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A NEW INDEX APPROACH TO MEASURE LOST BENEFITS FROM PROGRESSION TO BLINDNESS

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Abstract

Objectives: An index approach for measuring the reduction in daily activities of patients suffering from an eye disease associated with progressive visual loss is proposed. The approach is illustrated using data collected from patients with cataract.
Method: The approach uses recently developed methods based on index theory together with measurements of daily activities. In a simulation based on observations of visual acuity and daily activities in patients with cataract, indexes of changes in benefits were estimated for varying levels of visual acuity.
Results: Results show the development of loss in benefits resulting from a progressive deterioration in visual acuity. The results indicate a 40% loss in benefits at low levels of visual acuity, equivalent to a potential increase in benefits of 75% for these individuals following successful treatment.
Conclusions: The proposed index approach may prove useful for measuring reductions in daily activities resulting from the progressive loss of vision in eye disease. The approach has successfully measured the reduction in daily activities in patients with cataract and may be applicable in patients with other eye diseases, including age-related macular degeneration and open-angle glaucoma.

Keywords: Blindness, Cataract, Linear programming, Outcome measures

A number of common eye diseases, including cataract, age-related macular degeneration (AMD), and open-angle glaucoma, are characterized by a slow and progressive loss of vision. The overall prevalence of cataract increases with age (6), and the prevalence of advanced cataract is higher in females than in males (7). Klein et al. (7) found that cataract and a best-corrected visual acuity less than 0.625 occurred in 25.4% of females and 12.6% of males aged 75 years or older. The natural progression of cataract is slow, however, and Gloor and Farrel (5) found that the annual deterioration in visual acuity is about 1.5 lines on the Snellen chart. AMD is a leading cause of blindness in Australia, with prevalence rising from zero in individuals under 55 years of age to 18.5% in those over 85 years (15). In the Baltimore Eye Survey, the prevalence of AMD was 2.1% in Caucasians older than

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70 years (4). In the Beaver Dam Study, late AMD was diagnosed in 7.8% of individuals 75 years and older (8), and the 5-year incidence of late AMD was 5.4% in the same age group (9). In open-angle glaucoma, there is a gradual loss of vision that rarely leads to blindness. In a Swedish population-based survey, open-angle glaucoma was diagnosed in 5.7% of individuals between 65 and 74 years of age (1), while in the Blue Mountains Eye Study, the prevalence of open-angle glaucoma was 3% in individuals 50 years and older (14).

Research, therefore, demonstrates that cataract, AMD, and open-angle glaucoma are common eye disorders that increase in frequency with age and are characterized by a slow progressive loss of vision. In the case of cataract and AMD, progressive vision loss often leads to blindness as an end stage. In contrast, glaucoma seldom progresses to blindness. Although cataract is the leading cause of blindness globally, in regions where cataract surgery is widely available, AMD may be the leading cause.

The slow progression of these diseases has an increasing influence on visual function in daily life. As a result, activities such as reading, watching TV, shopping, and participating in hobbies are performed with increasing difficulty. Over time, some patients are forced to give up certain activities because of their poor vision. Each stage during this gradual deterioration can be characterized by a specific loss of visual function that can be compared with normal function before the onset of the disease.

A number of methods have been developed to measure self-assessed visual function in patients with cataract (10;13;21). For example, the Swedish National Cataract Register (NCR) uses the Catquest Questionnaire to measure the impact of cataract surgery on patients' self-assessed visual function (7;11), and the NCR database contains information for a large number of patients with various degrees of visual loss due to cataract. These data can be used to calculate an average of self-assessed visual function for each degree of visual loss due to cataract and to support an analysis of the interaction between visual acuity loss and the loss of visual function in daily life. Although similar analyses should be possible for AMD and glaucoma, large databases containing visual function data for patients with these disorders are less available. Therefore, cataract is used in the present study to model the interaction between the loss of visual acuity and visual function in daily life.

