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The Economics of Screening Programs

By
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The Economics of Screening Programs

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The purpose of screening programs is to discover at an early point in time serious diseases, such as cervical cancer and colorectal cancer, that can be treated at lower social costs than would be the case if detected at later stages of disease development. In general, three questions are at the forefront of screening programs: Given a specific screening activity, first, what is the optimal age to start screening individuals, and, second, how often should the individuals be screened? Third, given budget constraints, how should resources be allocated and expended across different types of screening programs? In this article, my aim is to derive a mathematical model that can be used to answer these three questions. Of course, to implement the model, one needs empirical information, and so I attempt to characterize here as well the types of data needed to answer the questions. Overall, my presentation builds on the prior analyses and findings of Gyrd-Hansen, Søgaard, and Kronborg (1996) and Gyrd-Hansen (1997).

Costs and Effects of a Specific Screening Program

Let

T = time horizon in years for a screening program
t = 0,1,2,3, . . . T
s = screening intervals in years
T/s = total number of screenings during the program period
a_{0i} = age of individual i at the start of the program
a_{00} = lowest age in the screened population
N_{00} = total initial number of individuals who take part in the screening
x_i = vector of individual variables that can affect the probability of developing, say, breast cancer (e.g., diet, number of children, family history, genes)

Moreover, let

$$h(x_i,a_{i0} + t, t) = f(x_i,a_{io} + t, t)\, dt/[1 - F(x_i,a_{i0} + t)]$$

be the conditional probability of developing cancer between t and $t + dt$, conditional on no cancer before t. Later, I discuss the specification of the hazard rate $h(.)$ and how the effects of the variables in the x-vector can affect the hazard rate. From the conditional probability given above we get

$$1 - \mathbf{F}(\mathbf{x_i}, \mathbf{a_{i0}} + \mathbf{t}, \mathbf{t}) = \exp[-\int_0^{\mathbf{t}} \mathbf{h}(\mathbf{x_i}, \mathbf{a_{i0}} + \mathrm{t}, \mathrm{t})\, \mathbf{d}\mathrm{t}$$

Thus, when the hazard rate is specified, the probability, $F(.)$ follows. Specifically, $F(x_i, a_{i0} + t,t)$ is the probability that individual i develops cancer at age $a_{io} + t$, and, consequently, $1 - F(.)$ is the probability of no cancer.

Costs

Let C be the present value of the costs associated with a specific screening program. These costs consist of two parts: screening costs and net-treatment costs.

In what follows, I assume that the probability of detecting cancer through screening is equal to the probability $F(.)$ that individual i has cancer. Later, I consider the matter of false-positive and false-negative screening results. Let r denote the real rate of interest, let c_1 denote the screening costs per screened individual, and let c_2 denote the unit treatment costs; c_1 may include costs of screening tests, diagnostic tests, mailing, test analysis, and administration. For expository reasons I assume that these unit costs are constant over time. Thus, we have

$$\mathbf{C} = \sum_{\mathbf{i}=1}^{\mathbf{N}_{00}} \sum_{\mathbf{k}=1}^{\mathbf{T/s}} (1+\mathbf{r})^{-\mathbf{ks}} \{\mathbf{c}_1 [1 - \mathbf{F}(\mathbf{x_i}, \mathbf{a_{0i}} + \mathbf{ks}, \mathbf{ks})] + \mathbf{c}_2 \mathbf{F}(\mathbf{x_i}, \mathbf{a_{0i}} + \mathbf{ks}, \mathbf{ks})\}$$

