Highlights

- Review of Cost Effectiveness of Domestic Radon Remediation
- Review of developments and future trends in Lung Cancer Diagnosis, Treatment and Survival
- Domestic Radon Remediation Programmes remain cost effective, despite improvements in Lung cancer diagnosis, treatment and survival
- Public Participation in Radon Remediation Programmes remains key.

Radon, a gaseous radioactive decay product of naturally-occurring uranium is widely distributed in the environment in rocks and soils and, in certain circumstances, can accumulate in the built environment. Initial studies confirmed a direct link between exposure to both radon gas and its short-lived radioactive progeny, and increased lung-cancer incidence, and demonstrated that radon levels in domestic housing can be sufficiently high to expose occupants to increased risk of lung-cancer. Subsequent studies worldwide have shown that it is cost-effective to detect and reduce domestic radon levels in order to reduce this risk.

Recent advances in the early detection of lung-cancer, coupled with the development of improved treatment procedures, have progressively improved survival from the disease, with the numbers surviving at 5 years doubling over recent years, during which period the real costs of lung cancer treatment have risen by around 30 %. In the meantime, however, in addition to radon and tobacco-smoke, other airborne pollutants have been identified as risk-factors for lung-cancer. This paper reviews both these actual developments and anticipated future trends, and concludes that since these advances in diagnosis and treatment of lung-cancer have had only a modest effect on cost-effectiveness, it is still important to conduct radon monitoring and remediation programmes. While the general increase in life-expectancy improves the cost-effectiveness of radon remediation programmes significantly, reducing tobacco-smoking incidence reduces that cost-effectiveness but with the overall benefit of reducing radon-related lung-cancers. The challenge remains of encouraging affected householders to remediate their homes to reduce radon levels.

Cost-Effectiveness of Radon Remediation Programmes in the UK in the 2020s

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1 Introduction

Lung-cancer accounted for around 35,600 deaths in the United Kingdom (UK) in 2016, representing 21% of all cancer deaths (CRUK, 2018). Although tobacco-smoking has long been identified as the major risk-factor, responsible for around 70% of lung-cancers, radon, by virtue of its radioactive heavy-metal progeny, is now known to be a significant additional risk factor, with the effects of radon and tobacco-smoking together, initially considered to be multiplicative, now regarded as sub-multiplicative. (BEIR VI, 1999).

Radon, a naturally-occurring gaseous radioactive decay product of uranium, is present with varying geographical concentrations in rocks and soils throughout the earth's crust, and in building materials incorporating or manufactured from these. Although radon dissipates rapidly in outdoor air, it concentrates in the built environment, typical ingress routes being cracks in walls and floors, drains and loose-fitting pipes, the mean UK domestic radon concentration being around 20 Bq.m^{-3} (Wrixon et al., 1998).

The most significant radon isotope, ^{222}Rn, decays by α-emission (half-life 3.8 days) via a decay-chain ending in the stable lead isotope ^{206}Pb. That decay-chain includes three α-emitting progeny, i.e. ^{218}Po, ^{214}Po and ^{210}Po, which are readily adsorbed onto atmospheric particles. Inhalation of ^{222}Rn and these progeny provides the majority of the radiation dose received by the respiratory system (Darby et al., 2001). A direct consequence of this is the well-established association between enhanced levels of environmental radon and increased risk of lung-cancer (BEIR VI, 1999) and the recognition of radon as a significant factor in the incidence of lung-cancer among smokers, these observations being reinforced by case-control studies of residential radon exposure (e.g. Darby et al., 2004).

Public-health initiatives to measure and reduce radon levels have consequently been widely established, and many countries, including members of the European Union and the USA, have now implemented National Radon Action Plans. The cost-effectiveness of such programmes in the UK was first reviewed by Kennedy et al. (1999), who assessed the costs of lung-cancer treatment and the costs and benefits of radon remediation. The survival gain from remediation procedures was estimated using life-expectancy data from cancer registries and the UK National Life Tables. Published costings for lung-cancer treatment at that time were rare: at the time of the Kennedy study, only one analysis relating to the UK had been published (Sanderson et al., 1994), with another (Wolstenholme and Whynes, 1999) then still in press. Sanderson et al. reported unit costs for each element of lung-cancer treatment and the average cost per case, using a sample of 196 patients treated at Southampton General Hospital, UK, around 1990. Kennedy et al. (1999) used lung-cancer data for Northamptonshire from 1996.

A subsequent major study (Gray et al., 2009) included lung-cancer treatment costs taken from Wolstenholme and Whynes (1999), updated to account for inflation. This incorporated an estimate of the costs of improved palliative care, together with revised costs for NHS annual per capita expenditure on all other health-care during added life-expectancy, based on costs for 2007 (DoH, 2007).

In all of these studies, and in our analysis here, the start-up costs, initial publicity and administration running costs of implementing a radon remediation programme are not included.

Subsequent reviews of cost-effectiveness of radon remediation in the UK have addressed the labour and materials costs of radon remediation (Denman et al., 2005), the public response to calls for remediation (Denman et al., 2009), the impact of tobacco-smoking cessation programmes (Denman et al., 2004; Denman et al., 2014), the geographical distribution of radon-bearing rocks (Denman et al., 2013) and the impact of changing the Radon Action Level (Denman et al., 2002). However, there has been no review of the impact of changes in lung-cancer survival since the studies of Kennedy et al. (1999) and Gray et al. (2009). Clinical developments during this period now permit earlier diagnosis and significantly more sophisticated treatment of lung-cancer, both developments contributing towards enhanced survival rates. In addition, general population life-expectancy has risen significantly over the past two decades.

This paper reviews the cost-effectiveness of radon remediation programmes in the light of these developments, using official UK Government published datasets, and considers recent concerns that airborne pollution is also a risk-factor for lung-cancer.

2 Materials and Methods

Current and recent (1999 onwards) literature on improvements to lung-cancer diagnosis and treatment has been reviewed. In particular, cost-analyses presented in the report prepared by Incisive Health Ltd[1]. for Cancer Research UK[2] (Birtwistle and Earnshaw, 2014) have been used extensively to develop a new assessment of the impact of advances in diagnosis and treatment of lung-cancer. This report considered colonic, rectal, ovarian and non-small-cell lung-cancers in the UK, and provided separate cost-effectiveness analyses for each of these cancers under three scenarios: the then-current general situation; the outcome of raising standards universally to then-current best practice; anticipated improvements in diagnosis and treatment.

2.1 Lung-Cancer Diagnosis

Lung-cancer is a disease predominantly affecting the elderly, with age-dependent incidence in the UK over the period 2014-16 peaking at age 70-74 for females and 70-79 for males (CRUK, 2018), with average age at diagnosis of 72.1 for females and 72.2 for males (ONS, 2019a). Allowing for age-group demographics, the incidence rate peaks at age 80-84 for females and 85-89 for males (Birtwistle and Earnshaw, 2014), with 67% of new cases being found to be advanced, i.e. Stages III or IV, (NCIN, 2019).

Figure 1 demonstrates the variation over time of lung-cancer incidence in males and females from the 1970s to the present. Although lung-cancer incidence in males has remained persistently higher than in females over this period, with incidence declining steadily following a peak around 1980, incidence in females continues to increase with little sign of peaking (ONS, 2019a,b). However, the gap is narrowing steadily, with the male:female incidence ratio decreasing from 3:1 in 1990 to 1.5:1 in 2011, and to 1.28:1 in 2017.

The decrease in male lung-cancer incidence over recent decades reflects the decline in tobacco-smoking prevalence among men, from 80% in 1950 (Peto et al., 2000) to 16.5% in 2018 (ONS, 2018). In contrast, smoking increased in popularity among women during the second half of the 20th century, rising from 40% in 1950 to a peak of around 50% around 1970 (Peto et al., 2000) before falling, in line with male smoking prevalence, to 13% in 2018 (ONS, 2018). The UK Government White Paper on Smoking (HMSO, 1998) notes a rise in smoking prevalence in young girls from 1988 to 1996.