PURPOSE

From an economic point of view, there are two main questions related to measuring the well-being of an individual with progressive loss of vision and blindness:

1. What is the loss in benefits for an individual resulting from a reduction in eyesight?
2. What are the potential gains from an improvement of vision or from delaying the progression to blindness?

The purpose of this study was to develop an index approach to addressing these questions. An illustration of the proposed approach was developed using data collected from individuals with cataract disease.

METHODS

The term *benefits* refers to the activities performed by an individual in normal daily life. These included reading a book or newspaper, shopping, and watching TV. It is important to note that the set of activities performed by an individual during a specified period of time (day/week/month/year) is only *one* of many possible combinations of activities that could be achieved by the individual. Therefore, only a subset of all attainable activities is observed during any one period.

A reduction in eyesight as a result of eye disease may restrict an individual's attainable benefits, thereby shrinking the whole set of attainable activities. There may be a disproportionate effect on activities, with greater effects on some activities than on others, leading to an overall reduction in the individual's activity level. Furthermore, while the effect on one activity could be characterized by a reduction in the frequency of the activity, the effect on another may be characterized by an increasing difficulty in performing the activity. The extent of difficulty in performing an activity may be seen as an indication of the quality of an activity.

It was assumed that there is a correlation between health and benefits for an individual. Because health encompasses both the physical and mental states of the body, two or more dimensions may be required for a complete description. For example, the clinical measure of visual acuity is only one aspect of the description of the overall state of health of an individual. Clinical measures showing the presence of other diseases or disorders are examples of other aspects of health that can be included in the overall description of an individual's state of health. In this study, the description of health was limited to vision-related aspects of health. Similarly, benefits that also generally require a number of dimensions to be described are limited here to vision-related benefits.

The set of activities that can be attained at different levels of health may be impossible to identify directly from observations. Therefore, a model is needed to describe the relationship between health and activities. Vision-related benefits (y) are a function of visual acuity (x) and other aspects of vision-related health (g). Because there are many dimensions to health, benefits, and other aspects of life, the traditional approach $y = f(x, g)$ cannot be used because this function is limited to a scalar or single component of benefits (y).

An alternative, the distance function, D (x, g, y), is able to handle many dimensions in x, g, and y. The distance function was developed in applied mathematics almost 80 years ago and was introduced into economics in the 1950s (12;20). During the last 10 years, the distance-function approach has been increasingly used in economics to measure productivity, efficiency, quantity changes, price changes, quality changes, and more recently, changes in health and quality of life (2;3;17;18).

Advantages of using the distance-function approach to model the relationship between health and benefits include:

- Flexible description of the relationship between health and benefits;
- No requirement for variables to be measured in the same unit;
- Integrated clinical measures of health and daily activities; and
- Effects on benefits can vary between individuals.

The distance-function approach is illustrated in Figure 1, which is based on an individual with a reduction in visual acuity and two activities in daily life (e.g., watching TV and shopping). While this simple case serves to illustrate the general approach proposed in this paper, it should be noted that there is no restriction on the number of activities or dimensions of health that can be included in a distance function.

In Figure 1 at time t, health is optimal and the set of activities that can be attained is bounded by the curve A, B, C, D. Thus, the individual is free to select from all points on or below the curve, i.e., all combinations and levels of the two daily activities. It is not possible to select from points above the curve. For the purpose of this illustration, it is assumed that information is available for all possible combinations and levels of activities and not only from observations based on those activities selected by the individual. This allows identification of the whole set of activities that can be achieved for a given level of health. The boundary (ABCD), and all combinations of activities below the boundary, creates the *capability set* (16;19). In this study, the capability set reflects the activities that