Let a_{00} denote the lowest age in the screened population. From the last equation above we can thus write C as

$$C = C(s, a_{00})$$
$$- \quad -$$

where - under $C(.)$ indicates the sign of derivative of the corresponding variable. The justification for the negative derivatives is as follows: (1) The lower the s value, the higher the number of screenings during the program period and hence the higher the screening costs; this contributes to a negative derivative. (2) The lower the s value (i.e., the more frequent the screenings), the higher the probability of detecting cancer and the higher the treatment costs; this contributes also to a negative derivative. (3) The lower the s value, the greater the number of people detected with cancer and the fewer the number of people who have to be screened in the future; this contributes to a positive derivative. Most likely (1) and (2) dominate, but, of course, it is an empirical question whether this is true. (4) The lower the a_{00} value, the greater the number of people who have to be screened at each point in time and the higher the screening costs; this contributes to a negative derivative. (5) The lower the a_{00} value, the lower the mean detection rate and hence the lower the costs; this contributes to a positive derivative. Most likely (4) dominates, but again this is an empirical question. False-positive screening results may add to costs and these costs should be included in either c_1 or c_2.

Effects

Let $S[z_i, a_{i0} + t, d_i(ks)])$ be the (state) probability that individual i is alive at time t, where z_i is a vector of variables that may affect health and hence survival. This vector may include the previous vector x_i. Now let us turn to the dummy variable $d_i(ks)$:

$d_i(ks) = 0$ if cancer was not detected at screening number k, $k = 1, 2, 3, \ldots$ (i.e., at time ks), the probability of this event is $1 - F(x_i, a_{i0} + ks, ks)$

$d_i(ks) = 1$ if cancer was detected at time ks, the probability of this event is $F(x_i, a_{i0} + ks, ks)$

Let

$$S^{*}_{t/s}(z_i,a_{i0}+t,t)=\sum_{k=1}^{t/s} E[S(z_i,a_{i0}+ks),\, d_i(ks)]_F =$$

$$\sum_{k=1} \{S(z_i,a_{i0}+ks,0)[1-F(x_i,a_{i0}+ks,ks)] + S(z_i,a_{i0}+ks,1)[F(x_i,a_{i0}+ks,ks)]\},$$

Thus $S^{*}(.)$ is the sum of the expected survival rates up until time t; expectation is taken over the probability distribution of the outcomes of screenings. One would expect the survival probability to be higher if cancer is not detected. However, false-negative results may increase the risk of dying at an early age. With regard to the success of treatment and hence survival, it may also matter how long the individual has had cancer. This may be captured by including an unobserved variable in the $F(.)$ probability distribution, which then reflects how long the individual has had cancer. This question is discussed below. Of course, the survival probability decreases with age.

The unit of effect is assumed to be expected life years gained. The total sum of discounted life years gained in the population is denoted L.

$$\mathbf{L}=\sum_{\mathbf{i}=1}^{\mathbf{N}_{00}}\sum_{\mathbf{t}=0}^{\mathbf{T}}(1+\mathbf{r})^{-\mathbf{t}}\,(\mathbf{T}-\mathbf{t})\,\mathbf{S}^{*}(\mathbf{z}_{\mathbf{i}},\mathbf{a}_{\mathbf{i}0}+\mathbf{t},\mathbf{t})$$

From this expression we get $L = L(s,a_{00})$, with both first derivatives being negative. The justification for this conclusion is as follows: (1) The lower the value s, that is, the more frequent the screenings, the higher the mean detection rate and the longer the individuals live; hence the derivative of L wrt s is negative. (2) The lower the value a_{00}, the higher the total potential of life years gained; this contributes to a negative derivative of L wrt to $a_{00.}$ (3) The lower the value a_{00}, the lower the mean detection rate; this contributes to a positive derivative. Most likely (2) dominates.

A Cost-Effective Screening Program

We have thus obtained the pair $C = C(s,a_{00})$ and $L = L(s,a_{00})$, and we can derive the efficient combinations of s and a_{00} by performing the following calculations:

Min $C(s,a_{00})$
wrt s,a_{00}
given $L(s,a_{00}) \leq L_{0,}$

where L_0 is a given number.

Let the associated Lagrangian be $R = C(s,a_{00}) - l\,[L(s,a_{00}) - L_0]$, where λ is the Lagrange multiplier. The first-order conditions are

$C'_s = l\, L'_s$
$C'_a = l\, L_a'$.

