Towards estimating the carbon footprint of external beam radiotherapy

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ARTICLE INFO

Keywords:
Carbon footprint
Sustainability
Radiotherapy

ABSTRACT

Purpose: The National Health Service (NHS) in the United Kingdom (UK) is aiming to be carbon net zero by 2040 to help limit the dangerous effects of climate change. Radiotherapy contributes to this with potential sources quantified here.

Method: Activity data for 42 patients from within the breast IMRT and prostate VMAT pathways were collected. Data for 20 prostate patients was also collected from 3 other centres to enable cross centre comparison. A process-based, bottom-up approach was used to calculate the carbon footprint. Additionally, patients were split into pre-COVID and COVID groups to assess the impact of protocol changes due to the pandemic.

Results: The calculated carbon footprint for prostate and breast pre-COVID were 148 kgCO2e and 101 kgCO2e respectively, and 226 kgCO2e and 75 kgCO2e respectively during COVID. The energy usage by the linac during treatment for a total course of radiotherapy for prostate treatments was 2.3 kWh and about 1 kWh for breast treatments. Patient travel made up the largest proportion (70–80%) of the calculated carbon footprint, with linac idle power second with ~10% and PPE and SF leakage were both between 2 and 4%.

Conclusion: These initial findings highlight that the biggest contributor to the external beam radiotherapy carbon footprint was patient travel, which may motivate increased use of hypofractionation. Many assumptions and boundaries have been set on the data gathered, which limit the wider application of these results. However, they provide a useful foundation for future more comprehensive life cycle assessments.

1. Introduction

The impacts of climate change are becoming increasingly apparent through a variety of extreme weather events, including severe flooding, wild fires, and heatwaves. It has also been suggested that climate change may increase the risks of lung, gastro-intestinal and breast cancers, through exposure to air pollution, disruptions to food and water supplies, exposure to industrial toxins and through the disruption of cancer services [1, 2]. Recognising the urgent need to address these issues the National Health Service (NHS) in the UK has committed to achieving carbon net zero by 2040 [3]. In 2019 the NHS was responsible for approximately 25 million metric tonnes CO2 equivalent emissions (CO2e), which is equivalent to roughly 5% of the UK’s entire carbon footprint [4]. It is clear that the need to reduce the carbon footprint of healthcare services, and its contribution to the climate crisis, is urgent.

A Carbon Footprint Analysis is a technique for evaluating the environmental impact of a system or process by estimating the amount of greenhouse gases (GHGs) it produces. Each of these GHGs has a global warming potential (GWP) value assessed over a measured timeframe, which estimates how much global warming they produce compared to...
carbon dioxide (whose GWP is defined to be 1.0). The sum of emissions of all of these gases, multiplied by their GWP, is the carbon dioxide equivalent (CO₂e) and is a measure of the carbon footprint of the process.

External Beam Radiotherapy (EBRT) uses high energy radiation to treat approximately 120,000 patients annually in the UK [5], 50% of all cancer patients [6]. Energy-intensive linear accelerators (linacs) are used to deliver definitive, conventional radiation treatment typically in 15–30 separate visits over 3–6 weeks. The radiotherapy pathway, from patient referral for treatment through to follow up, includes Computed Tomography (CT) scans and sometimes additional Magnetic Resonance Imaging (MRI) or nuclear medicine scans. Studies have shown the carbon footprint of these scans can be substantial [7,8]. The environmental impact of travelling for treatment has been investigated, with one study finding that a 15-fraction approach resulted in a travel distance of 392.3 km and a carbon footprint of 111.4 kg CO₂e, compared to a single-fraction approach which resulted in a travel distance of 87.1 km and a carbon footprint of 25.7 kg CO₂e [9].

The carbon footprint (quantified as carbon dioxide equivalent (CO₂e)) of linac operations has two known components: SF₆ and power consumption. Sulphur hexafluoride (SF₆) is a gas used in linacs and has a GWP of 23,500 [10], meaning that a small leak of this gas could have a significant carbon footprint. However, little is known about how much SF₆ is used in radiotherapy. Recent work has also estimated the carbon footprint of the power consumption of linacs during “beam on”, (i.e. when actively treating), showing that a prostate treatment of 5 fractions generated 2.18 kg CO₂e compared to 17.34 kg CO₂e for a conventional treatment (28 fractions) [11]. They also estimated the carbon footprint of the power use when a TrueBeam (Varian Medical Systems, Palo Alto CA) was in “Ready”, “On - No mode”, and “Standby” mode (i.e. not actively treating) as 5.2 kgCO₂e, 26.8 kgCO₂e, and 48.5 kgCO₂e, respectively per day. It has also been suggested that an increase in the adoption of hypofractionated treatments during the COVID pandemic resulted in a 39% reduction in carbon footprint [12].