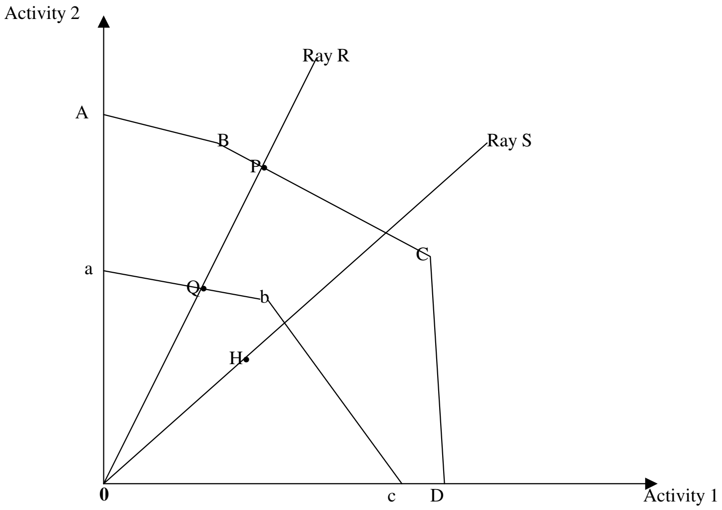

Figure 1. Illustration of the distance function and construction of index of changes in capability sets.

can be achieved at a given level of health. The form and "size" of the capability set will differ for different levels of health.

At time $t + 1$, the individual has experienced a reduction in visual acuity and the capability set has shrunk. The set of attainable activities at time $t + 1$ is bounded by the curve abc. Although the frequency, or quality, of both activities has been reduced, the effect on a single activity may depend on the initial mix of activities.

The distance function has a value less than 0 at all points along any ray from the origin, for example, along rays R or S in Figure 1. Furthermore, its value is 1 at all points on the boundary (e.g., ABCD) for a specified level of health and has a value less than 1 at all points below that boundary. Thus, the distance function identifies boundaries and can be used to estimate values at any point above or below a specific boundary. Although points above a specific boundary cannot be observed, it may be necessary to construct such points in order to estimate changes in capability sets. For example, if observed point P is compared with the boundary abc, point P is above the boundary and therefore does not belong to the capability set bounded by abc. For constructed points above a boundary, the distance function takes a value greater than 1. The distance-function approach allows an estimate to be made of the index score for a change in activity levels by comparing the points from one capability set with the points and boundary of another capability set.

The relative loss of benefits for an individual between time t and $t + 1$ is defined as the loss of activities due to a reduction in the capability set. If the boundary at time $t + 1$ is used as the reference, the distance function takes a value of 1 at any point on the boundary abc. At a point above the boundary, e.g., at point P, the distance function has a value greater than 1. Following the ray R in Figure 1, the distance from the origin to the intersection with boundary abc (point Q) is shorter than the distance from the origin to point P. The distance to point Q is normalized and defined as 1. The ratio of the distance from the origin to Q and the distance from the origin to P (with the distance to point P as the denominator) is less than 1, as defined below:

$$0\mathrm{Q}/0\mathrm{P} < 1. \tag{1}$$

An index score less than 1 is a measure of the relative loss of benefits along ray R. In a similar way, an index score can be calculated along ray S. The two rays show that the observed mix of activities may change as a result of deterioration in health. In Figure 1, point H illustrates that the average mix of activities has changed due to a reduction in health. Point H also illustrates that the average performance of the individual is below the boundary abc. Using the distance-function approach to estimate the indexes of lost benefits allows for changes in the mix of activities and does not assume that an individual always chooses the highest activity level. In Figure 1, the index of lost benefits resulting from a movement from P to H is estimated from the ratio of two distances:

$$0H/0P < 1. \tag{2}$$

Changes in the capability set and in the activity level resulting from a deterioration in health can be estimated based on simulated changes in the average performance of individuals using data collected for activities at varying health levels. The average performance of an individual in good health is used as the starting point. The next step is to use the average performance of individuals with reduced health to estimate an index score for lost benefits. Further estimate of indexes of lost benefits are based on successive reductions in health. Index scores are linked starting with the highest state of health and ending with the lowest observed state of health. The results show the loss in benefits as a result of successive reductions in health.