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[1] Incisive Health, 51 Welbeck Street, London, W1G 9HL, England. www.incisivehealth.com

[2] Cancer Research UK, 2 Redman Place, London, E20 1JQ, England. www.cancerresearchuk.org

Due to the often-significant time-lag between the smoking experience and the onset of lung-cancer, the effects of historical changes in smoking habits are still visible in current and recent lung-cancer incidence data.

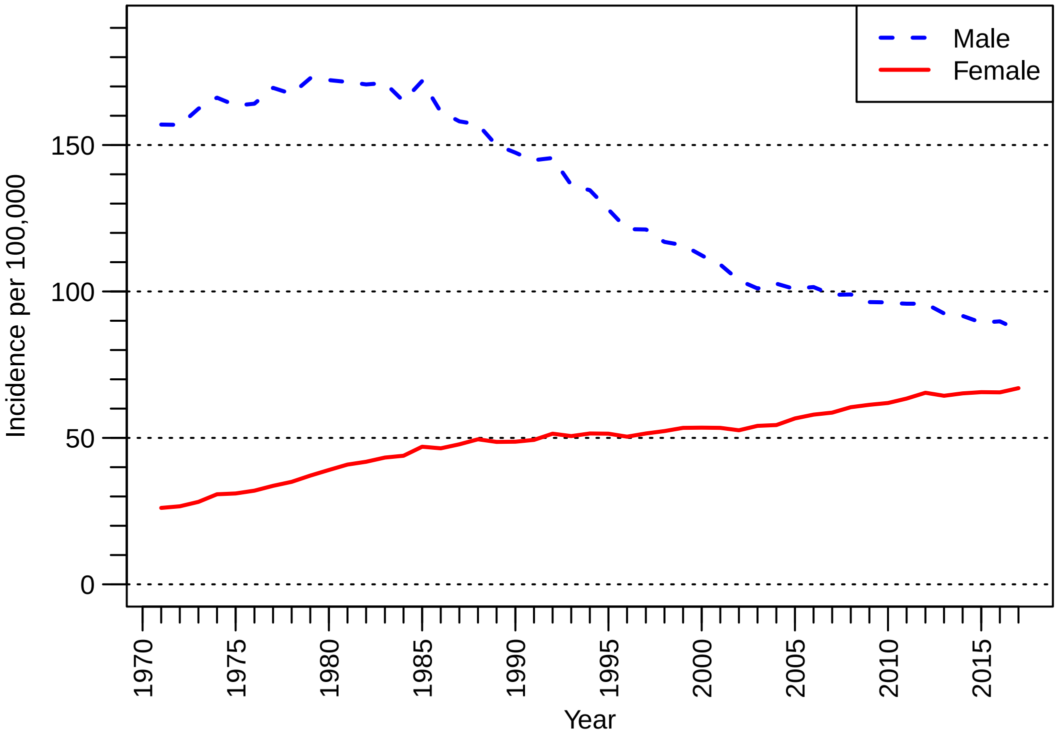

Figure 1: Age-standardised annual incidence (per 100,000) of lung-cancer in males and females in England. (ONS, 2019a,b)

More than a third of new lung-cancer cases in England are diagnosed when presenting as emergencies (NCIN, 2019); 70% of emergency presentations occur via Accident and Emergency departments, the remainder via emergency GP or inpatient/outpatient referral (NCIN, 2019). There is also evidence that many patients with suspicious symptoms do not seek medical advice promptly (Bjerager et al., 2006; Neal and Allgar, 2005). Poor prognosis, particularly in advanced stages, suggests that easier patient access and screening programmes would facilitate detection at an earlier stage, a supposition confirmed by Campbell et al. (2014), who showed that increased uptake of Chest X-Ray (CXR) assessment for persistent cough in a pilot walk-in scheme in Corby, UK, identified unsuspected lung-cancers at an earlier stage.

Low-dose computed tomography (LDCT) has higher tumour detection sensitivity than CXR, and is now emerging as the preferred screening technique, despite delivering a higher radiation dose. However, the rapid spread of lung-cancer dictates frequent screening which, if done by CXR or LDCT, involves significant radiation dose, which could itself induce cancer. At present there is some research support for the value of targeted screening programmes using LDCT (Cressman et al., 2018) for those most at risk, such as tobacco-smokers in deprived areas or people with persistent coughs, and a workshop in the UK noted that this approach was being actively pursued by research and local pilot studies (Moffat et al., 2018).

Final results of the Netherlands-Belgian randomised lung-cancer screening (NELSON) trial[3] reported a 26% reduction in lung-cancer mortality in a 10-year follow-up of asymptomatic males, and an increase to 67% of cancers at diagnosis being early stage and operable (De Koning et al., 2018). In January 2019, NHS England announced a 10-year plan (NHS, 2019), which included the intention to extend lung health checks, based on the methodology of a trial in Manchester, UK, targeting high-risk tobacco-smokers in deprived areas. In the first (baseline, T0) screening round of the Manchester trial (Crosbie et al., 2019a), 63% of lung-cancers were diagnosed at Stage I and 10.9% at Stage IV. This represented a significant improvement compared with the distribution of lung-cancers diagnosed across the same geographical area the year before the trial started (31% Stage I+II and 48% Stage IV). In the second annual screening round (T1) a year later, the trial reported an incidence of lung-cancer in their target population of 1.6%, with 79% at Stage I (Crosbie et al., 2019b).

Birtwistle and Earnshaw (2014) reported the average percentage of initial diagnoses made at each stage during 2014 in the UK as a whole, together with corresponding figures for the best-performing Clinical Commissioning Group (CCG). These are shown in Table 1, together with the results from the Manchester trial.

Table 1 – Recently reported UK detection rates for Stages of lung-cancer

Stage	Percentage Diagnosed at each Stage			
	UK Average 2014 (Birtwistle and Earnshaw, 2014)	Best CCG 2014 (Birtwistle and Earnshaw, 2014)	Manchester trial 1st Round T0 (Crosbie et al., 2019a)	Manchester trial 2nd Round T1 (Crosbie et al., 2019b)
1	15%	22.2%	63.0%	79.0%
2	8%	11.8%	17.4%	0.0%
3	22%	18.9%	8.7%	10.5%
4	55%	47.1%	10.9%	10.5%

Finally, there is the future prospect of improved early detection using lung-cancer biomarkers, but this technology is still in the development phase (Roointan et al., 2019).

2.2 Lung-Cancer Survival

Lung-cancer survival has improved over the years. In the USA, 5-year survival was 16% in the period 1986-1991, rising to 24% in 1998-2003 and to 31% in 2004-2009 (Dillman et al., 2014). In the UK, 1-year survival was 20% in 1999, and had risen to 32% by 2011 (CRUK, 2018), while 5-year survival was 4.6% in 1971-1972, 6.0% in 1990-1991, rising to 9.6% in 2010-2011 (ONS, 2015). Similar trends have been reported elsewhere. In Norway, although there was only limited improvement in survival of patients with metastatic disease at diagnosis, 5-year survival in males with localised disease improved from 26% to 64% (Brustugun et al., 2018). In the UK, a recent report from the Health Foundation (Richards et al., 2018) has noted that while considerable progress has been made in cancer care in the last 30 years, considerable work remains to be done to improve diagnosis and treatment to the optimum.