However, the carbon footprint of the RT pathway remains largely unknown, despite its potential impact on the environment [13]. This study aims to estimate the carbon footprint of various components of RT at multiple centres and identify areas where future mitigation efforts can be focused. In addition to this, COVID-19 has resulted in routine policy changes (for example increased use of hypofractionation and personal protective equipment (PPE)) that may have altered the total carbon footprint for each patient. This study therefore additionally aims to quantify and compare the carbon footprint across multiple centres before and during the pandemic.

The paper is structured such that data from The Christie (Centre 1) are presented first as the main centre and the data from the additional centres follows, and are used to validate the results from Centre 1. Where applicable these are further divided into the components of the carbon footprint that were investigated.

2. Method

2.1. Scope and boundary

2.1.1. Centre 1

The boundaries of this work were from the point of referral for radiotherapy until the first follow up appointment and included the following aspects of the RT pathway for The Christie (Centre 1, main centre): patient travel to and from the hospital, pre-treatment imaging (CT and MRI), energy used by the linac during treatment and when idle between treatments, SF₆ gas leakage and personal protective equipment (PPE). The Christie (Centre 1) is a very large centre on the outskirts of a large city.

2.1.2. Other centres

Pilot data on a subset of these aspects were also collected at three other centres to examine the variability of the carbon footprint across different centres. The catchment areas of the additional centres varied: Mount Vernon Cancer Centre (Centre 2) is a medium size centre in the outskirts of the London conurbation, Guys and St Thomas’ (Centre 3) is a medium sized centre in the centre of London and the South West Wales Cancer Centre (Centre 4) is a small centre with a rural catchment area around Swansea Bay.

Centres 1 and 4 had Elekta linacs whereas Centres 2 and 3 had Varian linacs. Due to time limitations and the complexities of working across centres the data collected were limited in scope and depth. A summary of the data collected at each centre is shown in Table 1.

The functional unit for this work is one completed treatment course for one patient, with the carbon footprint (unless otherwise stated) being reported per patient.

2.2. Patient selection

2.2.1. Centre 1

Activity data for a total of 42 patients from within the breast IMRT (20 patients) and prostate VMAT (22 patients) pathways were collected at Centre 1. This number was chosen to make the manual extraction of data manageable in a reasonable time frame. These patients were further divided into “pre-COVID” (Jan-Mar 2020) and during “COVID” (Jan-Mar 2021) groups for comparison. For the pre COVID group, data from 10 prostate patients treated with 60 Gy in 20 fractions and 10 breast patients treated with 40 Gy in 15 fractions were extracted. For the COVID group, the prostate dataset consisted of 10 patients treated with 60 Gy in 20 fractions and two patients treated with a stereotactic ablative radiotherapy (SABR) technique (36.25 Gy in 5 fractions); this reflected the implementation of a SABR protocol used to treat approximately 5% of these patients to limit footfall and therefore infection risk during COVID. The COVID breast dataset consisted of 10 breast patients receiving ultra-hypofractionated RT (26 Gy in 5 fractions).

2.2.2. Other centres

Centres 2 and 4 collected data for 20 breast and 20 prostate patients for both the pre-COVID and COVID timepoints at each centre with the same dose fractionations. These data were used to investigate the variability of the carbon footprint across different centres and to provide a more comprehensive understanding of the carbon footprint of RT in different settings.

2.3. Data collection and emission factor sources

Table 2 presents a summary of the activity data that were extracted, the method of extraction, and the conversion factors used in the analysis. Further details of the methods are provided in the following sections.

