Radon and Lung Cancer: A Cost-Effectiveness Analysis

Earl S. Ford, MD, MPH, Alison E. Kelly, MA, Steven M. Teutsch, MD, MPH, Stephen B. Thacker, MD, MSc, and Paul L. Garbe, DVM, MPH

Abstract

Objectives. This study examined the cost-effectiveness of general and targeted strategies for residential radon testing and mitigation in the United States.

Methods. A decision-tree model was used to perform a cost-effectiveness analysis of preventing radon-associated deaths from lung cancer.

Results. For a radon threshold of 4 pCi/L, the estimated costs to prevent 1 lung cancer death are about $3 million (154 lung cancer deaths prevented), or $480,000 per life-year saved, based on universal radon screening and mitigation, and about $2 million (104 lung cancer deaths prevented), or $330,000 per life-year saved, if testing and mitigation are confined to geographic areas at high risk for radon exposure. For mitigation undertaken after a single screening test and after a second confirmatory test, the estimated costs are about $920,000 and $520,000, respectively, to prevent a lung cancer death with universal screening and $130,000 and $80,000 per life-year for high risk screening. The numbers of preventable lung cancer deaths are 811 and 527 for universal and targeted approaches, respectively.

Conclusions. These data suggest possible alternatives to current recommendations. (Am J Public Health. 1999;89:351–357)

At least 11 economic analyses of radon reduction programs have been reported.1,6–14 EPA's analysis concluded that preventing a radon-associated lung cancer death would cost about $700,000.1 Several analyses have concluded that targeted screening programs are more cost-effective than programs aimed at all home occupants.12,14 Differences in assumptions and analytic design, however, make these analyses difficult to compare. In addition, most of the analyses have not incorporated medical, productivity, or program costs. Because of the inconsistency in previous economic analyses, we conducted a cost-effectiveness analysis that incorporated newer data.

Methods

We developed a decision tree15 that included 5 major scenarios: (1) a no action program; (2) a universal screening program based on EPA recommendations; (3) a targeted screening program similar to the universal program, except that it is targeted at homes in areas considered to be at risk for elevated radon levels; (4) a modified universal screening program whereby radon mitigation of a household is allowed after the completion of a single radon test; and (5) a modified targeted screening program (Figure 1). For options 2 and 3, we modeled the decision tree in accordance with EPA recommendations for radon testing and mitigation, except that the recommendation to mitigate was based on the results of 2 consecutive short-term tests being above a certain threshold or on positive results of a confirmatory long-term test instead of the average result of two successive short-term tests. For options 4 and 5, we modified the decision tree to allow mitigation after a single positive short-term radon test. In addition to the analyses for the entire population, we also conducted separate analyses by smoking status and age. All models incorporated probabilities for compliance.

At the time this study was conducted, Earl S. Ford, Alison E. Kelly, and Paul L. Garbe were with the National Center for Environmental Health, Centers for Disease Control and Prevention, Atlanta, Ga. At the time this study was conducted, Steven M. Teutsch and Stephen B. Thacker were with the Epidemiology Program Office, Centers for Disease Control and Prevention.

Requests for reprints should be sent to Earl S. Ford, MD, MPH, Centers for Disease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion, Division of Nutrition and Physical Activity, 4770 Buford Hwy, Mailstop K26, Atlanta, GA 30341 (e-mail: esf2@cdc.gov).

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Universal and targeted screening strategies

Target population — Yes — Buy test — Do test — >4 pCi/L — Retest — Short-term test — >4 pCi/L — True + test

No — Don’t buy test — No test — ≤4 pCi/L — No retest — Long-term test — ≤4 pCi/L — False + test

A — A — A — B — C — A — D — B — A — D

Modified universal and modified targeted screening strategies

Target population — Yes — Buy test — Do test — >4 pCi/L — Retest — Short-term test — >4 pCi/L — True + test

No — Don’t buy test — No test — ≤4 pCi/L — No retest — Long-term test — ≤4 pCi/L — False + test

<4 — >4 pCi/L — Miti-gate — No miti-gate

A — A — A — B — C — A — D — B — A — D

Probability of dying

A True - test — A
False - test — A

Probability of not dying

B True - test — A
False - test — A

C True + test — A
False + test — A

D Mitigate — >4 pCi/L — A
<4 pCi/L — A

Note. Probabilities for decision and terminal nodes vary depending on location in decision tree and type of screening strategy.

