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Original Article

Variable and fixed costs in NHS radiotherapy; consequences for increasing hypo fractionation

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ABSTRACT

Background/Purpose: The increased use of hypofractionated radiotherapy changes department activity. While expected to be cost-effective, departments' fixed costs may impede savings. Understanding radiotherapy's cost-drivers, to what extent these are fixed and consequences of reducing activity can help to inform reimbursement strategies.

Material/Methods: We estimate the cost of radiotherapy provision, using time-driven activity-based costing, for five bone metastases treatment strategies, in a large NHS provider. We compare these estimations to reimbursement tariff and assess their breakdown by cost types: fixed (buildings), semi-fixed (staff, linear accelerators) and variable (materials) costs. Sensitivity analyses assess the cost-drivers and impact of reducing departmental activity on the costs of remaining treatments, with varying disinvestment assumptions.

Results: The estimated radiotherapy cost for bone metastases ranges from 430.95€ (single fraction) to 4240.76€ (45 Gy in 25#). Provider costs align closely with NHS reimbursement, except for the stereotactic ablative body radiotherapy (SABR) strategy (tariff exceeding by 15.3%). Semi-fixed staff costs account for 28.1–39.7% and fixed/semi-fixed equipment/space costs 38.5–54.8% of provider costs. Departmental activity is the biggest cost-driver; reduction in activity increasing cost, predominantly in fractionated treatments. Decommissioning linear accelerators ameliorates this, although can only be realised at equipment capacity thresholds.

Conclusion: Hypofractionation is less burdensome to patients and long-term offers a cost-efficient mechanism to treat an increasing number of patients within existing capacity. As a large majority of treatment costs are fixed/semi-fixed, disinvestment is complex, within the life expectancy of a linac, imbalances between demand and capacity will result in higher treatment costs. With a per-fraction reimbursement, this may disincentivise delivery of hypofractionated treatments.

Over the past two decades, the use of hypofractionated curative radiotherapy has increased as greater conformality has reduced late toxicity in surrounding organs at risk. For common indications, this change can have a major impact upon activity within a radiotherapy department. Recent examples include the use of moderate hypofractionation for prostate cancer and more recently ultra-hypofractionation in both prostate and breast cancer [1–3]. The latter leading to a dramatic fall in delivered fractions in the UK during COVID-19 [4]. Internationally, for over 20 years, ultra-hypofractionation has been the standard of care in palliative radiotherapy, particularly for bone metastases [5,6].

Hypofractionation reduces treatment burden for patients, whilst maintaining outcomes and should minimise healthcare costs; a valuable advantage where spending within constrained healthcare budgets may deprive others of beneficial treatment. Hypofractionation may also be beneficial in capacity planning. With population growth and aging, cancer diagnoses are predicted to rise requiring increasing radiotherapy capacity [7]. Whilst

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Fig. 1. Agreed LTHT radiotherapy pathways for bone metastases (in minutes). **Legend:** Continuous lines represent a time-driven allocation; dotted lines are allocated per activity as defined in Table 1. Imaged – imaged fraction. Chat – first-day and last-day discussion with radiographer team. Imaged #: 2D or KV imaging for all (total fraction time: 16 min) excl. SABR, for which CBCT was performed 3 times (total fraction time: 30 min). #: The time for a standard fraction without image is 10 min. Additional activity-based allocations: For each patient attendance, the administrative team perform a variety of tasks such as staffing reception, booking radiotherapy, transport and/or interpreter etc., Similarly the nursing team conduct ad hoc and planned reviews throughout treatment delivery, hence we used an attendance basis.

Table 1
Department throughput parameters 2016/2017.

Department throughput per year	
Annual treatment courses	6597
Computer planned 3D conformal	3263
VMAT or IMRT technique	1904
SABR	50[1]
Mould room attendances[2]	1168
Fractions delivered	76,412
Patient attendances[3]	83,009

Legend:
[1] The delivery of SABR for bone metastases was commissioned for oligo-metastatic disease during the study period and throughput for this technique was assumed to align with that agreed at commissioning (150 courses over 3 years).
[2] Total mould room attendances across the department over a year, not just those in the bone metastases cohort.
[3] Total observed number within the department in a year. Patient attendances includes both a planning & consent visit and all fractions delivered.

investment will undoubtedly be required, efficiency in the use of existing facilities has the potential to reduce this.

Despite the clinical evidence and efficiency imperative, there are financial challenges to providers in adopting hypofractionated regimens; reimbursement is often lower than for a standard fractionation course [8,9]. However, due to capital investment in equipment and facilities, many of the resources required to deliver radiotherapy cannot be released when fractions are forgone. Reimbursement based on fractionation may therefore act as a perverse incentive to fractionate. Understanding of these factors is required when planning, deciding reimbursement and monitoring radiotherapy provision; a process referred to as commissioning in the English National Health Service (NHS) and led by a national body.