By eliminating l, we get $C'_s/C'_a = L'_s/L'_a$. This equation, together with $L_0 = L(s,a_{00})$, determines s and a_{00} as a function of L_0. Inserting this in the cost function, we get $C_0 = c(L_0)$. By varying L_0 we obtain min cost as a function of life years gained.

As shown in Figure 1, where the numbers in parentheses indicate s in years and a_{00} in years, the $c(L)$ function is upward sloping and convex. All points above this upward sloping curve are generated by inferior (nonefficient) combinations of s and a_{00}.

Cost-Effective Selection of Screening Programs

Let us assume that a government is considering a number of screening programs, say, for the following five diseases: colorectal cancer, cancer cervicis uteri, cancer mammae, cancer prostatae, and cardio vasculare. Let us further assume that there is a fixed budget (discounted amount) B available for these programs. The goverment's problem is to determine how best to allocate resources among these programs, given the budget constraint B. The economist's answer is that resources should be allocated in a cost-effective way. To arrive at the solution that characterizes this efficient allocation of resources, one needs to maximize the sum of life years gained across the programs with respect to life years gained in each program, given that the costs across programs should sum to B.

Let L_k and C_k denote the life years gained and costs in screening program k (the possible double counting of life years gained has to be adressed carefully).

$$\text{Max} \sum_{k=1}^{5} L_k$$
$$\text{wrt } L_k,\ k = 1, 2, 3, 4, 5$$
$$\text{given} \sum_{k=1}^{5} C_k = B$$

The corresponding Lagrangian is

$$Q = \sum_{k=1}^{5} L_k - m\,[\sum_{k=1}^{5} c_k(L_k) - B],$$

where m is the Langrange multiplier in this case. This maximization yields the following first-order condition: $1 = mc'_k(L_k)$, for all k, which implies that $c'_1(L_1) = c_2'(L_2) = \ldots = c'_5(L_5)$. These four equations, together with

$$\sum_{k=1}^{5} c_k(L_k) = B,$$

determine all L_k and hence C_k from $C_k = c_k(L_k)$. Thus, the optimal number of life-years gained in each program, and hence the scale of each program given by C_k, are found when resources are allocated across the five programs in such a way that the costs of the last life year gained is approximately the same across all programs.

Since I have been told by medical doctors that the easiest and least costly disease to screen is cancer cervicis (perhaps with the exception of cancer prostatae), and that more life years can be gained by screening for this disease relative to the others, it follows that the largest share of the funds

should be used in screening cancer cervicis. To get a detailed prescription that the authorities should follow, one needs to estimate the model and calculate the solution numerically.

Empirical Problems

The most important and difficult magnitudes to estimate are the detection and survival probabilites. Let me concentrate on $F(.)$ First, let the hazard $h(.)$ be given by

$$h(x_i, a_{i0} + t, t) = h_0(x_i, a_{i0} + t, t)u$$

where u is a random variable that captures unobserved variables affecting the chances of developing cancer and/or the possibility that the individuals have had cancer for a long period before screening. To proceed with estimation, one needs to specify the functional form of $h_0(.)$ and the probability distribution of u. A widely used specification of $h_0(.)$ is $b(t)\exp(x_i, a_{i0} + t)$, where $b(t)$ is a baseline hazard.

If u is Gamma-distributed with variance $s^2(x_{1i})$, where x_{1i} accounts for a possible effect on the variance of individual characteristics, say, genes, then

$$E[h(.)] = h_0(.)[1 + s^2(x_{1i})I(.)]^{-1}$$

where $I(.) = \int h_0(., t)dt$.

The unknown parameters can be estimated on a data set that includes individuals whodeveloped cancer in a considered observation period and others who did not. The $f(.)$ values contribute to the overall likelihood from those developing cancer and the $[1 - F(.)]$ values contribute to the likelihood of those without cancer at the end of the observation period. The unknown parameters can be estimated through a maximum likelihood procedure.