FIGURE 1—Simplified decision tree presenting various options of radon testing and mitigation.

The analysis examined the lifetime costs and effects of these approaches to reducing exposure to radon and prevention of lung cancer in a stationary population of about 250 million people whose age structure reflected the 1990 US Census. The societal approach included all costs and benefits. To facilitate modeling and comparisons of differences among strategies, we assumed a 2-year period during which an intervention would occur and decisions and actions about radon testing and mitigation would be performed and implemented.

Costs

The costs are presented in 1993 dollars and include those associated with both the intervention (program, testing, and mitigation costs) and radon-related lung cancer deaths (direct medical costs and productivity losses from lung cancer morbidity and mortality). In order to convert future costs to 1993 dollars, they were discounted 4% per year.

The universal screening program cost used in this analysis was $18,776,000 (50% of the 5-year average of EPA funding of $18,000,000 along with $9,776,000 in non-federal funds related to residential radon exposure) (F. Marcinowski, US EPA, e-mail, April 1994). The cost for a very intensive targeted program ($28,500,000) was based on a community radon intervention in the Washington, DC, area and then applied to counties having high potential for residential radon exposure nationwide. The testing and mitigation costs used in this analysis were based on 1992 estimates adjusted to 1993 dollars. The per individual costs were $41.66 for a long-term test and $11.66 for a short-term test. The cost of mitigation, adjusted to 1993 dollars and discounted at 4%, was $1801.72 per person.

The total cost due to lung cancer included direct medical costs and productivity losses from lung cancer morbidity and mortality. Data were aggregated by gender. We used the weighted average of the excess medical expenditures related to lung cancer for male and female smokers of $2554 to estimate the excess medical expenditures for radon-related lung cancer over a 3-year course of illness. For productivity losses from morbidity, we estimated that 9% of
those with lung cancer would be 100% disabled by their disease, 20% would be 80% disabled, 40% would be 50% disabled, and 31% would be 20% disabled (M. Siegel, written communication, 1994), for an average productivity cost of $12,159. We estimated that productivity losses from mortality totaled $85,196. Thus, the average total cost of a radon-related lung cancer death used in this analysis was $99,910.

**Probabilities and Risks**

We estimated compliance probabilities (best estimate probabilities) for purchasing a radon test, completing the test, retesting, and mitigating (Table 1). Alternative sets of probabilities were based on either published data from a community intervention radon program in the Washington, DC, area or the assumption of full compliance with testing and mitigation recommendations.

Using national data when available, we estimated that an average of 1.7% of dwellings in the United States would be tested each year, 13.22 55.8% of people who obtained a test kit would complete the testing process, 13. 3.05% of occupants of dwellings would purchase a radon test each year, 40.7% of homes would be retested, 13 22.2% of homes testing positive would be mitigated, 13 22 and 95% of mitigation efforts would be successful. 13

We used the BEIR IV model to estimate the risk of dying from radon-associated lung cancer for the US population, assuming that the risk for exposure to 1.25 pCi/L of radon, the national mean, is equivalent to the baseline risk calculated from mortality data. 13 We calculated lung cancer and all-cause mortality rates for 1990 using national vital statistics and census data. (An appendix summarizing the lifetime risks used for the various radon thresholds is available from the first author.)

Using a 1-year alpha track detector as the referent (long-term test), we calculated that the sensitivity rates of a 2-day charcoal canister test (short-term test) were 83.1%, 84.5%, 88.2%, 74.0%, and 60.0% and that specificity rates were 71.9%, 90.9%, 96.9%, 98.0%, and 99.5% for radon thresholds of 2 pCi/L, 4 pCi/L, 8 pCi/L, 10 pCi/L, and 20 pCi/L, respectively (F. Marcinowski, US EPA, written communication, August 1994).