Figure 2 illustrates a simulation in the simple case of one activity and one health variable. Starting at A, the arrows are followed from A to B, where B represents the average activity level at a reduced state of health. An index score is estimated for this movement. From B, the arrows are followed to C, and an estimate is made of the index score for this movement. A further index score is estimated for the difference between C and D.

The process outlined provides the principles for constructing indexes of changes in benefits and health. The next step was to select an appropriate method to estimate index scores using individual data. Linear programming was used to estimate values for a distance function, which were then used to calculate index scores (2;3;17;18). In this approach, all observations for benefits and health are used to model the activity boundaries corresponding to a given level of health. If b_d is a vector of $d = 1, \ldots,$ D variables on frequency and quality of activities, x_h is a vector of $h = 1, \ldots,$ H variables on visual acuity, x_g is a vector of $g = 1, \ldots,$ G variables on other aspects on health, and if data are available from

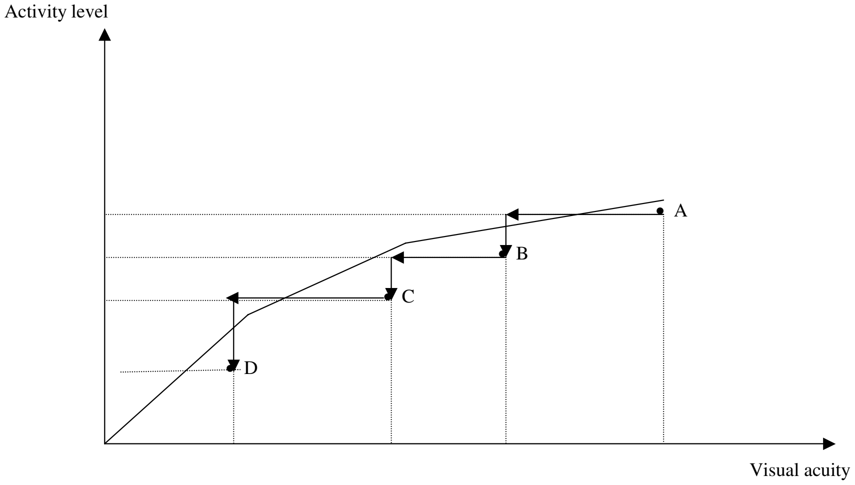

Figure 2. Illustration of simulation of successive reduction in visual acuity.

$i = 1, \ldots,$ I observations on these variables, the capability set for a given level of health and other aspects $P(x_h, x_g)$ is modeled as:

$$\begin{aligned} P(x_h, x_g) = \Bigg\{ b : b_d &\le \sum_{i=1}^{I} z_i b_{d,i}, \quad d = 1, \ldots, D && \text{(Frequency and quality of activities)} \\ x_{\mathrm{h}} &\ge \sum_{i=1}^{I} z_i x_{h,i}, \quad h = 1, \ldots, H && \text{(Visual acuity on best and worst eye)} \\ x_{\mathrm{g}} &\ge \sum_{i=1}^{I} z_i x_{g,i}, \quad g = 1, \ldots, G && \text{(Other aspects of health)} \\ \sum_{i=1}^{I} z_i &\le 1, z_i \ge 0, \quad i = 1, \ldots, I. \Bigg\} && \quad \textbf{(3)} \end{aligned}$$

The right side of the inequalities models the capability sets from observations of activities and health. The intensity variables z_i are used to construct points along the curve between observed points at the boundary, e.g., points along the line from B to C in Figure 1.

