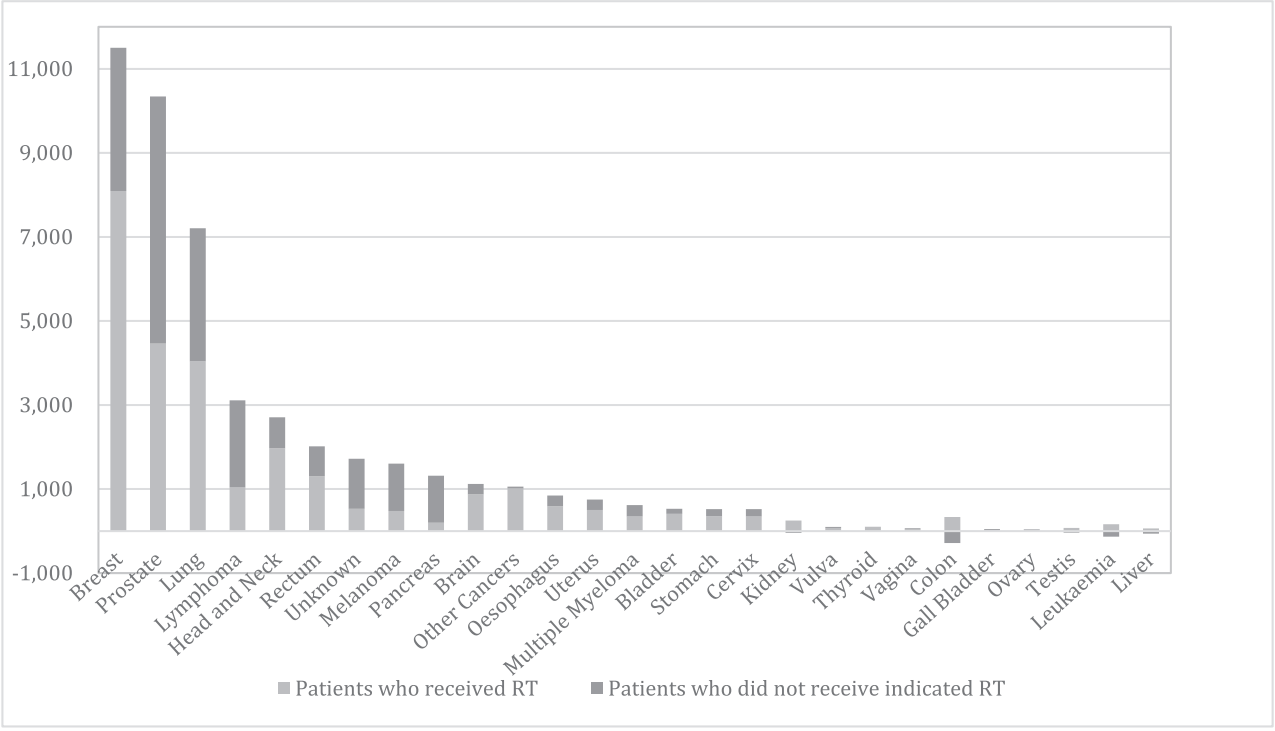

Fig. 1. Number of cancer patients who received and did not receive indicated radiotherapy within one year of diagnosis – NSW 2009–2011.