The prevalence of dwellings with radon levels above various thresholds for both the universal and targeted screening approaches and average radon concentrations were derived from the National Residential Radon Survey conducted in 1989/90. 14 Radon levels by radon risk level and by dwelling testing criteria were also calculated.

We based the universal screening option on the 1990 Census estimate of 100,480,000 dwellings with a population of 248,710,000. 1 For the targeted approach, we used a recent map, assigning each county to 1 of 3 zones of radon exposure. 14 Approximately 25.9 million homes with a population of about 71 million people are located in the high risk (zone 1) counties.

We calculated smoking-specific estimates of lifetime risk for lung cancer death 26,27 using relative risks from the American Cancer Society's Cancer Prevention Study 26,29 and age-specific estimates of smoking prevalence from the 1990 National Health Interview Survey Health Promotion and Disease Prevention Supplement. 22 In calculating the radon-associated risk for lung cancer, we used models that assumed that radon and smoking risks were multiplicative. A submultiplicative model is available from the authors. 13

Sensitivity analyses examined the impact of the possible ranges of probability estimates and costs on the cost-effectiveness estimates. Lower and upper bound limits of sensitivity parameters were derived from either published literature or various reports. Upper bound limits for behavioral probabilities reflected full compliance. We calculated the incremental costs associated with lowering incrementally the radon action threshold from 20 pCi/L to 2 pCi/L and the incremental costs for switching from one scenario to another. Because costs were discounted to reflect the time preference for money, deaths from lung cancer were also discounted at 4%.

### Results

**No Program**

Almost 13.5 million people would be expected to die from lung cancer in a cohort of 250 million people over the lifetime of the cohort.

**Universal Screening**

Using best estimate probabilities, the lowest cost-effectiveness ratio is achieved at the 4 pCi/L threshold (Table 2). We estimate that it would cost about $3 million to prevent 1 death from radon-associated lung cancer, or about $480,000 per life-year (Table 2). About 154 lung cancer deaths would be prevented during the lifetime of the population, estimated to be about 75 years. Using probabilities from the Washington, DC, study, 17 we estimate that it would cost about $9.4 million to prevent 1 lung cancer death and that 65 lung cancer deaths would be prevented. If all home occupants could be convinced to comply with current recommendations, the model shows that about 182,000 deaths could be prevented at a savings of about $91,000 each.

**Targeted Screening**

The most cost-effective ratios are achieved at the 4 pCi/L threshold; about 104 lung cancer deaths would be prevented at a cost of about $2 million for each death, or about $330,000 per life-year. In comparison, use of the Washington, DC, compliance results 18 suggests that about 49 lung cancer deaths would be prevented at a cost of about $4.9 million each. Using the full compliance scenario, about 122,000 deaths would be preventable at a cost of about $35,000 each at the 4 pCi/L threshold.

**Modified Universal Screening**

In this scenario, in which occupants could mitigate after a single positive radon test, about 811 lung cancer deaths would be prevented at a cost of about $920,000 each, or about $130,000 per life-year, according to best estimate probabilities for the 4 pCi/L threshold. However, the best cost-effectiveness estimates are achieved for the 8 pCi/L threshold. Use of compliance estimates from the Washington, DC, study 17 leads to a cost-effectiveness estimate of $710,000 and 2042 lung cancer deaths prevented. Using full compliance probabilities, the model yields results identical to those for the universal screening option.

**Modified Targeted Screening**

This scenario predicts that 527 lung cancer deaths would be prevented at a cost

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**TABLE 1—Behavioral Probabilities Used In Cost-Effectiveness Analysis**