A value for the distance function for any data point (j) for activities and health is obtained as the solution to the following linear programming problem:

$$\begin{aligned} &1/D\left(x_h^j, x_g^j, b_d^j\right) = \max \lambda \\ &\text{subject to} \\ &\lambda b_d^j \le \sum_{i=1}^{I} z_i b_{i,d}, d = 1, \ldots, D, \\ &x_h^j \ge \sum_{i=1}^{I} z_i x_{i,h}, h = 1, \ldots, H, \\ &x_g^j \ge \sum_{i=1}^{I} z_i x_{i,g}, g = 1, \ldots, G, \\ &\sum_{i=1}^{I} z_i \le 1, z_i \ge 0, i = 1, \ldots, I. \qquad \textbf{(4)} \end{aligned}$$

A value to the distance function is estimated as the inverse to the solution to the linear programming problem in equation 4, $1/\lambda$, the distance function takes a value greater than 1 if the activity level is above the boundary, corresponding to the chosen value of visual acuity and other aspects of health. Its value is 1 for points on the boundary and is less than 1 for points below the boundary. The linear programming problem in equation 4 is used to simulate benefit scores for successive reductions in health. In the simulation, average scores for activities and health were inserted on the left side of the inequalities.

ILLUSTRATION USING SWEDISH CATARACT DATA

The index approach described above was used to simulate the progression to blindness in patients with cataract using data collected from Swedish ophthalmology departments and registered in the Swedish NCR. Visual acuity data and observations from daily activities were collected before and after surgery from 3,079 patients who were included in the NCR. All patients included in the study had completed the Catquest Questionnaire before surgery and 6 months after surgery (10;11). The questionnaire included items concerning the performance rates for certain daily activities as well as the difficulties experienced in their performance. The simulation used five variables related to frequency and six variables related to the difficulty. The frequency of initiating the activities of shopping, walking, and participating in a hobby were ranked as: no activity = 0; once a week = 1; 2–4 times a week = 3; and daily = 7. The frequency of reading the newspaper was ranked as: no activity = 0; one newspaper a week = 1; one newspaper a day = 7; and several newspapers a day = 14. Time spent watching TV was ranked as: no activity = 0; once a week = 1; 1 hour daily = 7; and several hours daily = 14. Difficulties perceived in performing activities (reading newspapers, shopping, watching TV, walking on uneven ground, recognizing faces, and participating in hobbies) were ranked as: no difficulty was given a rank of 4; some difficulty, rank 3; much difficulty, rank 2; and extreme difficulty, rank 1 (i.e., a higher rank indicated a lesser problem and higher quality of the activity).

Visual acuity of the best eye and of the worst eye were measured at the patient's last visit before surgery and at the follow-up visit after cataract surgery. These measures were expressed using a LogMAR scale with values on a scale from 1.0 to 0, where 0 is best visual acuity with no reduction in vision and 1.0 is a LogMAR scale value of 1.0 or worse. Since the index approach required that vision be measured on a scale with higher numerical value for better eyesight, the LogMAR was converted to a scale that ranged from 0.1 to 1.1. In this scale, 1.1 represented no reduction in visual acuity and 0.1 represented the lowest level of visual acuity.

Because only one observation was available for each individual at each level of visual acuity, only one attainable activity level could be observed for each individual. It was assumed that data across individuals could be used to estimate the set of attainable activities for a specific individual. This assumption is not necessary for the suggested index approach but rather is a consequence of the fact that it may be very difficult or impossible to collect complete data over long time periods for all patients.

The data collected were limited to observations from persons with no other reported eye disease. It was not possible to include other aspects of vision-related health in the simulation. Individuals were treated as being homogeneous in other aspects of health, i.e., with respect to the vector of variables x_g, in equations 3 and 4 and in the model estimating index scores in equation 4, and x_g is replaced with one for all observations.

The frequencies at which the average individual performed activities for different combinations of visual acuity are summarized in Table 1. Except for watching TV, where only small changes were detected, frequencies of performing activities were generally reduced at low levels of visual acuity. Results demonstrate that quality, in terms of difficulty, decreased as visual acuity was reduced (Table 2).