2.3.1. Centre 1

2.3.1.1. Patient travel. To estimate emissions resulting from patient travel centres 1, 2 and 4 extracted postcodes from patient records and assumed all travel was by car. A route planning tool was used to estimate a realistic road travel route, based on average off-peak driving
Table 2
Summary of activity data, conversion factors and sources used in estimations of carbon footprint.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Activity data</th>
<th>Source</th>
<th>Conversion Factors used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient travel</td>
<td>miles travelled</td>
<td>Post codes from Mosaic/Aria (Centres 1, 2 and 4) or patient questionnaire (Centre 3)</td>
<td>Average petrol car, 0.281 kgCO₂/mile [14] and public transport, 0.0754 kgCO₂/kWh [14]</td>
</tr>
<tr>
<td>Pre-treatment imaging</td>
<td>Number of CT and/or MRI scans</td>
<td>Patient notes</td>
<td>1.2 kWh for a CT and 19.9 kWh for an MRI (detecting SF₆ leakages), UK electricity grid, 0.233 kgCO₂/kWh [14]</td>
</tr>
<tr>
<td>Linac energy - treatment</td>
<td>kWh</td>
<td>Power meter on linacs</td>
<td>UK electricity grid, 0.233 kgCO₂/kWh [14]</td>
</tr>
<tr>
<td>Linac power - idle</td>
<td>kWh</td>
<td>Power meter on linacs</td>
<td>UK electricity grid, 0.233 kgCO₂/kWh [14]</td>
</tr>
<tr>
<td>SF₆ leakage</td>
<td>kg</td>
<td>Weight of SF₆ cylinders</td>
<td>IPCC GWP100 [10] = 23,507</td>
</tr>
<tr>
<td>PPE</td>
<td>Estimated number of items used</td>
<td>Interviews with Radiographers in summer 2021</td>
<td>Gloves = 0.026 kg CO₂e, Aprons = 0.065 kgCO₂ and masks = 0.02 kgCO₂ [15]</td>
</tr>
</tbody>
</table>

conditions [16]. Patient notes/schedules were then used to identify the number of in-person appointments attended by each patient, and calculate a total distance travelled. The Department of Business, Energy, and Industrial Strategy (BEIS) conversion factor data [14] were then used to convert this distance into emissions, making the assumption that all patients travelled in an ‘average’ fuel economy car.

An additional larger analysis of patient travel was also performed at Centre 1 using data from UK Computer Aided Theragnostics (ukCAT) database [17] between January and March 2021. This extracted distance data for 167 and 14 patients who had prostate treatments in 20 fraction and 5 fractions respectively, as well as 72 and 176 patients who had breast treatments in 15 fractions and 5 fractions. This gave a better estimation of the distances travelled by these patients.

2.3.1.2. Power consumption. To calculate emissions due to linac energy consumption, direct measurements were made at Centre 1 using pre-installed power meters on three linacs. The power meters displayed a running total of energy used by the linac, and so by monitoring this value before and after delivering a patient treatment, the energy used could be calculated. The power consumption was measured for 20 prostate and 20 breast patients.

For Centre 1 the measured treatment power was also compared to the theoretical treatment power based on a manufacturer value of 18 kVA and 0.9 power factor, giving 16.2 kW. This value was multiplied by the beam-on time to give the power in kWh for each patient and the difference between this and the measured value calculated.

As linacs also consume energy when in an idle state (i.e. when they are not treating), idle energy measurements were also taken using the same power meters used for the treatment power measurement. It was assumed that the linacs were turned on at 6 am and turned off at 8 pm, with only two out of the 10 linacs on between these times at weekends. The average value was subtracted from treatment energy measurements. To ensure that idle energy use was still accounted for in overall emissions, annual idle energy use was calculated and split equally among all fractions delivered annually, resulting in an additional emission value per fraction. Some variability between different linacs was to be expected, so measurements were taken across all three available linacs at Centre 1, with a sub-sample being repeated on all three to ensure they were comparable with one another.

2.3.1.3. Sulphur hexafluoride. To quantify the emissions due to SF₆ lost from linacs at centre 1, periodic weight measurements of SF₆ tanks during routine maintenance of linacs were utilised. These tanks are used to re-pressurise SF₆ within the feeding waveguide of linacs, which takes place during routine maintenance. By analysing the lost mass of SF₆ in the container over time, the rate of SF₆ leakage from the linac could then be estimated. Data for ten linacs were available with between 9 and 3 years of measurements for each linac, taken from engineering service records. A weighted average of leakage data to account for different number of fractions treated on each linac was then taken and then leakage split equally among all fractions delivered annually, resulting in a leakage value per fraction.

2.3.1.4. Pre-treatment imaging. Patient notes were also used to identify the number of pre-treatment scans (CT and MRI) that patients received. Values for energy use per scan taken from literature [7] were then used alongside BEIS conversion factors for energy use of the national electricity grid to convert to CO₂e emissions.

2.3.1.5. Personal protective equipment. Emission contributions from the use of PPE were quantified using values taken from literature [15]. The types of PPE considered included face masks, surgical gloves and single-use aprons. Estimated numbers were provided by radiographers, determining how many of each item were used per radiographer and per patient.

Where stated an independent t-test was performed to determine if differences were significant, with anything lower than p = 0.05 considered significant.