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[3] http://www.nelsonproject.nl

2.3 Life-Expectancy

Average life-expectancy at birth has continued to increase in England in recent decades, with ONS estimating that the average period life expectancy at birth at 2018 is 79.5 years for males and 83.1 years for females (ONS, 2019d). However, the rate of increase is falling (PHE, 2018). The current figures are around 5 years greater than when the data for the Kennedy et al. (1999) study was collected in 1990, at which point the period life-expectancy at birth was 73.1 years for males and 78.7 years for females (ONS, 2019d). The trend continues, as shown in Figure (ONS, 2019d), but recent analysis suggests this is now plateauing (Raleigh, 2018). The Public Health Profile of England 2018 (PHE, 2018) notes that "less than a century ago, deaths from infectious diseases were common and often death would follow a relatively short period of illness (Griffiths and Brock 2003)". However, chronic non-communicable diseases are now the leading causes of death and long periods of moderate or severe ill health often precede death (PHE, 2018).

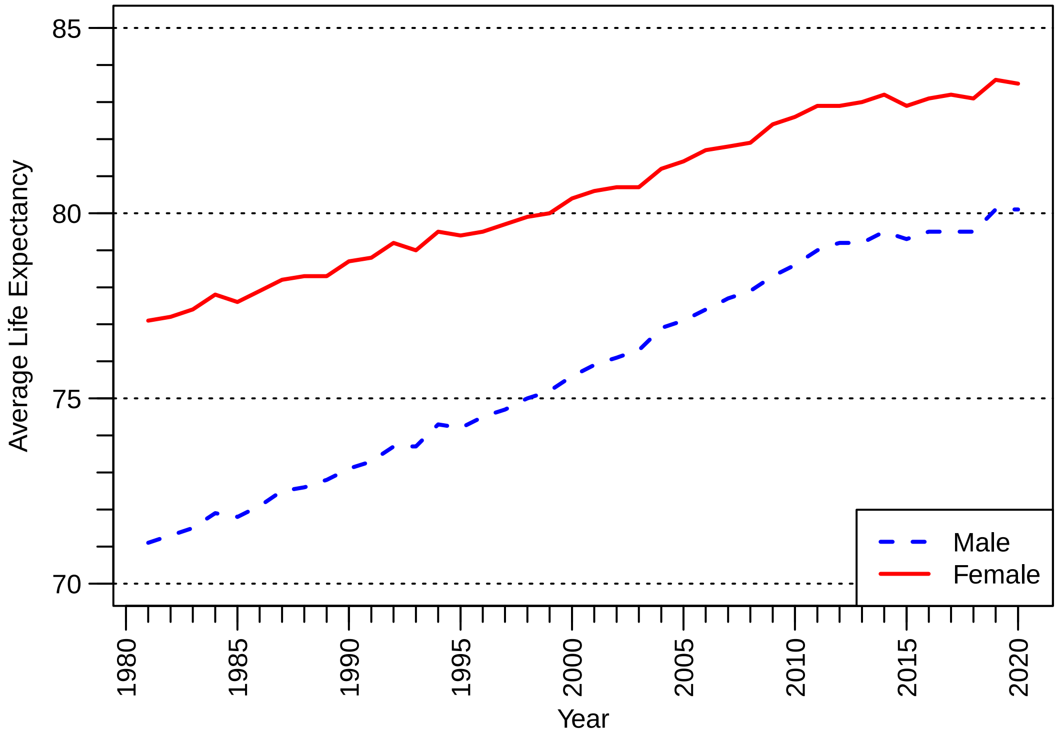

Figure 2: UK Period life-expectancy at birth. (ONS, 2019d)

The population of the UK is ageing. In England in 2017, 1.35 million people were aged 85 and over, almost half a million of whom were aged 90 and over. Population distribution among the elderly is important, as the older a person is, the more likely they are to live with chronic conditions such as dementia, diabetes and musculo-skeletal conditions (PHE, 2018).

However, this extension of life-expectancy would not necessarily lead to an increase in the average life-years gained by not contracting lung-cancer, as lung-cancer incidence rate increases with age, reaching a current maximum at around 85 years, as shown in Figure 3 (CRUK, 2018).

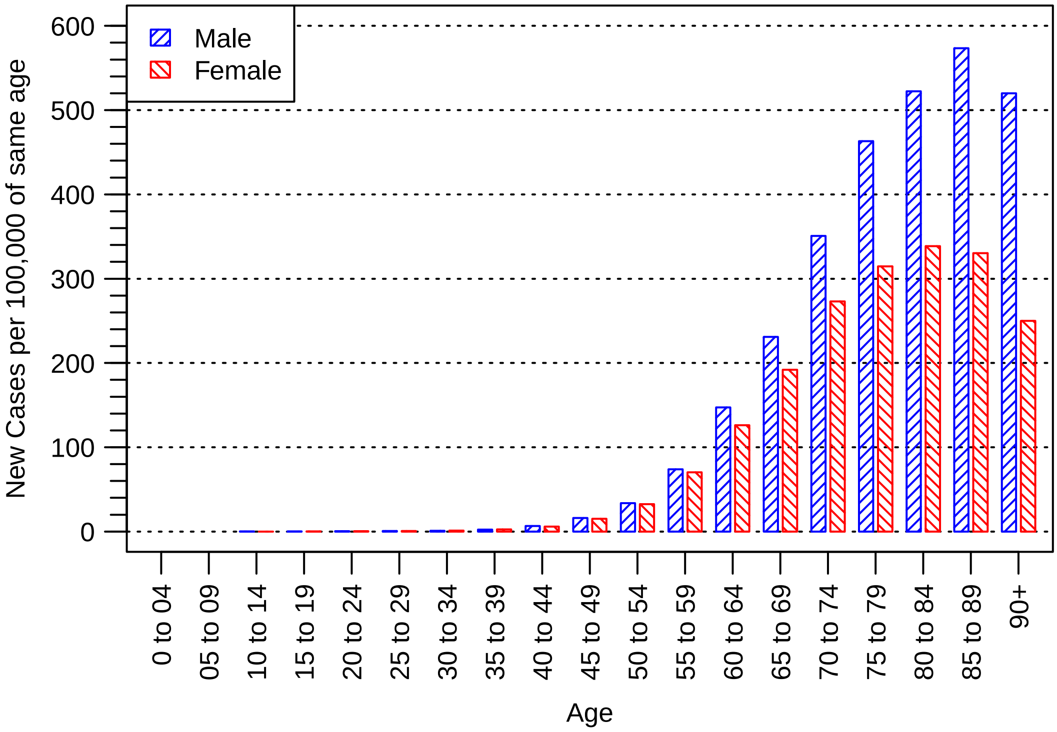

Figure 3: UK Lung-cancer incidence by age group, 2014-2016 (CRUK, 2018).

It is important to recognise that advances in treatment and earlier detection mean that lung-cancer incidence and life-expectancy data cannot be directly combined. Birtwistle and Earnshaw (2014) note that increasing life-expectancy and the increasing UK population will result in 1.7% increase in the number of lung-cancer cases annually.

2.4 Lung-Cancer Treatment

Treatment of lung-cancer can involve surgery, radiotherapy and chemotherapy, depending on the stage of disease. Surgery is used with curative intent in 49% of cases of localised disease in Stages I and II, while radiotherapy is used in 16% of cases in these stages (Birtwistle and Earnshaw, 2014).

Radiotherapy methods have become increasingly complex since the 1990s, with the introduction of more accurate computer-controlled equipment, able to establish the precise location of the cancer and to deliver the radiation dose accurately to the tumour without damaging nearby structures. Magnetic resonance-guided radiotherapy (Chin et al., 2019), gated to patient breathing, has the ability to target the tumour even more closely. Proton beam therapy is also likely to achieve similar improvements but at greater cost. Baker et al. (2016), in their review of radiotherapy advances in the treatment of lung-cancer, note some evidence of improved outcomes, with the caveat that “clinical benefit of such technology still needs to be demonstrated”. They particularly highlight whether modern radiotherapy techniques are superior to surgery in patients where surgery is an option, and note the current lack of evidence for enhanced benefits of proton beam therapy. Mesko and Gomez (2018), however, suggest that proton therapy will prove to be beneficial for some subsets, such as centrally-located early disease and previously irradiated tumours. There is also a role for simple palliative radiotherapy in advanced disease (Birtwistle and Earnshaw, 2014), with 10% of patients in Stage III and 71% of patients in Stage IV being treated in this way.