<table>
<thead>
<tr>
<th>Behavior</th>
<th>Best Estimate</th>
<th>Doyle et al. 17</th>
<th>Full Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Being a member of the target population</td>
<td>0.83</td>
<td>0.83</td>
<td>0.83</td>
</tr>
<tr>
<td>Purchasing short-term test</td>
<td>0.0305</td>
<td>0.065</td>
<td>1.0</td>
</tr>
<tr>
<td>Using short-term test if purchased</td>
<td>0.558</td>
<td>0.558</td>
<td>1.0</td>
</tr>
<tr>
<td>Probability of retesting</td>
<td>0.407</td>
<td>0.071</td>
<td>1.0</td>
</tr>
<tr>
<td>Purchasing a short-term test for retest</td>
<td>0.91</td>
<td>0.91</td>
<td>0.91</td>
</tr>
<tr>
<td>Using long-term test if purchased</td>
<td>0.558</td>
<td>0.558</td>
<td>1.0</td>
</tr>
<tr>
<td>Mitigating</td>
<td>0.22</td>
<td>0.25</td>
<td>1.0</td>
</tr>
<tr>
<td>Postmitigation radon test &gt;4 pCi/L</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

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of about $520,000 each, or about $80,000 per life-year, for the 4 pCi/L threshold. On the basis of compliance estimates from the Washington, DC, study, we estimated that it would cost $320,000 to prevent a death from lung cancer and that 1317 deaths would be prevented. Assuming full compliance, the results are similar to the targeted screening option. Potential savings are achieved at thresholds of 8 and 10 pCi/L.

Smoking

Using the universal screening scenario, best estimates of the probabilities, and a multiplicative model, we found that performing an intervention in the homes of smokers was more cost-effective than performing one in the home of someone who had never smoked (Table 3). The same pattern held for the other scenarios, but the cost-effectiveness estimates differed. Although the estimates for former, light, and heavy smokers remained relatively unchanged when a multiplicative approach was used (data not shown), the cost-effectiveness estimate for lifetime nonsmokers was substantially lessened. Nevertheless, even under this approach to calculating cost-effectiveness estimates, it remains more costly to prevent a lung cancer death among never smokers than among people who have ever smoked.

Age

From the first decade through the fourth decade of life, the cost-effectiveness estimates for the universal and targeted scenarios decrease, after which they progressively increase with increasing age (particularly after age 79). For the third through sixth decades of life, the cost-effectiveness estimates are less than $2 million to prevent a lung cancer death for the universal scenario and less still for the targeted scenario.

Sensitivity Analyses

For the universal scenario, increasing the probability of retesting for the presence of elevated radon levels, the probability of mitigating, or the probability of successfully mitigating improved the cost-effectiveness estimates (Table 4). In addition, maximizing the probabilities of completing 2 radon tests together reduced the cost-effectiveness estimate. Increasing the costs associated with lung cancer also led to a lowering of the cost-effectiveness estimates. Changes in these probabilities substantially affected the number of lung cancer deaths prevented as well. Whereas increasing the probability of purchasing a radon test did not greatly affect the cost-effectiveness

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### TABLE 2—Summary Results of Cost-Effectiveness Analysis of Radon and Lung Cancer Deaths Using Best Estimate Probabilities