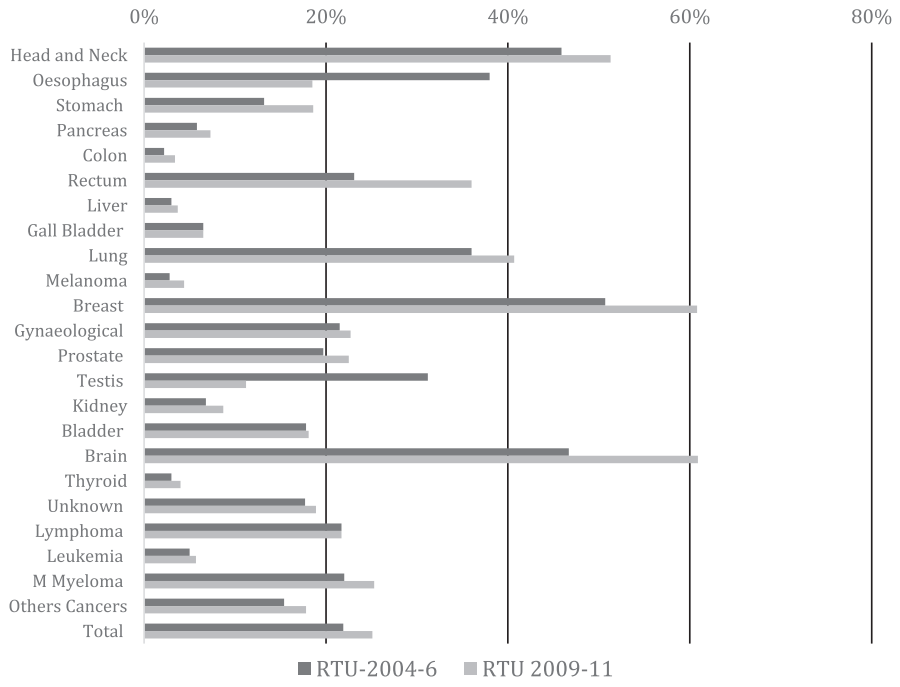

Fig. 2. RTU rates in 2004–2006 versus 2009–2011 across all tumour sites.

Table 2
univariate and multivariate logistic regression. All cancers, NSW 2009–2011.

		Univariate analysis			Multivariate analysis		
Variable	Description	*P* value	Odd ratio	95% CI (lower–upper)	*P* value	Odd ratio	95% CI (lower–upper)
Age (years)	Continuous	0.000	0.986	0.985–0.987	0.000	0.986	0.985–0.987
Age group	<45 years	0.000	2.265	2.131–2.406			
	45–59 years	0.000	2.712	2.585–2.845			
	60–69 years	0.000	2.395	2.285–2.509			
	70–79 years	0.000	2.108	2.009–2.211			
	80+ years		1.000				
Sex	Female	0.000	1.496	1.456–1.537	0.000	1.330	1.292–1.368
	Male		1.000			1.000	
Degree of spread	Local disease		1.000			1.000	
	Regional disease	0.000	2.326	2.247–2.407	0.000	2.278	2.199–2.359
	Distant metastasis	0.000	1.694	1.629–1.761	0.000	1.755	1.686–1.826
	Indeterminate	0.000	0.644	0.617–0.671	0.000	0.696	0.667–0.726
Country of birth	Australian born		1.000			1.000	
	Overseas born	0.000	1.106	1.067–1.147	0.037	1.041	1.002–1.082
	Unknown	0.000	0.754	0.731–0.777	0.000	0.761	0.737–0.786
Socioeconomic status (IRSD)	Most disadvantaged		1.000			1.000	
	Quintile-2	0.292	0.977	0.936–1.020	0.863	0.996	0.952–1.042
	Quintile-3	0.131	1.034	0.990–1.079	0.855	1.004	0.960–1.051
	Quintile-4	0.001	1.076	1.031–1.123	0.857	1.004	0.959–1.051
	Least Disadvantaged	0.824	0.995	0.953–1.039	0.000	0.912	0.870–0.956
Remoteness	Major Cities		1.000			1.000	
	Inner Regional	0.000	0.830	0.803–0.859	0.013	0.948	0.909–0.989
	Outer Regional	0.000	0.767	0.723–0.814	0.382	1.039	0.954–1.132
	Remote and V Remote	0.264	0.898	0.744–1.084	0.000	1.732	1.358–2.210
Distance (km)	Continuous	0.000	0.998	0.998–0.999	0.000	0.998	0.998–0.999
Distance Category	<50 km		1.000				
	50–99 km	0.000	0.872	0.828–0.918			
	100–149 km	0.000	0.823	0.768–0.883			
	150–199 km	0.000	0.820	0.738 0.912			
	200+ km	0.000	0.645	0.593–0.700			

used differing methodologies when calculating RTU, limiting direct comparisons.