Surgery has also developed during this time period, from radical lobectomy, which was first reported in 1960, to the introduction of limited resection for Stage I lung-cancers in 1995 (Aokage et al., 2017). The introduction of diagnostic methods to improve the localisation of the disease has led to further clinical trials to establish improved patient outcomes (Aokage et al., 2017). Finally, Birtwistle and Earnshaw (2014) note that chemotherapy is used to palliate advanced disease, with 8% of patients in Stage III and 81% of patients in Stage IV receiving this treatment.

2.5 Radon Remediation

There have been no significant changes in methodologies for radon testing and remediation since the 1990s. The 'gold-standard' radon measurement in the UK remains the three-month etched-track method using two detectors, one placed in the main living-room and one in the main bedroom (Wrixon et al., 1988). If raised levels are found in existing houses, the usual method of remediation is the provision of a sump under the building, together with an extraction pump if necessary. In 1999, Kennedy et al. (1999) quoted the cost of an individual commercial radon measurement as £35; by March 2019, this had risen to around £50. However when corrected for inflation between 1999 and 2019 by applying the UK Retail Price Index (RPI), this represents a reduction in the real-terms cost of testing of 20.5% (£27.80 in 1999 terms). It should be noted that UK Value Added Tax (VAT) is levied on both radon testing and remediation works and is included in all of the costs quoted here. The VAT rate increased from 17.5% to 20% in 2011, and this change is reflected within the RPI.

Changes in remediation costs are more difficult to quantify, as these vary with the size and characteristics of each house. Figure 4 shows the time evolution of inflation-corrected remediation costs in a series of 123 houses in the counties of Northamptonshire, Oxfordshire and Somerset, UK, remediated by a single contractor between 1993 and 2001. The linear regression line indicates an inflation-corrected average decrease in remediation cost of £86.5 per annum, explains 17% of the variance and is statistically significant with $p \ll 0.001$. The average remediation cost for these houses, again inflation-corrected to January 2019, is £1,311. Similarly, the average remediation cost in 62 homes reported by Kennedy et al. (1999), corrected to January 2019, was £1,147, while Gray et al. (2009), using data derived from Naismith et al. (1998) for a sample of 943 houses of varying sizes and characteristics, reported an inflation-corrected average remediation cost of £1,070. All three data-series are contemporaneous. There are no comparable available data from recent years, but the UK Radon Association's most recent advice (2019) states that "Costs are likely to run from around £800 for a simple measure, and a single retrofit sump system may cost between £1,000 and £2,000".

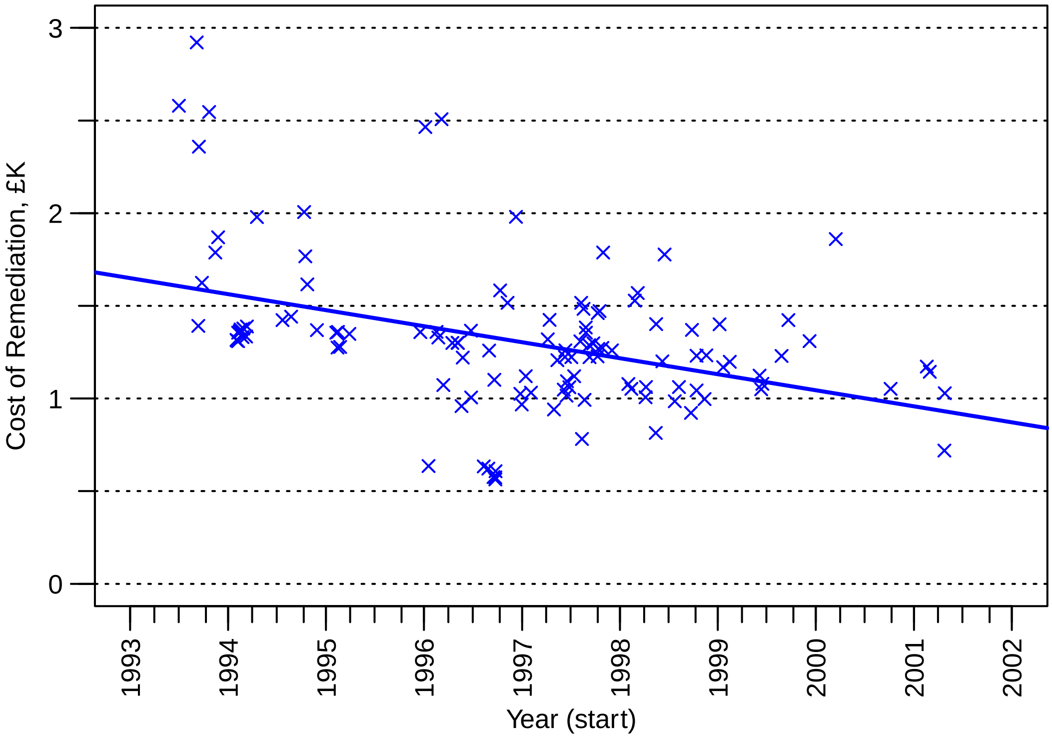

Figure 4: Cost of remediation of 123 houses in period January 1993 to Apr 2001, corrected by RPI to January 2019.

2.6 Smoking Incidence

As tobacco-smoking and exposure to radon are sub-multiplicative risk factors for lung-cancer, smoking prevalence and smoking-cessation programmes will impact on the number of radon-induced lung-cancers. Modelling, assuming a multiplicative interaction, by Denman et al. (2014) showed a 4% decrease in the cost-effectiveness of radon remediation for every 1% reduction in incidence of tobacco-smoking. In 2018, 14.7% of UK adults aged 18 and above smoked tobacco, down from 19.9% in 2010 (ONS, 2018).

2.7 Social Factors

Twigg et al., (2004) analysed the geographical distribution of smoking-attributable mortality in England, based on published risk factors for mortality of current and ex-smokers from various diseases, small-area counts of death by cause, and small-area estimates of current and ex-smoking behaviours. Highest prevalence of tobacco-smoking clustered around the urban areas of inner London, the Midlands and the North of England, essentially the most deprived areas in the country. Lung-cancer has the strongest correlation with social deprivation of the four most common cancers in Scotland (Tweed et al., 2018), and the largest number of excess cases for 37 cancer sites across socially deprived areas studied in England (NCIN, 2014).

In addition to tobacco-smoking, air pollution is estimated as being responsible for 2,328 lung-cancer deaths in the UK in 2010 (RCP, 2016), somewhat higher than the estimate by Public Health England (PHE) of around 1,100 deaths from radon-induced lung-cancer (HPA, 2009). Among the potentially injurious components, there is strong evidence implicating PM2.5 particulates with the incidence of lung-cancer (Hamra et al., 2014; Huang et al., 2017) but less evidence implicating NO_2 (Hamra et al., 2015). Air pollution is generally higher in urban than in rural areas, demonstrating significant positive correlation with social deprivation (Briggs et al., 2008). This evidence, together with increased risks of cardiovascular and respiratory diseases, has resulted in national and international campaigns to reduce urban air pollution, especially diesel exhaust emissions.

By contrast, three studies reviewing the relation between domestic radon levels and social deprivation in the UK revealed only weak inverse correlation (Briggs et al., 2008; Kendall et al., 2016; Denman et al., 2019). The latter showed that radon is primarily a problem in rural areas in the UK, suggesting that public health campaigns on radon and air pollution can be complementary, and that the growing evidence of air pollution as a significant risk factor for lung-cancer should not affect risk estimates for radon.