The World Health Organisation has defined healthcare costs as fixed, semi-fixed, and variable, recognizing the correlation of cost with the patient volume [10,11]. A large, but unknown proportion of radiotherapy costs are fixed/semi-fixed (e.g. large upfront investment in buildings and equipment, considerable semi-fixed staff costs) [9,12]. Semi-fixed costs behave as fixed costs until a threshold of activity is reached and a step change occurs, e.g. where an additional linear accelerator is installed or removed[2].

[2] Notably, the latter may not be possible depending upon the mechanism by which the equipment was purchased, e.g. lease-hold versus capital investment.

Consequently, reductions in reimbursement through hypofractionation, may not result immediately in realisable savings (and thus health gains) within providers [11,13].

In order to address the possible perverse incentives in current commissioning structures, there is a need to understand the nature and drivers of radiotherapy costs and how increasing hypofractionation impacts upon the cost of delivering remaining treatments. Using varying treatment strategies for bone metastases as an exemplar, this study uses a time-driven activity-based costing (TD-ABC) approach to determine the cost of radiotherapy delivery for a large NHS provider. This accounts for approximately 40% of palliative treatments and incorporates a variety of regimens and techniques [14–16]. The flexibility of TD-ABC makes it ideally suited to calculating the costs associated with the delivery of a known series of steps, requiring expensive medical devices, which aggregate to a variety of treatment courses [17,18]. The resulting model can inform both overall radiotherapy cost, reimbursement tariff and, importantly, identify the principle drivers of cost and consequences of increasing hypofractionation.

Methods

We used a TD-ABC approach to estimate the cost of radiotherapy strategies for painful bone metastases at a single, large NHS provider, Leeds Teaching Hospitals NHS Trust (LTHT) [18]. Strategies considered were a non-computer planned single 8 Gy fraction, 30 Gy in 10 fractions (computer and non-computer planned), stereotactic radiotherapy (VMAT using 3 fractions) and a computer planned 45 Gy in 25 fraction course.

Radiotherapy delivery consists of a predictable series of activities. In TD-ABC, activity costs are calculated as the cost per minute of all necessary resources multiplied by the time taken for delivery of the activity (see Eq. (1)). Activity costs are then summed to provide a total treatment cost. Costs are included from a healthcare provider perspective for 2016/17, using a full absorption approach to capture all costs in line with NHS's reference costs guidance [19].

Whenever possible activities were costed using a time-driven approach. Where the activity time was short, unpredictable or a resource was used simultaneously for multiple patients, the cost was allocated on an activity basis (e.g. per attendance, course or treatment plan). Model development was in Excel and presented graphically in appendix Fig. A1.

Table 2
Base-case costs in LTHT radiotherapy department: input parameter in Euro for the financial reference year of 2016/2017.

Time-driven resources		Cost per minute	Total cost per year	Capacity
Personnel		(€/min)	(€)	(mins)
Individuals[1]	Doctor	1.31	131.26	100,800
	Physicist	0.70	65.72	94,050
	Dosimetrist	0.57	53.47	94,050
Radiographer teams[2] (per unit)	Treatment			
	MLC	1.83	241498.39	131,444
	Agility	1.93	192,007.63	99,693
	Simulation	3.76	301983.02	80,328
Equipment[3] (including personnel and space for maintenance)	Linear accelerators			
	MLC	3.30	433241.26	131,444
	Agility	4.66	465095.06	99,693
	CT simulator	3.90	313472.03	80,328
Space[4] (including utilities)		**Cost per minute**	**Total cost per year**	**Space**
		(€/min)	(€)	(m^2)
	Linear accelerator bunker	0.64	73627.53	88
	CT simulator	0.93	74882.56	90
Activity based:		**Events/yr**	**Total cost per yr**	**Cost per event**
Personalised immobilisation	Space	1168	91625.52	77.94
	Personnel	1168	167435.32	143.27
	Material (thermoplastic shell) consumable	5% bone metastases courses		43.55
Radiotherapy planning	Space			
	All computer planned treatments	3263	166.47	44.39
	Additional incremental cost for VMAT treatments	1904	(weighted)	11.37
	Software			
	Contouring and treatment delivery software (incl. R + V)	83,009	273041.58	3.29
	Planning software (for computer planned only)	3263	246442.88	75.53
	Individual QA for VMAT	1904	28080.68	14.75
SABR specific costs	Multi-disciplinary team meeting[5] (per course)			73.58
	MRI for fusion[6] (external scan NHS fee)	50% of SABR courses		200.58
	Implementation budget			
	Staff	150	33503.11	223.35
	Capital	150	31468.65	209.79
Other staff [7]	Administrative staff (excl. clinician secretaries)	83,009	698522.26	8.41
	Nursing review clinic	83,009	318888.73	3.84
	Radiographers parental leave	83,009	105135.19	1.27
Departmental overheads	Departmental management			
	Nursing/radiographer staff time	83,009	398797.16	4.80
	Dosimetry staff time (for computer planned only)	3263	111.77 (weighted)	29.80
	Dosimetry staff time (Incremental additional cost VMAT)	1904		7.63
	Space			
	Indirectly allocated space	83,009	1800979.88	21.70
	Management space	6597	53588.24	8.13
	Budget			
	Departmental consumables budget (per attendance)	83,009	96689.21	1.17
	Review clinic consumables budget (per attendance)	83,009	79483.21	0.96
Hospital overheads:	Trust level overheads	15.4% of total departmental costs		
External resources (excluded from NHS tariff):	Initial OPA with clinician			314.05
	Transport	40% attendances		33.24
	Interpreter	1% courses		57.31