2.3.2. Other centres

2.3.2.1. Patient travel. The carbon footprint of patient travel for Centres 2 and 4 were extracted the same way as at Centre 1. However, Centre 3 used a slightly different methodology, where a patient questionnaire (see supplementary material) of 99 patients was used instead of patient notes to estimate the distance travelled by patients. For comparison with other centres emissions from patient travel by car was calculated, however the questionnaire also asked which mode of transport was taken which was also used to calculate travel emissions in this urban area with a network of public transport links.

2.3.2.2. Power consumption. Centres 3 and 4 used a Fluke 1738 3-phase power logger (Everett, Washington, USA) to collect linac energy data. The same portable device was used at both centres which samples data at 10.24 kHz recording every second for each power phase. An energy study was conducted with current loops and voltage probes attached to each of the 3 phases and a neutral. Fluke Energy Analyse Plus software was used to extract summed data over all three phases, including the average apparent power and average apparent energy per second. Apparent power and energy values were analysed instead of active power and energy, so the full demand from the utility is used in calculations, therefore no ‘power factor’ has been taken into account in calculations. This data logger was attached to a Varian TrueBeam in Centre 3 for one week, and to an Elekta Versa HD in Centre 4 for one week.

The apparent power data over the week were used to compare to manufacture published information [11,18]. Previously literature has just used these values for calculations of power in different machine states [11,19]. A recent measurement of linac power has been performed through measuring the power used per MU. However, this did not capture power in different states and assumptions were made for the power factor [12]. This is therefore the first publication with detailed
linac power values in a clinical setting. The Fluke data over a time period were separated into ranges for analysis to represent the different linac states, using an in-house Python script.

The apparent energy was used to calculate the energy consumed during one fraction of a conventional prostate treatment through time correlation of Fluke data and treatment data, identifying 20 prostate patients in each centre for analysis. The time selected per treatment was approximated based on beam on/off times, not the treatment appointment time slot which would be longer than this to allow for patient set up and imaging. The energy per fraction was then scaled to the treatment course and BEIS conversion factors for energy use on the national grid were used to convert to emissions. As the linac still consumes power in an idle state, a fraction of this should be considered for every patient treatment as done in Centre 1. The idle power for each fraction was also removed from the measured treatment energy to indicate the additional energy required for a treatment. This was performed by calculating the energy consumed over the ‘treatment’ time slot using the average measured apparent power in the idle state.

Additional energy consumption from other sources e.g., imaging, has not been considered in this data; however, work is continuing in Centre 4 to give further information.

2.3.2.3. Pre-treatment imaging. At Centres 2 and 4, patient notes were also used to identify the number of pre-treatment scans (CT and MRI) that patients received and were analysed in the same way as for Centre 1.

3. Results

3.1. Centre 1

From the carbon equivalent emissions from collected data for patient travel, linac power consumption, pre-treatment imaging, SF6, and PPE in Centre 1, the estimated mean carbon footprint for a prostate treatment pre-COVID and during COVID were 149.1 kg CO2e and 226.9 kg CO2e respectively (Fig. 1a and Table S1 in supplementary data). For breast treatments pre-COVID and during COVID the mean carbon footprints were 101.8 kg CO2e and 74.82 kg CO2e respectively (Fig. 1a). Patient travel accounted for the majority of the carbon footprint, ranging from 76% to 86% of the total carbon footprint (Fig. 1b). The energy used by the machine while in an idle state was the second largest proportion of the carbon footprint accounting for between 8% and 19% of the total. There were no significant differences between the pre-COVID and COVID groups for prostate (p = 0.29) or breast (p = 0.28) treatments despite increased PPE and reduction in fractionation schedules, likely due to the large variation in patient travel distance and the small sample collected.

3.1.1. Patient travel

At Centre 1, it was assumed that everyone travelled in an average-sized petrol car to give a carbon footprint from travel alone of 186.1 kg CO2e (82% of the whole carbon footprint at Centre 1). Alternative scenario modelling for patient travel at Centre 1 shows that if every patient travelled via a four-wheel drive vehicle the carbon footprint from travel alone would be 225.5 kg CO2e (84.7% of the whole carbon footprint at Centre 1). If every patient travelled via a small hybrid car this would reduce to 151.4 kg CO2e (77.5% of the whole carbon footprint) and to 37.8 kg CO2e (47.8% of the whole carbon footprint) if they all travelled via train.