<table>
<thead>
<tr>
<th>Cost per lung cancer death prevented, including medical costs and productivity losses, $</th>
<th>2 pCi/L</th>
<th>4 pCi/L</th>
<th>8 pCi/L</th>
<th>10 pCi/L</th>
<th>20 pCi/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Universal screening</td>
<td>3,050,000</td>
<td>3,030,000</td>
<td>4,420,000</td>
<td>9,100,000</td>
<td>68,440,000</td>
</tr>
<tr>
<td>Targeted screening</td>
<td>2,500,000</td>
<td>2,040,000</td>
<td>2,220,000</td>
<td>4,430,000</td>
<td>14,670,000</td>
</tr>
<tr>
<td>Modified universal screening</td>
<td>1,660,000</td>
<td>920,000</td>
<td>600,000</td>
<td>790,000</td>
<td>5,500,000</td>
</tr>
<tr>
<td>Modified targeted screening</td>
<td>1,180,000</td>
<td>520,000</td>
<td>300,000</td>
<td>460,000</td>
<td>9,470,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost per lung cancer death prevented, excluding medical costs and productivity losses, $</th>
<th>2 pCi/L</th>
<th>4 pCi/L</th>
<th>8 pCi/L</th>
<th>10 pCi/L</th>
<th>20 pCi/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Universal screening</td>
<td>3,360,000</td>
<td>3,340,000</td>
<td>4,720,000</td>
<td>9,410,000</td>
<td>68,740,000</td>
</tr>
<tr>
<td>Targeted screening</td>
<td>2,800,000</td>
<td>2,340,000</td>
<td>2,530,000</td>
<td>4,740,000</td>
<td>14,980,000</td>
</tr>
<tr>
<td>Modified universal screening</td>
<td>1,970,000</td>
<td>1,230,000</td>
<td>910,000</td>
<td>1,100,000</td>
<td>2,850,000</td>
</tr>
<tr>
<td>Modified targeted screening</td>
<td>1,490,000</td>
<td>830,000</td>
<td>610,000</td>
<td>770,000</td>
<td>9,780,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost per life-year, $</th>
<th>2 pCi/L</th>
<th>4 pCi/L</th>
<th>8 pCi/L</th>
<th>10 pCi/L</th>
<th>20 pCi/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Universal screening</td>
<td>700,000</td>
<td>480,000</td>
<td>690,000</td>
<td>1,440,000</td>
<td>1,380,000</td>
</tr>
<tr>
<td>Targeted screening</td>
<td>570,000</td>
<td>330,000</td>
<td>360,000</td>
<td>730,000</td>
<td>580,000</td>
</tr>
<tr>
<td>Modified universal screening</td>
<td>380,000</td>
<td>130,000</td>
<td>110,000</td>
<td>150,000</td>
<td>500,000</td>
</tr>
<tr>
<td>Modified targeted screening</td>
<td>220,000</td>
<td>80,000</td>
<td>70,000</td>
<td>100,000</td>
<td>2,410,000</td>
</tr>
</tbody>
</table>

---

### TABLE 3—Cost-Effectiveness Analysis, Stratified by Smoking Status, for Radon Threshold of 4 pCi/L

<table>
<thead>
<tr>
<th>No. of lung cancer deaths prevented</th>
<th>Universal Screening</th>
<th>Targeted Screening</th>
<th>Modified Universal Screening</th>
<th>Modified Targeted Screening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Never smoked</td>
<td>16</td>
<td>11</td>
<td>90</td>
<td>58</td>
</tr>
<tr>
<td>Former smoker</td>
<td>46</td>
<td>33</td>
<td>255</td>
<td>165</td>
</tr>
<tr>
<td>Light smoker</td>
<td>58</td>
<td>41</td>
<td>322</td>
<td>209</td>
</tr>
<tr>
<td>Heavy smoker</td>
<td>25</td>
<td>18</td>
<td>142</td>
<td>92</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost per lung cancer death prevented, $</th>
<th>Universal Screening</th>
<th>Targeted Screening</th>
<th>Modified Universal Screening</th>
<th>Modified Targeted Screening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Never smoked</td>
<td>15,750,000</td>
<td>10,310,000</td>
<td>5,240,000</td>
<td>3,440,000</td>
</tr>
<tr>
<td>Former smoker</td>
<td>2,470,000</td>
<td>1,530,000</td>
<td>650,000</td>
<td>340,000</td>
</tr>
<tr>
<td>Light smoker</td>
<td>1,450,000</td>
<td>850,000</td>
<td>300,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Heavy smoker</td>
<td>870,000</td>
<td>470,000</td>
<td>100,000</td>
<td>30,000</td>
</tr>
</tbody>
</table>
TABLE 4—Sensitivity of Cost-Effectiveness Estimates and Number of Lung Cancer Deaths Prevented to Varying Probabilities Using 4 pCi/L Threshold