Legend:
Radiographer and dosimetrist time allocated to management/maintenance was attributed on an activity basis (per attendance and per course (weighted for VMAT) respectively).
All equipment and software was assumed to have a lifetime of 10 years.
The cost of physics and engineering staff time, space and equipment attributable to management and maintenance was incorporated into the linear accelerator costs. This time was weighted towards the Agility machines which required 25% more maintenance due to their imaging capability.
[1] Capacity for these staff is based on contractual working time.
[2] Radiographer costs are incorporated per team to ensure backroom functions are captured. The average cost per minute for one full time equivalent (FTE) was 0.42€ for simulation radiographers and 0.44€ for treatment machine radiographers. Capacity for these staff is based on observed machine activity.
[3] Linac capacity was based on observed activity in LTHT.
[4] The cost per m^2 per minute is calculated based upon the cost per m^2 of the total building per year (collected from finance data) and then divided by the total observed

number of minutes of activity in the area in question.
[5] Only the costs of the SABR MDT are included within this model. All patients with cancer are discussed within a wider diagnosis specific MDT at the point of diagnosis, however, as palliative radiotherapy to bone metastases is often delivered later in the disease trajectory based on review or referral from other clinicians no MDT cost was considered outside of the radiotherapy department.
[6] This is accounted for as a material cost. However the time radiographers spent on the MRI fusion is allocated on a time-driven basis.
[7] Staff time which cannot be attributed to an individual patient was allocated on an activity basis (per attendance). This includes administrative staff, nursing staff who complete ad hoc reviews and salary costs for staff on parental leave (included as three radiographers at any one time). The average cost per minute for administrative staff was 0.28€ assuming a practical capacity of 30 hours per week.

Time-driven allocation

Three types of information are required to estimate time-driven costs: department throughput, resources and pathway timings. The combined information allows calculation of a cost per minute for each resource with the pathway timings allowing calculation of activity cost.

i. Department throughput

Radiotherapy activity was extracted from the local record and verify system and is summarised in Table 1.

ii. Staff, equipment and space resources

The resources required, capacity, total cost and cost per minute are presented in Table 2. Radiographer time was included based on team membership and activity. In this way, the cost of team members carrying out backroom functions (e.g. offline image review) was captured (full absorption).

Staff contributions to management/maintenance, non-patient specific clinical duties and research/implementation were identified[3]. The cost of physicist/engineering time attributed to management/maintenance was included in the time-driven cost of the linear accelerators, alongside physics office space and maintenance equipment, whilst these other costs were incorporated on an activity basis.

Clinical Oncologists in the UK spend a proportion of their time delivering systemic therapy [16]. Only the time delivering activities in the radiotherapy department was included in the model, with the practical capacity of doctors being based upon a standard NHS job plan [17].

iii. Treatment pathways

The treatment pathways' activities and resources for each included strategy were defined in consultation with senior radiographers, physicists and oncologists to reflect departmental practice (Fig. 1). Treatment delivery times were based on linear accelerator appointment times. In order to identify treatment planning times, a department-wide survey was undertaken March–April 2017 (appendix Table A1).

Activity-based allocation

Software costs, dosimetry/physics' space for planning, administrative staff, radiographer's and dosimetry staff management as well as departmental budget and generic spaces, (e.g. waiting rooms) could not be allocated a timing. As such, an activity based approach was used e.g. per attendance, course, treatment plan etc (see Table 1). Costs of staff and space for creating immobilisation devices were included by equally dividing between the number of patients having mould room appointments within the year.

[3] This was done through discussion with senior members of the multi-disciplinary radiotherapy team.

For stereotactic ablative body radiotherapy (SABR), the cost of a multidisciplinary team meeting (MDT) within the radiotherapy department was included. In addition, the costs of implementing the SABR technique (including capital and staff time (physicist, engineer, oncologists and radiographers)) were split between all patients to receive the treatment[4].

Materials

A small number of discrete consumables, and internal tariffs for MRI scans are the material component included as an average cost per course.

Hospital overheads

Hospital-level overheads including portering, security, IT, human resources and management, were included at 15.4% of the total departmental treatment costs.[19]

External costs

The share of radiotherapy costs reimbursed outside of tariff for clinic appointments, patient transport and interpreter services are considered separately based on NHS tariff and local agreements (see Table 2).

Total costs comparison and breakdown

Using the TD-ABC model, the total cost of each of the five bone metastasis strategies was estimated from the healthcare provider perspective and compared to NHS reimbursement tariff. The share of these costs attributable to fixed, semi-fixed and variable costs was then assessed.