In depth analysis of the distance that patients travel at Centre 1 showed that the mean distance travelled for a round trip per fraction was 30.4 miles for 20 fraction prostate treatment and 51.0 miles for 5 fraction prostate treatment. The mean distance travelled by prostate patients was then 767 miles and 255 miles over a full treatment course. Similarly, for breast patients the mean distance travelled for a round trip per fraction was 34.5 miles for 15 fraction treatments and 35.4 miles for 5 fraction treatments, giving the mean distances travelled over the full course of 516 miles and 177 miles, respectively. This shows that over a larger sample of patients, the distances can be significantly reduced for hypofractionated treatments.

There was large variability in the distance that patients travel to Centre 1. A box plot of the distances travelled by prostate patients (orange) and breast patients (green) pre-COVID and during COVID is shown in Fig. 2. These are shown for the small sample used for the basis of this work (solid lines) and a larger sample of patient travel data (dashed lines). This shows that there were larger differences in the median and range of distances patients travelled for the small samples but for the large samples they were very similar. Clearly there is a need for a larger patient data set when doing these studies.

Using the median distances from the large samples and the proportion of patients treated with a hypofractionated approach ~5% of prostate patients and 60% of breast patients [20] during COVID—a more robust determination of the carbon footprint could be calculated. This gives 264.4 kg CO2e and 263 kg CO2e for prostate patients and breast patients respectively.

3.1.2. Power consumption

The results of the linac energy usage measurements for prostate and breast treatments, both pre and during the COVID-19 pandemic, are

![Fig. 1. For Centre 1, the absolute (a) carbon footprint in kg CO2e per patient of travel to and from RT, linac energy use for treating and in the idle state, SF6 and PPE for prostate and breast patients pre and during COVID. The percentage (b) contribution is also shown. The numbers of patients included in each sample are shown in brackets.](image-url)
presented in Fig. 3. It was found that the energy usage for a prostate treatment was higher than that for a breast treatment. However, when considered on a per fraction basis, the energy usage was comparable between the two types of treatments.

An independent t-test was conducted to determine if there were any significant differences in energy usage between the pre-COVID-19 and during COVID-19 patient groups. The results showed that there were no significant differences in energy use between the pre-COVID and during COVID patients for either prostate (p = 0.28) or breast (p = 0.06). Additionally, no significant difference was found between the energy usage of prostate and breast patients in the pre-COVID group (p = 0.13). However, a significant difference was found for the COVID group (p = 0.00005). This is likely due to the reduction in fractionation for breast between the two groups as the energy per fraction for prostate and breast were both about 0.144 kWh per fraction. The energy usage for Centre 1 during idle time over a year was approximated from measured idle energy at 393,300 kWh which with an estimated 8,081 fractions a year gave 5.12 kWh per fraction.

The results of the comparison between the measured treatment power and theoretical treatment power gave a systematically lower value for the measured power. For a full course prostate treatment the median difference was 3.8 kWh and 4.4 kWh, pre and during COVID respectively. For breast treatments the measured power was 5.5 kWh and 3.15 kWh lower than the theoretical power, pre and during COVID respectively.

3.1.3. Sulphur hexafluoride

The average leakage rate of SF$_6$ from the linacs was 0.14 kg CO$_2$e/yr/linac (median 0.17 kg/yr/linac) this was 0.31 kg CO$_2$e per fraction. In addition to this, engineer records also showed that over 4.5 years approximately 9 kg of SF$_6$ had been recovered from 14 linacs during maintenance and services.

3.1.4. Pre-treatment imaging

The carbon footprint of pre-treatment imaging was one of the smallest parts of the calculated carbon footprint. This was between 0.4 and 0.28 kgCO$_2$e per patient for CT, and between 0.39 and 0.52 kgCO$_2$e for MR as some patients had multiple scans.

3.1.5. Personal protective equipment

At Centre 1 with three radiographers present to set up each patient and two present to take them off the treatment couch the PPE equipment used was estimated to be: ten gloves and five aprons per fraction, and three masks per day, as gloves and aprons are changed each time the bunker is entered.

3.2. Other centres

Pilot data from parts of the radiotherapy pathway from other radiotherapy centres have been combined with Centre 1 for prostate patients during COVID and are shown in Fig. 4 (and supplementary data Table S2).

3.2.1. Patient travel

The carbon footprint of travel was calculated at each centre with a range between 227.9 kg CO$_2$e and 72.9 kg CO$_2$e.
3.2.2. Power consumption

3.2.2.1. Power measurement in different linac states. Measured data for Centres 3 and 4 have been analysed and separate states identified from typical usage and published values. These results have been compared against published values in Tables 3 and 4.