<table>
<thead>
<tr>
<th>Value</th>
<th>Universal Best Estimate</th>
<th>Modified Universal Best Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost-Effectiveness, $/per Lung Cancer Death Prevented</td>
<td>No. of Deaths</td>
</tr>
<tr>
<td>Base scenario</td>
<td>Best estimate</td>
<td>3 031 176</td>
</tr>
<tr>
<td>Purchasing STT</td>
<td>0.0305 → 0.27</td>
<td>2 785 072</td>
</tr>
<tr>
<td>Processing STT</td>
<td>0.558 → 1</td>
<td>2 231 014</td>
</tr>
<tr>
<td>Processing second STT</td>
<td>0.558 → 1</td>
<td>2 311 229</td>
</tr>
<tr>
<td>Processing LT</td>
<td>0.558 → 1</td>
<td>2 800 207</td>
</tr>
<tr>
<td>Processing STT, second STT, LT</td>
<td>0.558 → 1</td>
<td>1 758 335</td>
</tr>
<tr>
<td>Retesting</td>
<td>0.407 → 0.071</td>
<td>1 159 330</td>
</tr>
<tr>
<td>Mitigating</td>
<td>0.22 → 0.13</td>
<td>5 320 681</td>
</tr>
<tr>
<td>Postmitigation &gt;4 pCi/L</td>
<td>0.05 → 0.40</td>
<td>4 954 928</td>
</tr>
<tr>
<td>Cost of lung cancer, $</td>
<td>99 910 → 49 955</td>
<td>3 184 918</td>
</tr>
<tr>
<td>99 910 → 199 820</td>
<td>2 723 692</td>
<td>154</td>
</tr>
</tbody>
</table>

Note. STT = short-term test; LTT = long-term test.

estimate, it did result in a large increase in the number of lung cancer deaths that could be prevented. However, in no case was more than a fraction of the theoretical number of preventable deaths achieved.

The results from the sensitivity analyses were generally similar for the modified universal scenario. The biggest departure was that decreases in the probability of retesting resulted in decreases in the cost-effectiveness estimate and in the number of lung cancer deaths that could be prevented. The choice of a discount rate can strongly influence cost-effectiveness estimates; these estimates were $1.8 million for the universal scenario and $1.4 million for the targeted strategy at a 0% discount rate and $4.8 million for the universal scenario and $3.3 million for the targeted strategy at a 7% discount rate.

Incremental Cost-Effectiveness Analysis

Incremental costs increased as the radon threshold was lowered from 20 pCi/L to 2 pCi/L, and especially when the threshold was lowered from 4 pCi/L to 2 pCi/L (Table 5).

Depending on the radon threshold, either the targeted or modified targeted scenario had the lowest cost, and either the universal or modified universal scenario had the highest total cost. At 4 pCi/L, the incremental costs were $150 000 for moving from a targeted to a modified targeted scenario and $1.66 million for moving from a modified targeted to a modified universal scenario.

Discussion

The issue of radon testing and mitigation has been contentious owing to the potentially high costs that would be borne by homeowners and to the lingering controversy over the magnitude of the risks from residential radon exposure. Assuming that excessive exposure to radon elevates the risk of dying of lung cancer, how best to implement a radon testing and mitigation program becomes an important consideration.

The differences in cost-effectiveness among models raise the question of model superiority. The universal model using the best estimate of probabilities suggests that only about 4000 homes would be mitigated annually, whereas the modified universal model suggests that about 45 000 homes would be mitigated annually. The latter is more consistent with results from the first

TABLE 5—Incremental Cost Analysis for Preventing Radon-Associated Deaths From Lung Cancer

<table>
<thead>
<tr>
<th>Radon Level, pCi/L</th>
<th>No. of Lung Cancer Deaths Prevented</th>
<th>Total Cost, $</th>
<th>Incremental Cost, $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Universal screening</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>95</td>
<td>289 520 000</td>
<td>3 070 000</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>152 170 000</td>
<td>1 880 000</td>
</tr>
<tr>
<td>8</td>
<td>23</td>
<td>100 830 000</td>
<td>540 000</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>94 040 000</td>
<td>340 000</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>90 940 000</td>
<td>...</td>
</tr>
<tr>
<td>Modified universal screening</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>340</td>
<td>566 030 000</td>
<td>4 210 000</td>
</tr>
<tr>
<td>4</td>
<td>264</td>
<td>242 450 000</td>
<td>1 510 000</td>
</tr>
<tr>
<td>8</td>
<td>171</td>
<td>103 090 000</td>
<td>220 000</td>
</tr>
<tr>
<td>10</td>
<td>113</td>
<td>90 100 000</td>
<td>40 000</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>86 930 000</td>
<td>...</td>
</tr>
<tr>
<td>Targeted screening</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>49</td>
<td>123 200 000</td>
<td>3 490 000</td>
</tr>
<tr>
<td>4</td>
<td>34</td>
<td>68 640 000</td>
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<tr>
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Note. Lung cancer deaths were discounted and rounded. Costs were rounded to nearest $10 000.
Sensitivity analyses show the large improvements in cost-effectiveness that could be achieved if adherence to existing recommendations were increased. Cost-effectiveness can be improved by increasing the proportion of people who would retest their homes and mitigate if necessary. To prevent the maximum number of lung cancer deaths, compliance with all of the recommendations needs to be maximized. Similar conclusions were reached by Bierma.8