Sensitivity analyses

In order to assess the major drivers of treatment costs, one-way deterministic sensitivity analyses were carried out. Fraction delivery time was assumed to be 10 minutes for unimaged fractions, 16 for imaged and 30 minutes for SABR. To consider the consequences of hypofractionation on the cost of remaining treatments, the number of fractions delivered was systematically reduced beyond the average capacity of a single linear accelerator (7400 fractions per year) [20] with varying levels of reductions in staff, equipment and both. Following implementation of hypofractionation it was assumed that the released linac capacity was not required to improve waiting times or treat currently underserved populations.

TD-ABC cost equation to calculate the total treatment cost.

$$Total\ Cost_{Activity} = \left(Time_{Activity} \times \left(\mathrm{Cost}_{\mathrm{Staff\ per\ minute}} + \mathrm{Cost}_{\mathrm{Equipment\ per\ minute}+\mathrm{Cost}_{\mathrm{Space\ per\ minute}}}\right)\right) + Cost_{Materials} \quad (1)$$

Nota Bene: In accounting literature, we refer to cost per minute as the capacity cost rate (CCR).

[4] Projection of patients anticipated to receive the treatment within the commissioned period of 3 years.

Table 3
Overall totals in Euro and breakdown for differing fractionation patterns and delivery of bone metastases RT strategies (excluding external costs).

	Materials	Time-driven planning costs			Time-driven treatment delivery costs			Activity-based costs (incl. departmental overheads)					Hospital over-heads	Total provider costs (tariff equivalent)	Total external costs
		Staff	Equipment	Space	Staff	Equipment	Space	Staff	Space	Software	Budget	Implementation			
Total Single 8 Gy - non-computer planned	2.19 (0.51%)	104.19 (24.2%)	58.53 (13.60%)	17.90 (4.16%)	29.40 (6.83%)	52.73 (12.25%)	8.96 (2.08%)	36.65 (8.515%)	51.52 (11.97%)	6.58 (1.53%)	4.37 (1.015%)	0.00 (0.00%)	57.45 (13.34%)	430.48	337.14
			180.62 (41.96%)			91.10 (21.16%)				99.12 (23.03%)					
Total 30 Gy in10 - non-computer planned	2.19 (0.15%)	104.19 (6.97%)	58.53 (3.92%)	17.90 (1.2%)	194.75 (13.03%)	349.38 (23.38%)	59.37 (3.97%)	201.61 (13.49%)	246.78 (16.51%)	36.18 (2.42%)	24.05 (1.61%)	0.00 (0.00%)	199.42 (13.34%)	1494.35	473.94
			180.62 (12.09%)			603.51 (40.386%)				508.62 (34.036%)					
Total 30 Gy in10 - computer planned	2.19 (0.12%)	136.50 (7.25%)	58.53 (3.11%)	68.92 (3.66%)	227.82 (12.11%)	408.71 (21.72%)	69.46 (3.69%)	231.41 (12.30%)	291.17 (15.47%)	111.70 (5.94%)	24.05 (1.28%)	0.00 (0.00%)	251.09 (13.34%)	1881.55	473.94
			263.95 (14.03%)			705.98 (37.52%)				658.33 (34.99%)					
Total SABR 24 Gy in 3- computer planned	102.63 (3.18%)	621.51 (19.26%)	466.96 (14.47%)	138.29 (4.29%)	173.34 (5.37%)	419.87 (13.01%)	66.47 (2.06%)	110.74 (3.43%)	150.66 (4.67%)	103.43 (3.21%)	8.75 (0.27%)	433.14 (13.43%)	430.55 (13.34%)	3226.35	364.65
			1226.78 (38.02%)			659.68 (20.44%)				806.72 (25.01%)					
Total 45 Gy in 25# - computer planned	2.19 (0.05%)	136.50 (3.22%)	58.53 (1.38%)	68.92 (1.63%)	562.39 (13.26%)	1362.26 (32.12%)	215.65 (5.09%)	506.32 (11.94%)	616.61 (14.54%)	88.69 (2.09%)	56.83 (1.34%)	0.00 (0.00%)	565.93 (13.34%)	4240.84	719.32
			263.96 (6.23%)			2140.30 (50.47%)				1268.46 (29.91%)					

Legend: Trust overheads were calculated as 15.4% of the sum of all other costs within the RT dept. (excl. external cost), the percentage shown here reflects the share of total treatment cost these overheads account for.

Results

The estimated cost of delivering radiotherapy for bone metastases ranges from 430.95€ for a single fraction to 4240.76€ for a fractionated 45 Gy in 25 fractions course. Table 3 shows a detailed breakdown of costs with treatment delivery accounting for the largest share where a fractionated treatment is undertaken (37.5–50.5% of total cost). Activity-based departmental costs represent 25–35% of the total, although again these are lower for shorter, more hypofractionated treatments.