The measured Power values are lower than published, as seen in Centre 1’s comparison of treatment energy (section 3.2). The Elekta measured irradiation power is 12.5kVA; if a power factor of 0.9 were used this would result in 11.25 kW, 4.95 kW lower than the estimate previously used. This may explain part of the discrepancy.

3.2.2.2. Linac idle energy. The idle energy previously referred to is the energy used when the machine is on in the day but not irradiating, there is also standby energy (overnight) to consider. These have been calculated from the week of measurements on each machine. The machine at Centre 3 was at standby all weekend, whereas the machine at Centre 4 had a service and QC tests performed. In Centre 4 all QC testing is performed at weekends and the machine is often in use, therefore this data has been used in the calculation, although this is likely to be an overestimate of annual energy. Further work is needed to determine variation across machines, centres, and the contribution of QC testing. However, an estimate from the data of the idle energy per fraction is 5.8 kVAh for Centre 3 and 4.5 kVAh for Centre 4. This is comparable with the estimate by Centre 1 of 5.12 kWh per fraction.

This gave a carbon footprint of 27.0 kgCO₂e and 21.0 kgCO₂e for Centres 3 and 4 respectively.

3.2.2.3. Prostate patient treatment power consumption. Based on the data for 20 patients from each centre, the average energy per fraction for a 10 MV VMAT prostate treatment at Centre 3 was 1.6 kVAh (s.d. 0.26 kVAh), and with idle removed was 0.89 kVAh (s.d. 0.05 kVAh). The average energy per fraction for a 6 MV VMAT prostate treatment at Centre 4 was 0.67 kVAh (s.d. 0.14 kVAh), and with idle power removed was 0.23 kVAh (s.d. 0.05 kVAh).

Centre 1 calculated 0.144 kWh per fraction, which is lower but comparable to 0.23 kVAh (s.d. 0.05 kVAh) measured at Centre 4 on a similar machine with the Fluke monitor. This could be due the use of apparent energy instead of active energy or the higher sampling rate of the Fluke capturing spikes, or calibration of energy monitors.

For a 20 fraction prostate treatment course, Centre 4 had an average apparent energy of 4.7 kVAh (s.d. 0.93 kVAh) which is comparable to the 2–3 kWh measured at Centre 1. Centre 3 has an average apparent energy for a course of prostate treatment of 17.8 kVAh (s.d. 1.1 kVAh).

The treatment power for the two centres with Elekta linacs had a carbon footprint of 0.7 kg CO₂e and 1.1 kg CO₂e, whereas the centre with Varian linacs had a carbon footprint of 4.1 kg CO₂e.

4. Discussion

The present study is the first to estimate the carbon footprint of various components of the radiotherapy (RT) pathway across multiple treatment centres in the UK. Previous studies have investigated individual aspects of the RT pathway [9,11] or multiple sources [12] but none have examined multiple contributors across multiple centres. This is also the first study to examine the contribution that SF₆ makes, and to measure the linac power consumed in different operational states. Our findings indicate that patient travel to and from the treatment centre was the biggest contributor to the carbon footprint, forming 70–80% of the calculated carbon footprint of the aspects examined. Around 120,000 cancer patients are treated with RT annually in the UK [5] and considering an average value of 136.7 kg CO₂e across all the patients analysed at Centre 1, the total across the UK would be 16,404 CO₂e from RT a year. This equates to driving 97.4 million km in an average sized car. This is only 0.07% of the entire NHS carbon footprint which was estimated as 25 MtCO₂ [4]. However, the estimate for the NHS included the supply chain forms about 60% of the total and this study did not estimate the emissions from the supply chain so it very likely a gross underestimate. In addition to this the NHS footprint from care activities consists of many different care pathways and modalities, each of which, whilst negligible in itself, needs to be reduced in order to bring the overall care footprint within acceptable bounds.

The average leakage rate of SF₆ from the linacs was 0.14 kg/yr/linac. If this rate were applied to all the linacs in the UK, which is between 340 [21] and 246 [22] linacs, and using the GWP of SF₆, a total UK wide carbon footprint from SF₆ leakage from RT linacs would be between 1.143,000 and 827,000 kg CO₂e per year. Additionally, during service and maintenance it was found that on average 142 g of SF₆ had been extracted and recycled per linac per year. If this wasn’t recycled across the UK this could contribute an additional 1,142,000 kg CO₂e per year. For context the national grid in the UK estimates that 9,040 tonnes of SF₆ was released from electricity transmission and distribution equipment in 2018 and is thought to be increasing [23,24]. The carbon footprint of this would be about 216 MtCO₂e, equivalent to about 83 million return flights between London and Los Angeles.