Conclusion

Since death is an irreversible state, and death may occur long before time horizon T for some of the screened individuals, and since uncertainty is involved, one can argue that a better model than that described above is a stochastic dynamic programming model. To develop such a model is beyond the scope of this article.

One can also argue that the unit of effect should be something more general than life years gained, say, the impact on the indirect utility of individual i, where the arguments in the indirect utility function could be life years gained, pain, labor income, and so on. Moreover, the decision concerning the amount B that is allocated by society at large for health care (here screening) deserves to be analyzed based on applied welfare analysis. Again, these issues are beyond the scope of this article.

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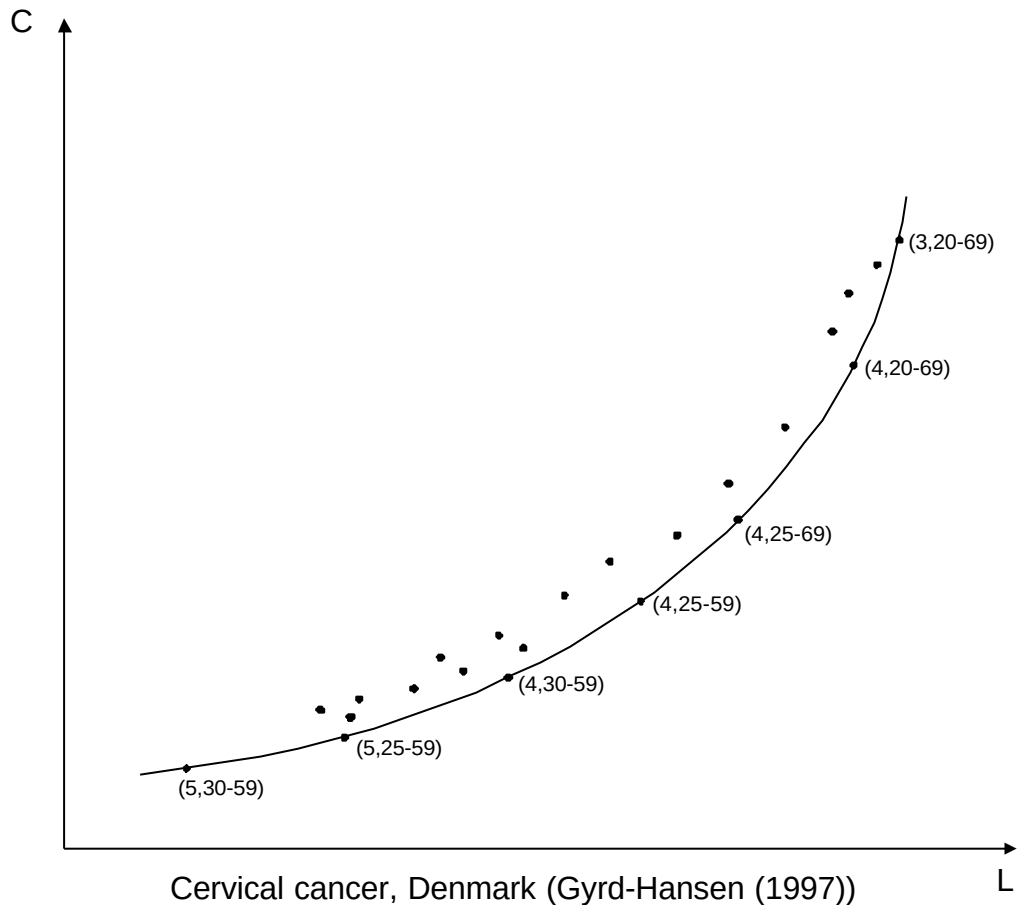
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Cervical cancer, Denmark (Gyrd-Hansen (1997))
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Figure 1