The modelled costs align closely with NHS reimbursement tariff (Fig. 2a). One exception to this is seen in the SABR strategy where tariff during early commissioning exceeded total provider costs by 15.3%.

Whilst semi-fixed staff costs account for 28.1–39.7% of the total treatment cost, a somewhat larger proportion (38.5–54.8%) is attributable to fixed and semi-fixed space and equipment costs (see Table 3 and Fig. 2b).

Fig. 3 demonstrates that the cost drivers are similar across fractionated strategies, but differ for hypofractionated courses, including SABR. The main cost driver for all conventional radiotherapy is the number of fractions delivered annually, followed by resource cost i.e. personnel, equipment and space. Conversely for SABR treatment, equipment cost is the largest cost driver. Additional sensitivity analyses recognising alternative assumptions of number of patients undergoing SABR within the initial 3-year period (150 cases) reveal that a 33% change results in a change in costs of −1.88% to 3.75%.

Expanding the assessment of the consequences of reducing fraction numbers across the department, Fig. 4 illustrates the impact on remaining treatment course costs (percentage change), with the greatest impact seen in fractionated treatments. Disinvestment from semi-fixed (staff) costs has a relatively modest impact upon remaining total costs whilst disinvestment from semi-fixed (linear accelerators) costs has a greater impact on total cost although this can only be realised at thresholds aligning to equipment capacity.

Discussion

This study demonstrates good alignment between NHS reimbursement tariff and the cost of providing radiotherapy for bone metastases. An exception to this is the discrepancy between the provider costs of SABR and higher reimbursement tariff. The tariff for established treatments is calculated based upon the submission of reference costs to NHS England by multiple provider organisations, these provide a framework for reimbursement incorporating planning and treatment delivery separately and recognising some elements of complexity. This process probably explains the alignment seen here [19]. In contrast, the tariff for emergent treatments such as SABR is based upon estimates of expected costs, from limited providers, prior to routine implementation across the NHS and may also aim to incentivise delivery of a novel intervention. The provider cost is sensitive to assumptions of demand and in line with existing literature is likely to demonstrate a learning curve effect, with costs reducing with increasing expertise [21,22]. Similarly Lievens et al. have previously shown that complex treatments are associated with more variable costs between providers [22]. As such, estimates of provider cost may vary both between providers and over time. Further assessment will be required as routine reimbursement expands.

Beyond the cost associated with a novel intervention, we demonstrate that 40–50% of the cost of radiotherapy is attributable to space and equipment (fixed and semi-fixed costs respectively), whilst a further 30–40% reflects radiotherapy department

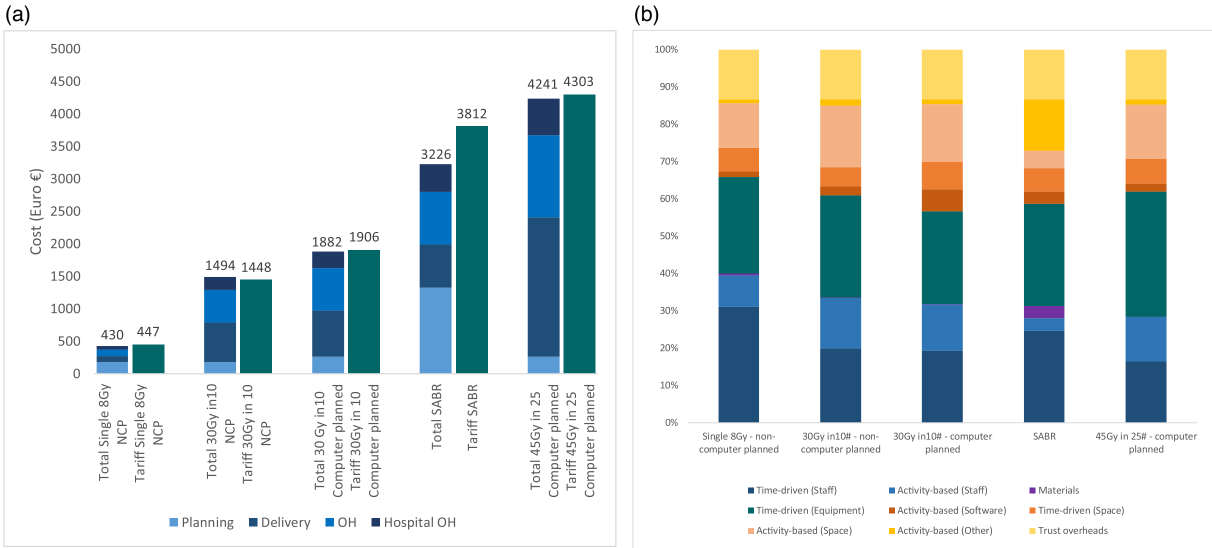


Fig. 2. (A) Monetary comparison of UK healthcare payer tariffs (NHS) and large healthcare provider (LTHT, in Euro 2016/2017) costs of bone metastases RT treatment across five treatment strategies. (B) Breakdown of total provider costs according to source of cost. Cost types are identified by colours: variable = purple, semi-fixed: staff = blue, equipment = green and fixed = shades from orange to yellow. See appendix Table A2 for further detail. **Legend:** (A) TD-ABC estimation of LTHT radiotherapy delivery costs (2016/2017). Interpreters, transports costs and initial outpatient clinic costs were not included in the costs estimates, as these are not reimbursed within the radiotherapy tariff. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