Carbon footprinting within radiotherapy is still a relatively new field and there are only a limited number of studies to compare our results to. Previous research has shown that patient travel has a significant carbon footprint [9]. At Centre 1 the average total distance travelled by breast patients receiving 15 fractions was 363.9 km which is very similar to the 392.3 km reported by Coombs et al, 2016 [9] who looked at 6 centres across the UK. The Centre 1 measurement of an average 0.71 kg CO₂e for the carbon footprint of the linac power consumption for 20 fraction prostate patients is comparable with independent measurements at Centre 4 of 1.1 kg CO₂e. This is difficult to compare with work performed by Shenker et al, 2022 [11] due to the different dose and fractionations and conversion factors used. However, their values of 2.18 kg CO₂e for prostate stereotactic body radiotherapy (SBRT) and 17.34 kg CO₂e for conventional treatment are much larger than our measurements. This could be due to the difference in machine manufacturer or estimation/calculation methods. Centre 3 with the same machine manufacture measured 4.1 kg CO₂e for the irradiation power of a conventional 20# prostate treatment, again lower than Shenker et al [11] who used estimated times of irradiation and manufacturer power values, which has been measured as 18kVA lower in a clinical setting. A recent study that compared the carbon footprint of radiotherapy patients before and during the COVID-19 pandemic found that there was a 39% drop in the carbon footprint during COVID due to the increase from 17% to 27% of patients treated with hypofractionated radiotherapy [12].

The study is limited by the small sample size (N = 102 in total) and is

| Table 3 | A comparison of power usage in 4 states for a working day for Varian TrueBeam. * shows data from Shenker et al [11].
<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td>Power (kW) *</td>
<td>Measured Power (kVA)</td>
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<tr>
<td>Irradiating</td>
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</tr>
<tr>
<td>Standby</td>
<td>7</td>
</tr>
<tr>
<td>(overnight)</td>
<td>11</td>
</tr>
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<td>Ready</td>
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</tbody>
</table>
hierarchically limited by the boundaries set and thus the quantified carbon footprint of our study only accounts for the components of the radiotherapy treatment pathway that were observed. However, as it is a pilot study it none-the-less highlights and prioritises the main contributors. In the future a comprehensive life cycle assessment (LCA) may be considered, this is an internationally standardized modelling tool to quantify all inputs and outputs of a system. Additional components to consider in future LCA may include, but are not limited to, positioning devices, quality assurance and commissioning measurements, medicines, computing resources, staff travel, image storage and servers, machine consumables (e.g. distilled water) and capital investment in the buildings and equipment. These were excluded from the present study to enable the work to be performed in a manageable time frame and because this study deals with the carbon emitted by the treatment pathway itself, rather than the context of the wider oncology service in which it sits. This work has also excluded PET/SPECT and other nuclear medicine imaging as the carbon footprint of these scans has not been documented and they are rarely used for prostate and breast patients. Centre 1 has 3 satellite centres but for simplicity it was assumed that all patients travelled to the main treatment site. However, the results will still provide a benchmark for future work and will inform efforts to reduce the carbon footprint of RT.

The study found that travel is a significant contributor to the carbon footprint per patient but this is based on assumptions on the mode of transport and travel route. It was assumed that all patients travelled by an average petrol car meaning that this is not an accurate measurement of the true carbon footprint of travel. Centre 3 used a different approach to estimating the distance travelled by patients, using a questionnaire rather than patient notes, and this enabled a more accurate determination of the carbon footprint of patient travel. It was also assumed that they travelled from home rather than from work. As all four centres had different geographical patient catchment areas, there would be a large difference in the use of public and active transport, leading to variation in the carbon footprint of travel. The majority of the carbon footprint of RT was from patient travel which highlights the need for increasing the use of public or shared transport, virtual appointments, reduced fractions, as expected due to the reduced travel. However, a statistically insignificant increase in the carbon footprint for prostate treatments was seen during COVID where the use of hypofractionation had increased. This is contrary to what is expected and to what has previously been reported in the literature [12]. This is likely due to the small sample of patients and large random variations in the distances patients travel. The larger dataset of patient travel in Centre 1 confirms that with a larger dataset the expected reduction in travel distance is seen when patients are treated with hypofractionated RT. This should help motivate more trials comparing standard and hypofractionated treatments because if hypofractionation is clinically at least non-inferior, its use could significantly reduce the carbon footprint of radiotherapy.