Radiotherapy underutilisation was observed across almost all tumour sites in NSW during the study period, with the greatest deficit seen in breast followed by prostate, lung, lymphoma and head and neck cancers. These findings are comparable to results from a Canadian study that reported on RTU rates within 1 year of diagnosis during 2004–2008 [17]. These were 52% (vs. 61% in

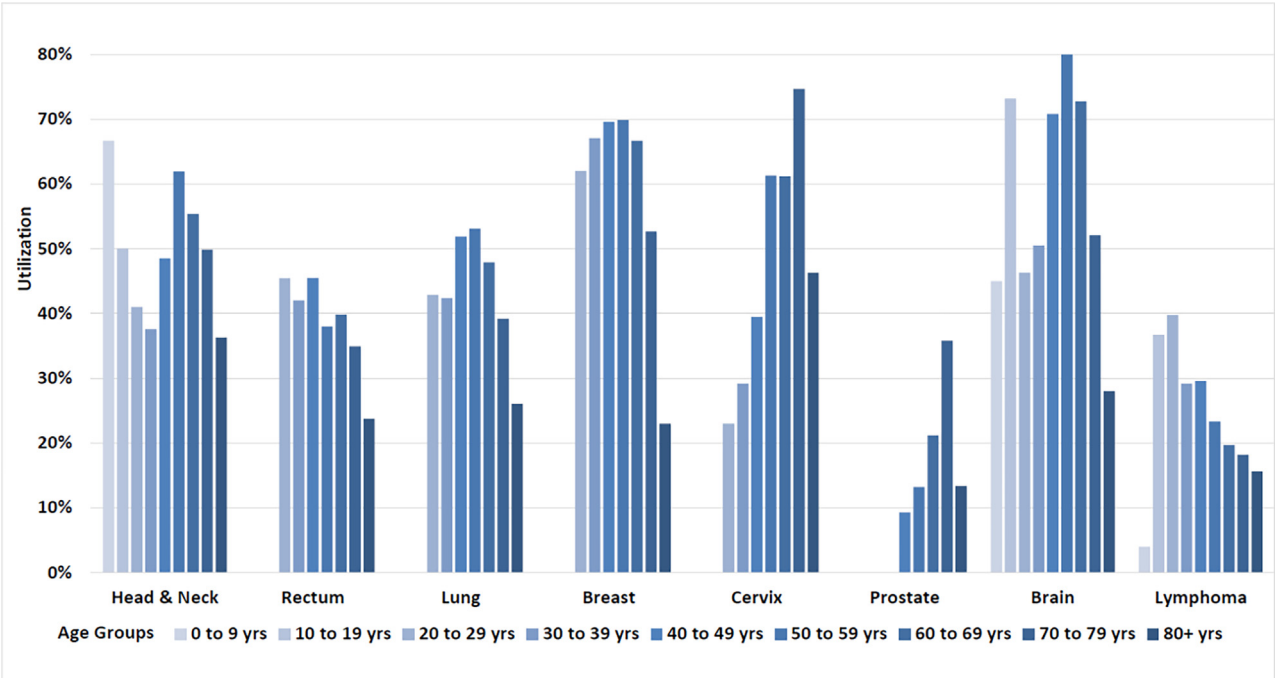

Fig. 3. Effect of age on radiotherapy utilisation for different tumour sites.

Table 3
Actual radiotherapy utilisation rate by distance group – NSW 2009–11 and 2004–06.

	2009–2011		*2004–2006*[*]	
Distance Group	% Total	1-year A-RUR	% Total	1-year A-RUR
<50 km	82%	26%	78%	22%
50–99 km	8%	23%	5%	22%
100–149 km	4%	22%	4%	20%
150–199 km	2%	22%	4%	20%
200+ km	3%	18%	9%	18%
Total	100%	25%	100%	22%

[*] Figures re-calculated to exclude ACT patients and those who received RT beyond 12 months of diagnosis.

our study) for breast cancer, 49% (vs. 47%) for cervix cancer, 37% (vs. 41%) in lung cancer, 27% (vs. 23%) for prostate cancer and 39% (vs. 36%) for rectal cancer. All rates were well below the estimated optimal rates.

It is important to note that radiotherapy is not being given in situations where published evidence support LC and/or OS advantages. The estimated shortfall in 5-year LC and OS is a particularly significant finding of this study. As shown in Table 1, it has been estimated that over this 3-year study cohort, 5026 and 1162 patients had a compromised LC and OS respectively. This equates to loss in LC of 1687 patients and 387 deaths per annum.