However, a number of other social factors impact on the estimates of cost-effectiveness of radon remediation. The average household size in England and Wales has been slowly declining from 2.41 in 1997 to 2.37 in 2019 (ONS, 2019c) and is predicted to reach 2.16 in 2033 (CLG, 2010); this reduces the net total health benefit from remediating each home. There has also been an increase in the number and density of high-rise apartment blocks in urban areas. This is significant as radon levels are generally lower in higher floors of high-rise buildings.

3 Results

The move to earlier diagnosis, and the improved survival of those with earlier-stage cancers, suggests that meaningful assessment of cost-effectiveness, and particularly its time-dependence, necessitates separate review of each stage and then combination of the results of those separate reviews.

3.1 Life-Years Lost

The Office of National Statistics (ONS) provides estimates of average life-expectancy for people of specific ages, with two principal methods: period life-expectancy, where current mortality rates are used for projections, and cohort life-expectancy, where a trend in mortality rates is estimated from the trend of increasing life-expectancy. At age 72 years, the mean age of lung-cancer diagnosis, the estimated average cohort life-expectancy in England in 2018 is a further 14.3 years for males and 16.1 years for females, while the period life-expectancies are 13.6 and 15.5 respectively (ONS, 2019d). The following analysis assumes cohort life-expectancy, to reflect continuing improvements in healthcare. Estimates of the average life-years lost for people diagnosed at each stage can be calculated from Birtwistle and Earnshaw (2014), who report values for median survival in the UK at each stage, as shown in Table 2.

Table 2: Mean survival and life-years Lost for UK lung-cancer cases, using cohort life expectancy for 2018

Stage	**Median Survival (months)**	**Life-years lost per cancer – Males**	**Life-years lost per cancer – Females**
1	22.5	12.4	14.2
2	10.9	13.4	15.2
3	6.5	13.8	15.6
4	2.6	14.1	15.9

For the year 2018, and allowing for the higher incidence in males, these figures indicate a UK-wide mean of 14.5 life-years lost per lung-cancer. This analysis assumes that both males and females present with the same staging profile and have similar survival rates. Comparison with the figure of

13.5 life-years lost used by Kennedy et al. (1999), indicates that increased general population life-expectancy is more significant than improved early diagnosis and improved treatment for lung-cancer itself. It should be noted that if the male:female ratio remained the same as in 1996, when males constituted 72.3 % of the incidence, mean life-years lost would be lower at 14.2.

Countrywide improvement of the standards of diagnosis and treatment to those of the best-performing Clinical Commissioning Group (CCG) in the UK would reduce the total life-years lost in England by 4,275 relative to the level obtaining in 2014 (Birtwistle and Earnshaw, 2014), and would result in little change in the mean life-years lost per lung-cancer, estimated to be 14.4. Although the Manchester trial was targeted at high-risk tobacco-smokers in deprived areas, and therefore did not affect the detection and diagnosis of lung-cancers in the general population including non-smokers (Bhopal et al., 2019), the high detection rates of Stage I cancer in the trial indicate scope for improvement beyond the results for the best-performing CCG.

All other considerations remaining unchanged, improved life-expectancy adds directly to the total of life-years lost when an individual contracts, and dies from, lung-cancer. Using the data of Birtwistle and Earnshaw (2014), if all lung-cancers are detected at Stage I, but survival rates do not improve, then the average life-years lost drops to 13.2. With 79% detection of Stage I, the Manchester trial second round nominally achieved an average life-years lost of 13.5.

All of the improvements in treatment improve survival, but do not cure lung-cancer. If the best survival rate of 64% (Brustugun et al., 2018) is combined with the best CCG detection rate, the life-years lost will be 12.0. If, in future, a curative treatment is developed for Stage I cancer, but detection rates remain the same, then the average life-years lost drop to 12.5, but if the detection rates of the Manchester trial are combined with the treatment for Stage 1 disease becoming curative, then this drops to 3.0 life-years lost.

3.2 Costs per Stage

Birtwistle and Earnshaw (2014) estimate the current costs of diagnosis and treatment of lung-cancer for each stage of the disease, including the costs of further treatment if the patient relapses. This permits modelling of anticipated costs consequent on the whole UK moving to the best practice of the highest performing CCG. It is estimated that an additional £6.5M would be required to achieve the saving of 4,275 life-years lost, giving an incremental cost-effectiveness of a move to best practice of £1,515 per life-year gained. These values can be combined with diagnosis rates, such as those in Table 3, to provide estimates of costs associated with future improvements in diagnosis and treatment.

4 Discussion

A number of factors have changed since publication in 1999 of the first estimates of the cost-effectiveness of radon remediation in England and Wales. Of these, increased life-expectancy, which impacts on the estimate of life-years lost by lung-cancer mortality, is the most significant and improves the overall cost-effectiveness by approximately 20%. This is balanced to some degree by the reduced prevalence of tobacco-smoking, which has reduced cost-effectiveness by 17% in the same period, and by the contemporaneous reduction in household size.

A number of studies investigating differences between males and females with lung-cancer, including an extensive literature review by Frega et al. (2019), have revealed differences in response and survival times to certain chemotherapy treatments. In a sub-group treated by surgery, females in

Japan (Nakamura et al., 2017) and Australia and USA (Wainer et al., 2018) had a higher prevalence of lung-cancer being an adenoma (benign tumour) than males, and consequent improved survival. However, for the present high-level analysis, such differences can be disregarded, as Ringer et al. (2005), in their study of the Mid-West US Cancer Registry, report no significant differences between males and females in staging at presentation, median age of presentation, and overall survival. Therefore, in this analysis, the median survival was taken as the same for both males and females.

However, as Frega et al., (2019) and others note, when treating an individual patient, their sex should be taken into consideration. Indeed, Frega et al., (2019) suggest that, in the future, developments in treatments such as immunotherapy may well be more beneficial to female patients than to males. Moreover, UK 5-year net age-adjusted survival is beginning to show a higher survival for females at 2010-11, with females at 11.6 % (95% CI, 10.6 – 12.7%), males at 8.4% (95% CI, 7.5 – 9.4%), and overall 9.6% (95% CI, 8.9 – 10.3%) (ONS, 2019b)

The increase in costs for diagnosis and treatment are summarised in Table 3. As expected, these have risen since the initial study of Kennedy et al. (1999), and the values quoted by Birtwistle and Earnshaw (2014) represent an increase in real terms of 30% when price inflation is taken into account. The discrepancy of the estimate of Gray et al. (2009), which is 96% higher in real terms is attributed to their inclusion of hospice and continuing care in their analysis, whereas the other analyses solely estimate the costs of a specific treatment episode.

Table 3: Health costs per lung-cancer

Study	Kennedy et al. (1999)	Gray et al. (2009)	This Study (2018)	
Prices at:	1997	2007	UK Average 2014	CCG Best Practice 2014
Mean NHS/hospice cost per lung-cancer case	£6,873	£16,840	£14,238	£14,353
Cost revised by RPI to January 2019 prices	£12,350	£24,250	£15,950	£16,080
Cost relative to Kennedy et al (1999)	1	1.96	1.29	1.30

Kennedy et al. (1999) conducted a one-way sensitivity analysis, demonstrating that an increase in health costs has only a slight reduction in cost-effectiveness. An updated analysis, including the additional variables discussed here, is presented in Figure 5, where the upper limit for showing the impact of changes in life-years lost has been taken to be 10, to fit with medium term trends in diagnosis and treatment. The modelling assumes that all houses with radon concentrations exceeding the Action Level are remediated. However, in the UK, householder response to finding elevated radon levels in their homes is modest, with only around 15% remediating and those with lower incomes being less able or less willing to pay the associated costs (Zhang et al., 2011); similar response rates have been found elsewhere (Hahn et al., 2019).