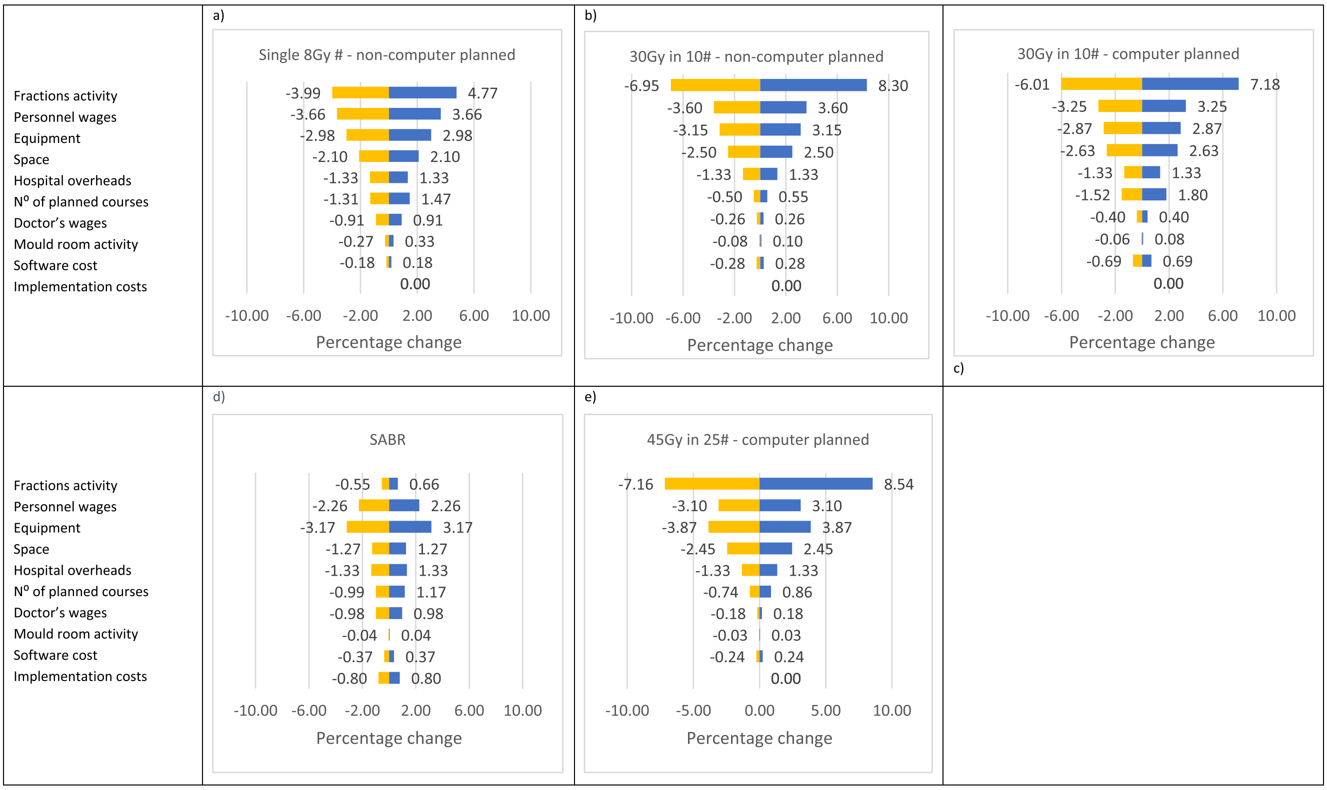
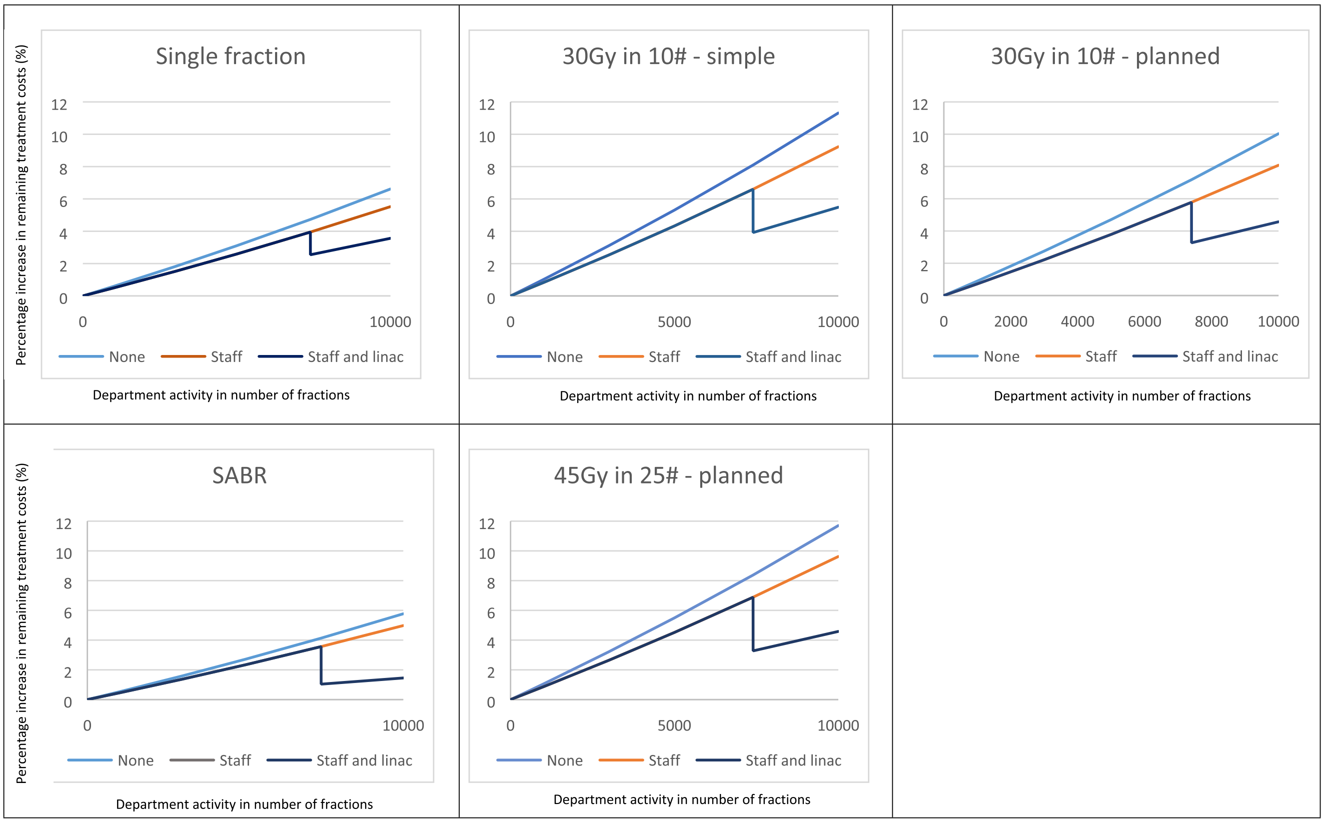