The findings in this study of a potential survival detriment are supported by other literature. Using similar methodology to our study, Mendez et al estimated a shortfall in radiotherapy of 111,000 patients out of 596,000 Brazilian patients registered with cancer in 2016. They estimated a loss of life for the 5 main cancers (breast, colorectal, cervix, prostate and lung) of approximately 5000 patients [18]. An Australian study has also identified that rectal cancer patients in Queensland who lived 200–399 km from a radiotherapy facility were at 30% greater risk of dying from rectal cancer than patients who lived within 50 km of a treatment centre [19]. An Italian study looking at outcomes for breast cancer patients based on journey times to the nearest radiotherapy facility has identified an excess mortality for untreated patients residing over 40 min away [20]. Others studies in medulloblastoma [21], Stage I and II Hodgkin's lymphoma [22,23], pancreatic cancer [24] and lung cancer [25] have also shown that radiotherapy underutilisation results in poorer survival. We have not identified studies that assessed shortfall on LC due to underuse of radiotherapy.

When assessed by tumour site, the greatest potential detriment in survival due to radiotherapy underutilisation was seen in lymphoma affecting 209 patients. Radiotherapy was used in only 22% of patients (versus an estimated optimal rate of 67%). There has been marked underutilisation of radiotherapy despite high-level evidence of radiotherapy benefit in lymphoma management, although lack of detailed data on lymphoma size and morphology (e.g. bulky lymphoma >5 cm, CNS lymphoma) in our dataset made it impossible to assess whether there were specific indications for radiotherapy that were not being treated. Our rates are comparable to an English study that examined A-RUR in lymphoma [26], showing a rate of 19% and 29% for non-Hodgkin's lymphoma and Hodgkin's lymphoma respectively. Another study using SEER database has demonstrated use of radiotherapy for early stage Hodgkin's lymphoma fell from 63% in 1998 to 43% in 2006. 5-year actual OS was 76% for those who have not undergone radiotherapy versus 87% for those who received radiotherapy [22].

Among breast cancer patients, a significant OS shortfall was seen in post-mastectomy patients with 1–3 positive nodes due to significant underutilisation of radiotherapy in this particular cohort (A-RUR 46%). This is despite high-level evidence of LC and OS benefit to radiotherapy use in node positive post-mastectomy patients [27,28]. A patterns of care study found that even in patients with strong indications for radiotherapy after mastectomy, where loco-regional recurrence was estimated to be greater than 30%, only 63% received radiotherapy. The most common reason for not receiving radiotherapy reported as lack of discussion of radiotherapy by the doctor or lack of perceived benefit [29].

Lung cancer represented another major tumour site where the low A-RUR (41% versus 73% optimal) was estimated to result in a significant negative effect on LC and OS in 324 and 126 patients respectively. Similarly, a study in Andalusia, Spain of 3051 lung cancer patients reported that their very low A-RUR of 20% resulted

in potential deaths of over 700 patients diagnosed in the year 2007 [25].

Increasing patient age was associated with reduced radiotherapy use. Patients aged 80 years and older represented 19% of the entire NSW cancer population and were half as likely to receive radiotherapy compared to patients in the younger age groups. While the most obvious explanation would be attributed to reduced fitness with age, it should be noted that in various clinical scenarios in the elderly, radiotherapy could be the preferred option over other treatment modalities such as surgery for bladder, prostate or cervix cancers or as a palliative treatment when poor performance status or comorbidities preclude delivery of a curative therapy. Tyldesley et al. identified a decline in the use of radiotherapy especially for adjuvant and palliative indications for patients older than 75 years. This relative decline exceeded the decline in functional status with age in the general population [26]. They concluded that most of the decline in A-RUR was related to a decline in referral to cancer centres [30]. There are many examples in the literature of inequality in the delivery of radiotherapy based on age [31–35], either because of patient's and/or physician's preference or beliefs.

The drop in A-RUR with age was earlier than would be anticipated in some tumours such as lymphoma (RTU drops after 29 years of age), rectal and breast cancers (after 69 years of age) and lung and brain tumours (after 59 years of age) (Fig. 2). This is despite evidence-based guidelines that would support radiotherapy use in older age groups.

Male gender was also associated with reduced A-RUR. When controlling for the gender-specific gynaecological, breast, prostate and testis cancers, male gender correlated with a greater use of radiotherapy by 5%. A study conducted on rural Victorian cancer patients reported higher A-RUR in females compared to males (34% vs. 20%) [36]. It is important that further studies are needed to examine decision-making and gender.