Figure 5 shows that the degree of householder response has the most significant effect on cost effectiveness, reducing it by a factor of around 4 if response drops to 20%. It also shows that other significant factors affecting cost-effectiveness of lung-cancer mitigation measures include the percentage of houses with radon concentrations found to be over the Action Level – the higher the percentage expected then the better the cost-effectiveness – supporting the concept of locally targeted remediation programmes for areas with high radon concentrations. Note that radon concentration in apartment blocks decreases with increasing elevation and reduces the average cost-effectiveness compared to houses. Increased life expectancy, due to improved healthcare for other diseases, and other social factors, is a major factor which also improves cost-effectiveness. As noted in section 3.1, earlier lung-cancer diagnosis will have a modest impact, reducing cost-effectiveness, while improvements in treatment, and in particular, the future possibility of early-stage disease becoming curable, will become increasingly significant, possibly making all radon remediation programmes ultimately redundant. Although the individual cost of treating lung-cancers is high and increasing, this has little effect on the cost-effectiveness of a radon remediation programme. Similarly a low-cost breakthrough treatment will reduce cost-effectiveness, but only marginally, unless it makes a major impact on survival. Therefore the challenge for remediation of radon risks remains the challenge of establishing public health programmes that ensure public participation.

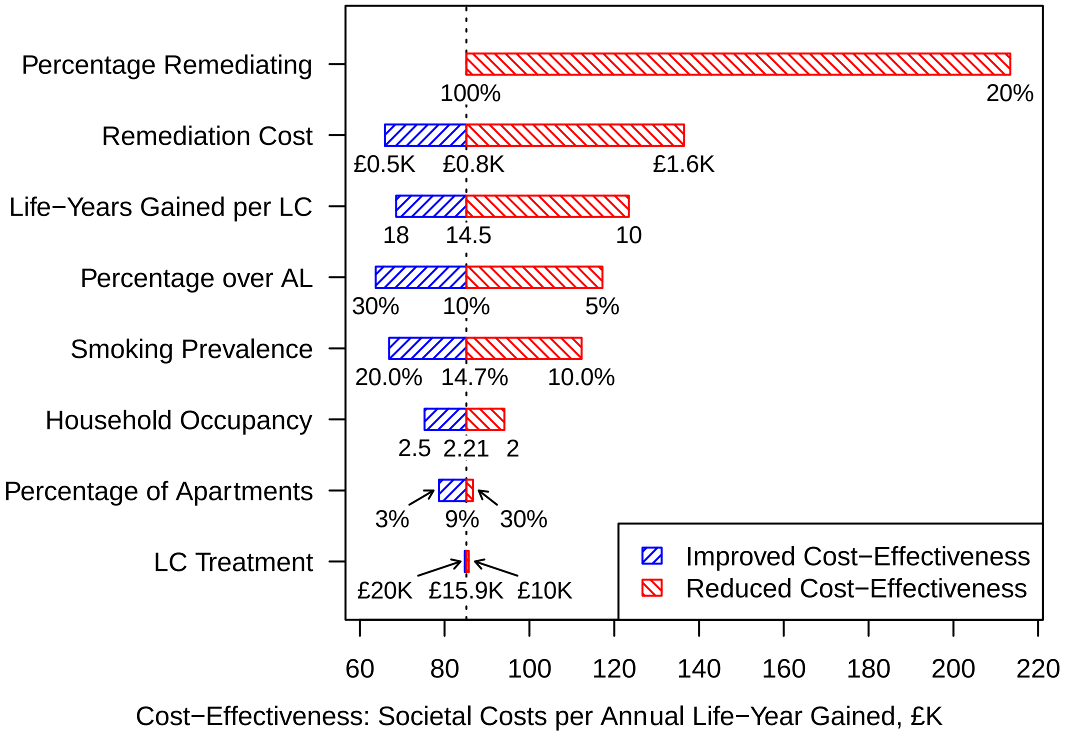

Figure 5: One-way sensitivity analysis for cost-effectiveness (£K per life-year gained annually) of radon remediation programmes

5 Conclusions

This paper has considered the developments in lung-cancer diagnosis and treatment, along with other factors, that have taken place since the first reports that remediation of domestic housing to reduce radon-induced lung-cancer risk was cost-effective. Lung-cancer treatment costs have risen by 30%, while the numbers surviving 5 years after lung-cancer diagnosis have doubled. It is clear that radon remediation programmes remain cost-effective and, if anything, are now more cost-effective than hitherto because of the overall increase in life-expectancy consequent on general improvements in healthcare, despite current improvements in lung-cancer treatment. The increase in general life-expectancy is more significant for the cost-effectiveness of radon-remediation programmes than the impact of reduction in prevalence of tobacco-smoking. While smoking cessation programmes remain more cost-effective than radon remediation programmes, and present an additional opportunity to reduce the risk from radon, the most important factor is achieving full participation of the target group of householders. Therefore, public awareness, targeted public health campaigns and health incentives remain crucial to reducing radon risk in the general population.

The growing evidence that urban air pollution, such as PM2.5, is a cause of lung-cancers does not detract from the significance of radon-remediation campaigns. However, it does show that, for the UK at least, radon remediation campaigns should be targeted at rural areas, while air pollution reduction initiatives are appropriate for urban areas.

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7 References

Aokage, K., Yoshida, J., Hishida, T., Tsuboi, M., Saji, H., Okada, M., Suzuki, K., Watanabe, S., Asamoura, H., 2017. Limited resection for early non-small cell lung-cancer as function-preserving radical surgery: a review. Jap. J. Clin. Oncol. 47, 7-11. https://doi.org/10.1093/jjco/hyw148

Baker, S., Dahele, M., Lagerwaard, F.J., Senan, S., 2016. A critical review of recent developments in radiotherapy for non-small cell lung-cancer. Radiat. Oncol. 11, 115. https://doi.org/10.1186/s13014-016-0693-8

BEIR VI (Committee on Health Risks of Exposure to Radon), 1999. Health risks of exposure to radon. Washington DC, USA: National Academy Press. ISBN 0-309-05645-4.

Bhopal, A., Peake, M.D., Gilligan, D., Cosford, P., 2019. Lung-cancer in never-smokers: a hidden disease. J. Roy. Soc. Med. 112, 269-271. https://doi.org/10.1177/0141076819843654

Birtwistle, M., Earnshaw, A., 2014. Saving lives, averting costs: an analysis of the financial implications of achieving earlier diagnosis of colorectal, lung and ovarian cancer. Incisive Health Ltd., for Cancer Research UK. https://www.incisivehealth.com/wp-content/uploads/2018/08/Saving-lives-averting-costs.pdf

Bjerager, M., Palshof, T., Dahl, R., Vedsted, P., Olesen, F., 2006. Delay in diagnosis of lung-cancer in general practice. Brit. J. Gen. Pract. 56, 863-868.