Fig. 3. Results of sensitivity analysis: Tornado plots demonstrating cost-drivers in four radiotherapy treatment strategies, with input parameters varied by a 10% in both directions (x-axis). Implementation costs are varied to reflect a 50% increase or decrease in activity due to the high levels of uncertainty in this parameter.

personnel costs (semi-fixed). The contribution of fixed/semi-fixed costs is consistent across all treatment strategies, being slightly higher in those where a shorter course is delivered. Staff costs account for a lower proportion (approximately 40%) than those demonstrated in other studies (approximately 50%), potentially reflecting the relatively higher cost of space within our hospital, due to the method of capital finance [23–25]. That space and equipment are major cost drivers suggests that the mechanism of securing capital investment in both buildings and equipment may have a significant impact upon the cost of treatment delivery [26]. This should be borne in mind when commissioning new capacity [27]. Notably, whilst space costs have a greater influence over



Legend: We assume an annual number of fractions per linacs per 7,400 [19], with an average delivery time per fraction of 13mins, applicable to radiographers and linacs capacity.

Fig. 4. Percentage change in treatment cost for each modelled strategy with reduction in department activity (fractions). Base-case change is shown (with no reduction in staff or equipment) and two separate scenarios in which staff numbers are reduced and a linear accelerator is decommissioned (semi-fixed costs). In both cases the resource cost per minute is based upon linear accelerator activity.

the cost of conventionally fractionated treatments, the relative proportion of costs attributable to medical time makes shorter courses more sensitive to doctor salaries.

Reflecting this cost breakdown, aligned with existing literature, the largest single cost driver of delivering conventional radiotherapy is the level of departmental fraction throughput [28]. This reflects its influence upon the cost per minute of a wide range of other parameters, including other major cost drivers such as equipment and space. This highlights the potential role of economies of scale resulting in cost variations between small and large providers. This maybe of particular importance in countries where smaller treatment centres make up a greater proportion of total capacity.

That such a large proportion of the cost of radiotherapy is fixed warrants further discussion. In the context of hypofractionation, implementation of treatments delivered to large numbers of patients (e.g. for breast or prostate cancer) will potentially result in a fall in departmental fractions delivered (although resources required for treatment planning are likely to rise), systematically increasing the cost of remaining treatments. It is reasonable to think this capacity will be required in the long-term to treat increasing numbers of patients [7]. While existing equipment and staffing are maintained, however, it may result in a deficit between reimbursement and provider's spending, sufficient to discourage providers from adopting ultra-hypofractionated regimens. Sharing the impact of these, potentially dramatic, changes in total reimbursement between payers and providers may help to ensure capacity is released through hypofractionation, supporting both efficient delivery of care immediately and greater capacity availability in future.