Previous data have shown a relationship between socioeconomic status and radiotherapy delivery and a decrease in curative treatment in the more deprived resulting in poorer survival [37]. This is consistent with our findings where patients living in the most disadvantaged areas were less likely to receive radiotherapy. Patients of lower SES generally have higher levels of comorbidity, less health awareness leading to lower rates of screening and later presentation as well as more financial constraints. All these factors may contribute to lower A-RURs although this varies across different tumour sites.

Higher A-RUR, as shown in multiple studies, is associated with increased urbanisation and proximity to treatment centre with resultant reduction in cancer mortality when compared to rural residence [9,19,36,38–40]. This is consistent with our findings. When compared to NSW data from 2004 to 2006 [9], patient accessibility to the cancer centres in 2009–2011 has improved and the proportion of patients who reside >100 kilometres away has dropped to below 10% (Table 3). This is due to additional 5 regional facilities that have opened since the first study. However, our study has also identified that the A-RUR drops off even at 50 km from a treatment centre. The improvement seen in patient accessibility between the 2 studies has almost certainly contributed to the slight improvement in overall A-RUR from 22% to 25%. Availability of specialist centres within a specified distance would also be expected to impact on A-RUR. However detailing the types and complexity of services provided and how they impact on A-RUR is beyond the scope of this paper and could be explored in further studies.

Improving access to and utilisation of radiotherapy will evidently result in better survival of cancer patients, with an added associated economic benefit [41]. The impact of reduced local control and reduction in overall survival is obvious for patients – additional pain and suffering, the ongoing morbidity of additional therapies and reduced lifespan. For some patients, locoregional recurrence can be salvaged but at the cost of additional disease-related and treatment morbidity. On other occasions it cannot be salvaged. In addition, there are significant health service and economic impacts of higher recurrence rates and poorer survival due to ongoing patient treatment needs, loss of productivity in the workplace, the potential for carers to also need to take leave and reliance on sickness benefits.

A multifaceted approach directed at the systems level, clinician level and patient level is required to improve RTU. Systems level approaches include provision of real time data measurement of A-RUR with comparison to peer institutions and jurisdictions, and mandating multidisciplinary team (MDT) discussion for selected patient groups with the greatest shortfall. Coordinated care involving MDT can increase the utilisation of non-surgical therapies [42], change initial management plans in a significant number of patients [43,44] and increase likelihood of receiving guideline-based care [44,45]. However, there is likely to be a selection bias in that patients presented at MDT meetings may be those who are fitter and thus more likely to receive treatment. This could be overcome if a broader range of patients of all ages and fitness levels are submitted for review by an MDT to confirm treatment agreed on complies with clinical protocols with appropriate referrals to respective teams.

Targeting behaviour change at the individual clinician level is more challenging. A systematic review of interventions identified the most effective interventions for behaviour change include individual education with academic detailing, audit, feedback and reminders [46]. Audit and feedback, where clinicians' practice is compared to an external reference such as peer group allows for continual improvement over time. This has a small to moderate effect depending on the way the intervention is designed and delivered [47]. The challenge is in identifying the "target audience" for an intervention. This would include referring doctors (such as respiratory physicians for lung cancer or haematologists for lymphoma) and general practitioners. Quality improvement processes mandated as part of continuous professional development by the Medical Board could help in this regard. Given the increasing use of electronic patient records, real-time clinical decision-support tools that identify patients who meet criteria for a radiotherapy indication could be developed. Developing and implementing interventions to a disparate group of clinicians would need buy-in from the relevant professional organisations.

Finally the profile of radiotherapy as a cancer treatment needs to be raised for patients so they actively ask about this as a treatment option. The Royal Australian and New Zealand College of Radiologists (RANZCR) is addressing this via its Targeting Cancer Campaign (https://www.targetingcancer.com.au/).

This study was limited by incomplete data on stage and performance status. This has limited our ability to examine in detail the specific indications where radiotherapy was underutilised. This study could not account for other factors that could have affected RTU such as referral pathways and patient's preference. And lastly the results are based on modelled estimates and this is subject to the inherent limitations of the models, although the models used have been built from evidence-based treatment guidelines and have undergone significant peer review and allow for variations in data.

In conclusion, this study has identified significant shortfalls in LC and OS at a population level due to underutilisation of radiotherapy. Multifaceted strategies from radiotherapy professional bodies targeting patients, referring doctors and health authorities are urgently needed to improve RTU and cancer outcomes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.radonc.2019.09.012.

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