Briggs, D., Abellan, J., Fecht, D., 2008. Environmental inequity in England: small area associations between socio-economic status and environmental pollution. Soc. Sci. Med. 67, 1612–1629. https://doi.org/10.1016/j.socscimed.2008.06.040

Brustugun, O.T., Grønberg, B.H., Fjellbirkeland, L., Helbekkmo, N., Aanerud, M., Grimsrud, T.K., Helland, Å., Møller, B., Nilssen, Y., Strand, T.E., Solberg, S.K., 2018. Substantial nation-wide improvement in lung-cancer relative survival in Norway from 2000 to 2016. Lung-Cancer 122, 138-145. https://doi.org/10.1016/j.lungcan.2018.06.003

Campbell, J., Pyer. M, Rogers S., Walter, D., Reddy, R., 2014. Enabling patients with respiratory symptoms to access chest X-rays on demand: the experience of the walk-in service in Corby, UK J. Public Health 36, 511–516. https://doi.org/10.1093/pubmed/fdt104

Chin, S., Eccles, C.L., McWilliam, A., Chuter, R., Walker, E., Whitehurst, P., Berresford, J., Van Herk, M., Hoskin, P.J., Choudhury, A., 2020. Magnetic resonance-guided radiation therapy: a review. J. Med. Imaging Radiat. Oncol., 64, 163-177. https://doi.org/10.1111/1754-9485.12968

CLG (Department for Communities and Local Government), 2010. Housing and planning statistics 2010. ISBN 978 1 4098 2668 2

Cressman, S., Peacock, S.J., Tammemägi, M.C., Evans, W.K., Leighl, N.B., Goffin, J.R., et al., 2018. The cost-effectiveness of high-risk lung-cancer screening and drivers of program efficiency. J. Thorac. Oncol. 12, 1210-1222. https://doi.org/10.1016/j.jtho.2017.04.021

Crosbie, P.A., Balata, H., Evison, M., Atack, M., Bayliss-Brideaux, V., Colligan, D., et al., 2019a. Implementing lung cancer screening: baseline results from a community-based ‘Lung Health Check’ pilot in deprived areas of Manchester. Thorax 74, 405–409. https://doi.org/10.1136/thoraxjnl-2017-211377

Crosbie, P.A., Balata, H., Evison, M., Atack, M., Bayliss-Brideaux, V., Colligan, D., et al., 2019b. Second round results from the Manchester ‘Lung Health Check’ community-based targeted lung-cancer screening pilot. Thorax 74, 700-704. https://doi.org/10.1136/thoraxjnl-2018-212547.

CRUK (Cancer Research UK), 2018. Lung Cancer Mortality Statistics. https://www.cancerresearchuk.org/health-professional/cancer-statistics/statistics-by-cancer-type/lung-cancer/mortality. Accessed Jan 2020.

Darby, S., Hill, D., Auvinen, A., Barros-Dios, J.M., Baysson, H., Bochicchio, F., Deo, H., Falk, R., Forastiere, F., Hakama, M., Heid, I., Kreienbrock, L., Kreuzer, M., Lagarde, F., Mäkeläinen, I., Muirhead, C., Oberaigner, W., Pershagen, G., Ruano-Ravina, A., Ruosteenoja, E., Schaffrath Rosario, A., Tirmarche, M., TomáBek, L., Whitley, E., Wichmann, H.E., Doll, R., 2005. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. BMJ 330(7485). https://doi.org/10.1136/bmj.38308.477650.63

Darby, S., Hill, D., Doll, R., 2001. Radon: A Likely Carcinogen at all exposures. Ann. Oncol. 12, 1341-1351. https://doi.org/10.1023/A:1012518223463

De Koning, H., Van Der Aalst, C., Ten Haaf, K., Oudkerk, M., 2018. # PL02.05. Effects of Volume CT lung-cancer screening: mortality results of the NELSON randomised-controlled population-based trial. J. Thorac. Oncol. 13, S185. https://doi.org/10.1016/j.jtho.2018.08.012

Denman, A.R., Crockett, R.G.M., Groves-Kirkby, C.J., Phillips, P.S., Gillmore, G.K., 2019. Exploring the relationship between social deprivation and domestic radon levels in the East Midlands, UK. J. Environ. Radioact. 199-200, 84-98. https://doi.org/10.1016/j.jenvrad.2019.01.010

Denman, A.R., Groves-Kirkby, C.J., Coskeran, T., Phillips, P.S., Tornberg, R., 2005. Evaluating the health benefits and cost effectiveness of the radon remediation programme in domestic properties in Northamptonshire, UK. Health Policy, 73, 139-150. https://doi.org/10.1016/j.healthpol.2004.11.005

Denman, A.R., Groves-Kirkby, C.J., Phillips, P.S., Tornberg, R., 2004. Using the European Community Radon software to estimate the individual health benefits of a domestic radon remediation programme. J. Radiol. Prot. 24, 83-89. https://doi.org/10.1088/0952-4746/24/1/007

Denman, A.R., Phillips, P.S., Tornberg, R., 2002. The costs and benefits of radon remediation programmes in existing homes: case study of action level selection. J. Environ. Radioact. 62, 17-27. https://doi.org/10.1016/s0265-931x(01)00147-3

Denman, A.R., Rogers, S., Timson, K., Phillips, P.S., Crockett, R.G.M., Groves-Kirkby, C.J., 2014. Future initiatives to reduce lung-cancer incidence in the UK: smoking cessation, radon remediation and the impact of social change. Perspectives in Public Health 135, 92-101. https://doi.org/10.1177/1757913914522785

Denman, A.R., Sinclair, J., Phillips, P.S., Crockett, R.G.M., Groves-Kirkby, C.J., 2013. The cost-effectiveness of radon reduction programmes in domestic housing in England and Wales: the impact of improved radon mapping and housing trends. Environ. Int. 59, 73-85. https://doi.org/0.1016/j.envint.2013.05.012

Denman, A.R., Timson, K., Shield, G., Groves-Kirkby, C.J., Rogers, S., Campbell, J.A., Phillips, P.S., 2009. Local health campaigns to reduce lung-cancers induced by radon and smoking - who responds?. Health Policy 93, 201-206. https://doi.org/10.1016/j.healthpol.2009.07.011

Dillman, R.O., McClure, S.E., 2014. Steadily Improving survival in lung-cancer. Clin. Lung Cancer 15, 331-337. https://doi.org/10.1016/j.cllc.2014.05.006

DoH (Department of Health), 2007. The government's expenditure plans: departmental report 2007: Department of Health (Cm 7093). London, Department of Health. ISBN 978 0 10 170932 3

Frega, S., Dal Maso, A., Ferro, A., Bonano, L., Conte, P., Pasello, G., 2019. Heterogeneous tumor features and treatment outcome between males and females with lung cancer (LC): do gender and sex matter? Crit. Rev. Oncol. Haematol. 138, 87-103. https://doi.org/10.1016/j.critrevonc.2019.03.012

Gray, A., Read, S., McGale, P., Darby, S., 2009. Lung-cancer deaths from indoor radon and the cost-effectiveness and potential of policies to reduce them. BMJ 338, a3110. https://doi.org/10.1136/bmj.a3110

Griffiths, C., Brock, A., 2003. Twentieth century mortality trends in England and Wales. Health Statistics Quarterly 18, 5-17. ISSN 1465-1645

Hahn, E.J., Wiggins, A.T., Rademacher, K., Butler, K.M., Huntington-Moskos, L., Rayens, M.K., 2019. FRESH: Long-term outcomes of a randomized trial to reduce radon and tobacco smoke in the home. Preventing Chronic Disease: Public Health Research, Practice, and Policy 16 (E127). https://doi.org/10.5888/pcd16.180634.

Hamra, G.B., Guha, N., Cohen, A., Laden, F., Raaschou-Nielsen, O., Samet, J.M., et al., 2014. Outdoor particulate matter exposure and lung-cancer: a systematic review and meta-analysis. Environ. Health Perspect. 122, 906-911. https://doi.org/10.1289/ehp.1408092

Hamra, G.B., Laden, F., Cohen, A.J., Raaschou-Nielsen, O., Brauer, M., Loomis, D., 2015. Lung-cancer and Exposure to Nitrogen Dioxide and Traffic: A Systematic Review and Meta-Analysis. Environ. Health Perspect. 123, 1107-1112. https://doi.org/10.1289/ehp.1408882

HMSO, 1998. Smoking kills – a White Paper on tobacco. The Stationery Office (London 1998) http://webarchive.nationalarchives.gov.uk/+/www.dh.gov.uk/en/Publicationsandstatistics/Publications/PublicationsPolicyAndGuidance/DH_4006684

HPA (Health Protection Agency), 2009. Radon and public health: Report of the independent Advisory Group on Ionising Radiation. Documents of the HPA, Report RCE-11. Chilton: Health Protection Agency. ISBN 978-0-85951-644-0