An alternative reimbursement structure, based upon the delivery of completed courses as opposed to fractions, would remove the incentive to fractionate but might introduce an undesirable drive towards excessive hypofractionation. During COVID-19, prospective fixed reimbursement was implemented within NHS-England, supporting services to deliver ultra-hypofractionated breast radiotherapy, thus maintaining services and keeping patients safe, without financial detriment to providers [29]. However, such an approach risks undermining innovation and driving up waiting lists [13]. Moving away from the pay per fraction (prospective variable) reimbursement structure towards a more mixed commissioning structure, combining prospective and retrospective variable components might offer an alternative option. Such an approach could recognise the fixed costs of space and equipment through a retrospective variable component, using a prospective variable component to drive complexity, fractionation and quality, in line with that required by commissioners. Whilst having potential to offer value for payers and stability to providers, this would be considerably more complex and require clear understanding of service priorities in order to align reimbursement accordingly. These results support previous studies recommending tariff modernisation and provide exemplar cost data to inform this process [9].

The extent to which the costs of forgone fractions are realisable is also of wider health economic importance. In the UK, the National Institute for Health and Care Excellence has grappled with the challenge of how to recognise savings associated with decommissioning existing equipment in the context of intra-operative radiotherapy for breast cancer [8]. They concluded that this resulted in significant uncertainty around the cost savings available. The extent to which decommissioning of equipment is possible will vary depending upon the size of the treating centre, proportion of fractions forgone and, importantly, the mechanism by which equipment is funded. Consequently, identifying the realisable cost savings available from hypofractionation or alternative interventions requires in-depth knowledge of the expected geographical distribution of both equipment and decommissioned fractions. In addition, decommissioning may incur engineering and contractual costs. The corollary of this should be recognised where significant capital investment is considered, e.g. for novel technology such as proton beam therapy and MR-linac. Alternative cost-effectiveness modelling scenarios incorporating both marginal and total costs may be valuable; if capital investment is already sunk[5], it might be appropriate to consider the marginal costs (within sensitivity analyses) where patients can be treated within existing capacity. Conversely, where new capacity is required for which capital investment has not yet been committed, all costs should be included.

This TD-ABC model has a number of limitations that need to be recognised. Firstly, we focus upon the cost per treatment for one treatment indication and not the total departmental costs. This allowed consideration of cost drivers across a range of treatment techniques, however, it is not possible to comment upon the overall departmental budget impact of changing treatment patterns. This will be the focus of future work, however, these results may none the less be valuable to service managers who have oversight of a whole department. A notable challenge, in this context, is quantifying any unmet demand. Here we assume no unmet demand exists. Multiple international studies have, however, demonstrated a mismatch between observed and optimal treatment utilisation, suggesting unmet demand does exist which may effectively offset a reduction in fraction activity [30]. The extent of this mismatch remains uncertain, particularly at an individual provider level, with this lack of certainty potentially reinforcing the perceived risk of financial loss if hypofractionation is implemented. Greater focus on identifying these "missing patients" would support improved confidence in service planning.

The costs presented also represent those of a single, large, NHS provider in 2016–17. The space costs shown may be relatively large due to the mechanism by which capital investment was secured. Equally, as a large provider, economies of scale are available potentially reducing overall costs. The time period included is not expected to change the conclusions of the study and indeed, the results may have greater significance following the covid-19 pandemic as increased treatment time is required to ensure infection prevention protocols are followed, with potential implications for departmental throughput. The implications of the results, however, pertain to publically funded healthcare systems with a prospective, fixed reimbursement system, these will differ where private providers and alternative reimbursement systems are considered with the consequent incentives to hypofractionate varying too. A small number of costs are not well captured within this model, notably research activity. This may result in a slight costing under-estimation. Finally, concerns about cost shifting as an artefact of accounting techniques have previously been highlighted [31]; the risk that the costs resulting from complex equipment may be inappropriately shifted onto simpler treatments. We minimise this by recognition of differing costs for machines of varying complexity. This concern maybe unrealistic though, this may not be an accounting artefact but simply a reality of modern radiotherapy departments where at times simple treatments are delivered using relatively complex equipment, thus maximising equipment usage but potentially increasing the cost of delivery.

We demonstrate that a large proportion of the costs associated with radiotherapy delivery are fixed or semi-fixed. Consequently, departmental activity is the major driver of treatment costs and the move towards hypofractionation increases the cost of remaining fractions in the absence of previously underserviced demand. This may act as a perverse incentive for providers to maintain fractionated regimens offering lesser value to payers and greater burden to patients. These data will help to inform modernisation of reimbursement tariffs to support the delivery of efficient services in the short, medium and longer term.

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Conflicts of interest

None.

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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.2021.11.035.

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