A number of methodological limitations must be borne in mind when evaluating these data. Because data for many of the variables were sparse, frequently dated, and of questionable generalizability, we often modeled data from national surveys. We also used probabilities for decision nodes that were based on probabilities for 4 pCi/L in estimating the cost-effectiveness estimates for other radon thresholds. Risk estimates were based on formulas developed from mining studies. Extrapolation of these data to the residential environment is uncertain.33,34 Because the total lung cancer and all-cause mortality rates were disaggregated on the basis of summary relative risk and prevalence estimates, some error may have been introduced into the resulting estimates. The average radon exposures for each terminal node were also estimates. For example, for people who failed to mitigate sufficiently, we assigned (using data from the National Residential Radon Survey) the average level of radon exposure that was above the action threshold for the entire population that tested above that threshold. If, in fact, mitigation had had some effect, but not enough to lower the reading below the action level, we would have underestimated the number of deaths that would have been prevented. Different techniques to model the relationship between short-term and longer term radon measurements are possible.35

Recent research has demonstrated that residential mobility has a significant impact on cumulative lifetime exposure to radon and on an individual’s risk for lung cancer.36 Our model does not include mobility. However, assumptions about the population’s risk remain unchanged. Modeling a dynamic population is likely to produce different cost-effectiveness estimates.

Our analysis, as well as those by others, did not factor in potential benefits, such as delayed onset of lung cancer, prevention of nonfatal lung cancer, and benefits to future generations from modifications of existing housing units, that would result in more favorable cost-effectiveness ratios. Furthermore, the present analysis did not attempt to examine the impact of construction guidelines for new homes. Our assumption that preventable lung cancer deaths would be equally spaced in time, starting at a certain age, is likely to have underestimated cost-effectiveness estimates. In addition, the cost estimated for the targeted program was based on an intensive program in Washington, DC, and may have overestimated the true costs of an effective targeted program. However, an overestimation of these costs would have tended to narrow the differences in cost-effectiveness estimates between universal and targeted programs, making the findings of our analysis even more robust.

In conclusion, more cost-effective residential radon mitigation programs can be developed by focusing on geographically defined areas where the risk of exposure to elevated levels of radon is high. Our analysis shows that it is more cost-effective to prevent radon-associated lung cancer deaths among people who smoke, from a public health perspective, however, helping smokers to quit smoking is obviously more desirable. Smoking cessation programs are more cost-effective.37-39 Substantial improvements in compliance are needed to maximize the number of lung cancer deaths that can be prevented. Experience has shown that actual compliance with recommendations falls far short of expectations,21,22,40 and increasing compliance may prove a difficult task. Therefore, examination of regulatory and behavioral options is needed. In addition, our analysis underscores the need for more current data on most of the decision nodes that we modeled in our decision tree. Finally, new cost-effectiveness estimates may need to be developed when additional data from residential case-control studies of radon exposure and lung cancer become available.

Contributors
E. S. Ford took the lead in performing the analyses and writing the paper. A. E. Kelly assisted with the analyses and the writing of the paper. S. M. Teutsch supervised data analysis and contributed to the writing of the paper. S. B. Thacker was instrumental in the conception of the paper and contributed to the writing of the paper. P. L. Garbe contributed to the writing of the paper. All authors are guarantors for the integrity of the research.

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11. Indoor Radon