Huang, F., Pan, B., Wu, J., Chen, E., Chen, L., 2017. Relationship between exposure to PM2.5 and lung cancer incidence and mortality: A meta-analysis. Oncotarget 8, 43322-43331 https://doi.org/10.18632/oncotarget.17313

Kendall, G., Miles, J., Rees, D., Wakeford, D., Bunch, K., Vincent, T., Little, M., 2016. Variation with socioeconomic status of indoor radon levels in Great Britain: the less affluent have less radon. J. Environ. Radioact. 164, 84–90. https://doi.org/10.1016/j.jenvrad.2016.07.001

Kennedy C.A., Gray, A.M., Denman, A.R., Phillips, P.S., 1999. A cost-effectiveness analysis of a residential radon remediation programme in the United Kingdom. Brit. J. Cancer 81, 1243–1247. https://doi.org/10.1038/sj.bjc.6690836

Mesko, S., Gomez, D., 2018. Proton therapy in non-small cell lung-cancer. Curr. Treat. Options Oncol. 19, 76. https://doi.org/10.1007/s11864-018-0588-z

Moffat, J., Hiom, S., Kumar, H.S., Baldwin, D.R., 2018. Lung-cancer screening - gaining consensus on next steps - proceedings of a closed workshop in the UK. Lung Cancer 125, 121-127. https://doi.org/10.1016/j.lungcan.2018.07.029

Naismith, S.P., Miles, J.C., Scivyer, C.R., 1998. The influence of house characteristics on the effectiveness of radon remedial measures. Health Phys. 75, 410-416. https://doi.org/10.1097/00004032-199810000-00008

Nakamura, K., Ukawa, S., Okada, E., Hirata, M., Nagai, A., Yamagata, Z., Ninomiya, T., Muto, K., Kiyohara, Y., Matsuda, K., Kamatani, Y., Kubo, M., Nakamura, Y., Biobank Japan Cooperative Hospital Group, Tamakoshi, A., 2017. Characteristics and prognosis of Japanese male and female lung-cancer patients: The BioBank Japan Project. J. Epidemiology, 27, S49-S57. https://doi.org/10.1016/j.je.2016.12.010

NCIN (National Cancer Intelligence Network), 2014. Cancer by deprivation in England: Incidence, 1996-2010: Mortality, 1997-2011. PHE publications gateway number: 2014093.

NCIN (National Cancer Intelligence Network), 2019. Routes to diagnosis 2006-2016 workbook (b), version 2.1b. London: NCIN. Online at http://www.ncin.org.uk/publications/routes_to_diagnosis

Neal, R.D., Allgar, V.I., 2005. Sociodemographic factors and delays in the diagnosis of six cancers: analysis of data from the "National Survey of NHS Patients: Cancer". Brit. J. Cancer 92, 1971-1975. https://doi.org/10.1038/sj.bjc.6602623

NHS (National Health Service), 2019. The NHS Long Term Plan, V.1.2 August 2019. Online at www.longtermplan.nhs.uk

ONS (Office of National Statistics), 2015. Survival from cancer improving and more people being diagnosed. Online at https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/articles/survivalfromcancerimprovingandmorepeoplebeingdiagnosed/2015-07-17

ONS (Office of National Statistics), 2018. Adult Smoking Habits in the UK. Online at https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/healthandlifeexpectancies/bulletins/adultsmokinghabitsingreatbritain/2018

ONS (Office of National Statistics), 2019a. Cancer Registration Statistics, England: Data for 2014, 2015, 2016 and 2017. Online at: https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/datasets/cancerregistrationstatisticscancerregistrationstatisticsengland.

ONS (Office of National Statistics), 2019b. 40 years of Cancer Registration Data. publisheddata_tcm77-411675.xls. Online at https://webarchive.nationalarchives,gov,uk.

ONS (Office of National Statistics), 2019c. Bulletin: Families and households in the UK: 2019. Online at https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/bulletins/familiesandhouseholds/2019

ONS (Office of National Statistics), 2019d. Expectation of Life, Principal Projection, England and Wales. Online at https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/lifeexpectancies/datasets/expectationoflifeprincipalprojectionenglandandwales

Peto, R., Darby, S., Deo, H., Silcocks, P., Whitley, E., Doll, R., 2000. Smoking, smoking cessation, and lung-cancer in the UK since 1950: combination of national statistics with two case-control studies. BMJ, 321, 323-329.

PHE (Public Health England), 2018. Health Profile for England, 2018. Online at https://www.gov.uk/government/publications/health-profile-for-england-2018

Raleigh, V.S., 2018. Stalling life-expectancy in the UK. BMJ. 362, k4050. https://doi.org/10.1136/bmj.k4050

RCP (Royal College of Physicians), 2016. Every breath we take: the lifelong impact of air pollution. Report of a working party. London: Royal College of Physicians. ISBN: 978-1-86016-567-2

Richards, M., Thorlby, R., Fisher, R., Turton, C., 2018. Unfinished business: an assessment of the national approach to improving cancer services in England 1995-2015. The Health Foundation, London.
ISBN 978-1-911615-20-0

Ringer, G., Smith, J.M., Engel, A.M., Hendy, M.P., Lang, J., 2005. Influence of sex on lung histology, stage, and survival in a midwestern United States tumor registry. Clin. Lung Cancer, 7, 180-185.

Roointan, A., Ahmad Mir, T., Ibrahim Wani, S., Mati-ur-Rehman, Hussain, K.K., Ahmed, B., Abrahim, S., Savardashtaki, A., Gandomani, G., Gandomani, M., Chinnappan, R., Akhtar, M.H., 2019. Early detection of lung-cancer biomarkers through biosensor technology: a review. J. Pharm. Biomed. Anal. 164, 93-103.
https://doi.org/10.1016/j.jpba.2018.10.017

Sanderson, H., Mountney, L., Harris, J., 1994. Cancer of the lung. Chapter 8 in Health Care Needs Assessment Vol. 1. Ed. Stevens A, Raftery J. Oxford: Radcliffe Medical Press.
ISBN 1-85775-047-0

Tweed, E.J., Allardice, G.M., McLoone, P., Morrison, D.S., 2018. Socio-economic inequalities in the incidence of four common cancers: a population-based registry study. Public Health 154, 1-10.
https://doi.org/10.1016/j.puhe.2017.10.005

Twigg, E., Moon, G., Walker, S., 2004. The smoking epidemic in England. NHS Health Development Agency, London.
ISBN 1-84279-318-7

UK Radon Association, 2019. Information-for-house-buyers-and-sellers.
http://www.radonassociation.co.uk/guide-to-radon/information-for-house-buyers-and-sellers/
Accessed 17th June 2019

Wainer, Z., Wright, G.M, Gough, K., Daniels, M.G., Russell, P.A., Choong, P., Conron, M., Ball, D., Solomon, B., 2018. Sex-dependent Staging in Non-small-cell Lung Cancer; Analysis of the effect of sex differences in the eight edition of the tumor, node, metastases staging system. Clin. Lung Cancer, 19e933-944 2018
https://doi.org/10.1016/j.cllc.2018.08.004

Wolstenholme, J.L., Whynes, D.K., 1999. The hospital costs of treating lung-cancer in the United Kingdom. Brit J Cancer 80, 215-218
https://doi.org/10.1038/sj.bjc.6690341

Wrixon, A.D., Green, B.M.R., Lomas, P.R., Miles, C.H., Cliff, K.D., Francis, E.A., Driscoll, C.M.H., James, A.C., O'Riordan, M.C., 1988. Natural radiation exposure in UK dwellings. National Radiological Protection Board, Didcot. Report NRPB R190
ISBN 0 85951 260 6

Zhang, W., Chow, Y., Meara, J., Green, M., 2011. Evaluation and equity audit of the domestic radon programme in England. Health Policy 102, 81–88
https://doi.org/10.1016/j.healthpol.2010.09.016