However, one study found that some patients will travel further for hypofractionated treatments [25] meaning that some of the reduction in carbon footprint could be counteracted by people travelling further for this option. This effect would presumably be less significant in future as more centres offer this option.

The power consumption of the linacs, was measured using two different power meters and approaches. Centre 1 used a different meter and approach compared to centres 3 and 4 who used the same meter. Despite the differences in measurement methods centres 1 and 4 showed close agreement in their results, likely due to both having similar Elekta linacs. However, centre 3 showed a higher value for treatment power which could be attributed to its use of a different linac manufacturer (Varian) as the meter was the same between centres 3 and 4 [11,18]. Comparison of the apparent power in different machine states to published values demonstrates that measured values are lower than published but of a similar magnitude. This is likely due to the publications referencing the highest possible consumption for site planning information, or due to the measured linac power supply not including power to ancillary equipment. In future measurements, it is important to consider the power consumed by not only the linacs but also the control room PCs, air conditioning units, lighting, and peripheral IT equipment, as well as the location of the power meter with respect to the cables, which may include the on-board imaging, vacuum pumps and water chiller. These measurements are still of interest because previously published studies have estimated rather than measured the power use of the linacs. Due to the significant resources needed to undertake these measurements the number and breadth of measurements was limited, and warrants further investigation.

Patient notes are not always clear and easy to find, meaning that some of the information taken from them (for example number of MRI scans taken as part of the RT pathway) may be unreliable. However, as this isn’t a large proportion of the carbon footprint it is unlikely to change the conclusions.

By demonstrating feasibility in prostate and breast patients this work could be expanded to other common treatment sites like head and neck and lung but as prostate and breast form 29% of all cancer cases in the UK this is still a good first estimate [26].

Although the sample size used in this study is small it illustrates areas where work needs to be done to measure and reduce the carbon footprint of radiotherapy, aiding the NHS net zero target. It is expected that hypofractionation would be useful to lower the carbon footprint of RT because of reduced patient travel [12], as would increasing the use of public transport by patients. Hypofractionated radiotherapy has also been shown to have a lower carbon footprint than surgery for lung patients [19] so may provide a lower carbon alternative to surgery for other treatment sites too. However, these solutions are faced with several barriers and require further research to provide robust evidence.

### 5. Conclusion

The carbon footprints for a variety of components for two widely-practised radiotherapy treatment pathways – prostate and breast - have been measured. Our initial findings highlight that major contributors to the carbon footprint include patient travel and, to a lesser extent, the linac idle power. The significant contribution of patient

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**Table 4**

<table>
<thead>
<tr>
<th>Power (kVA)**</th>
<th>Measured Power (kVA)</th>
<th>Time per day (hrs)*</th>
<th>Measured time per day (hrs)</th>
<th>Energy per day (kWh)*</th>
<th>kgCO2 per day*</th>
<th>Measured Energy per (kWh)</th>
<th>kgCO2e per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiating</td>
<td>18</td>
<td>1.6</td>
<td>0.8</td>
<td>112</td>
<td>48.5</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Standby</td>
<td>12</td>
<td>16</td>
<td>11.9</td>
<td>112</td>
<td>48.5</td>
<td>24</td>
<td>5</td>
</tr>
<tr>
<td>(Overnight)</td>
<td>2</td>
<td>16</td>
<td></td>
<td>112</td>
<td>48.5</td>
<td>24</td>
<td>5</td>
</tr>
<tr>
<td>Standby/Preparatory</td>
<td>10</td>
<td>6.75</td>
<td>6.4</td>
<td>62</td>
<td>26.8</td>
<td>72</td>
<td>17</td>
</tr>
</tbody>
</table>

* Shows data from Shenker et al [11]. ** Data from Elekta [18].
travel highlights the need for increasing the use of hypofractionated treatments (where clinically appropriate), public transport use and potentially more “sustainable” centres. From our initial data, RT contributes 16,404 tCO2e to the NHS carbon footprint in the UK in a year. Our findings can be used for establishing a benchmark for future carbon accounting studies including more holistic life cycle assessments and can be useful in aiding future decarbonisation efforts.

Funding

RC would like to acknowledge funding from the North West Greener NHS Innovation Fund and support of Cancer Research UK via funding to the Cancer Research Manchester Centre [CTRQQR-2021\100010]. MA acknowledges the support of the Engineering and Physical Research Council (Grant number EP/T028017/1). TM acknowledges the support of the Engineering and Physical Sciences Council [grant number EP/R023220/1].

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.

Acknowledgements

RC would like thank Ryan Young for his help with the SF6 data collection.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ejmp.2023.102652.

References