In the simulation of progression to blindness, index scores of changes in activity were estimated using the linear programming model in equation 4. The starting point for the simulation was a score of 1.1 for visual acuity in both eyes (no reduction in visual acuity), and the average activity level at this level of acuity. First, a value to the distance function was estimated at the starting point. Table 3 shows that the average activity level at the starting point was below the boundary (0.93). Next, estimates were made of changes in activity level due to a reduction in visual acuity, e.g., the movement from A to B in Figure 2. A value was estimated for the constructed, not observed, point with a benefit level corresponding to a visual acuity of 1.1 for both eyes, where visual acuity was 1.1 in the best eye and 1.0 in the worst eye. This constructed point may or may not belong to the capability set corresponding to 1.1 in the best eye and 1.0 in the worst eye. The result (Table 3) showed a small change in activity level from this change in visual acuity, with the index score decreasing from 0.93 to 0.92. The simulation then estimated changes in activity level and index scores for average activity levels resulting from successive changes in visual acuity. Overall, small changes in activity level occurred when visual acuity was only reduced slightly. At the lowest level of visual acuity, the benefit index score was 0.58, indicating a loss in benefits of more than 40%, or conversely, a potential gain of nearly 75% if visual acuity could be increased to 1.1 in both eyes. The results also show that different combinations of visual acuity result in similar benefit indices.

Table 1. Visual Acuity and Average Scores of Frequency of Activity

Best eye (VA)	Worst eye (VA)	Read	TV	Shopping	Walk	Hobby
0.1	0.1	5.67	10.10	1.80	3.62	1.98
0.4	0.1	6.34	9.66	2.09	3.60	2.36
0.6	0.1	7.27	9.94	2.54	4.29	2.58
0.6	0.4	7.22	10.62	2.29	4.20	2.87
0.7	0.1	7.24	10.59	2.10	3.27	2.96
0.8	0.1	8.39	10.33	2.11	4.14	2.72
0.8	0.4	8.18	11.61	3.03	4.68	2.45
0.8	0.7	8.90	11.23	3.00	5.17	3.07
0.9	0.4	8.92	11.42	2.41	4.87	3.03
0.9	0.6	8.53	10.68	2.58	4.45	2.97
1.0	0.1	8.44	10.70	2.43	4.64	2.65
1.0	0.7	8.11	10.91	2.70	4.92	3.41
1.0	0.8	8.30	11.64	3.21	4.64	3.19
1.0	1.0	8.68	11.59	2.79	4.95	3.37
1.1	0.1	9.08	11.18	2.95	4.41	3.33
1.1	0.6	8.20	10.83	2.83	5.00	3.17
1.1	0.7	9.44	11.80	3.40	4.76	2.92
1.1	0.9	9.29	11.20	2.77	5.11	3.44
1.1	1.0	9.41	11.55	2.97	4.90	3.51
1.1	1.1	9.61	11.61	3.29	5.23	3.72

Abbreviations: VA = visual acuity on a scale of 0.1–1.1; Read = reading newspaper; Shopping = seeing prices when shopping; Walk = walking; Hobby = participating in a hobby; TV = watching TV.

Table 2. Visual Acuity and Average Scores of Quality in Performing Activity

Best eye (VA)	Worst eye (VA)	Read	Face	Shopping	Walk	Hobby	TV
0.1	0.1	1.78	2.02	1.87	2.04	1.64	1.98
0.4	0.1	2.02	2.38	2.26	2.19	2.06	2.34
0.6	0.1	2.27	2.73	2.19	2.35	2.04	2.46
0.6	0.4	2.36	2.58	2.33	2.42	2.33	2.58
0.7	0.1	2.22	2.69	2.22	2.25	1.94	2.47
0.8	0.1	2.58	2.76	2.44	2.38	2.19	2.49
0.8	0.4	2.84	2.98	2.68	2.61	2.45	2.61
0.8	0.7	2.55	2.68	2.32	2.37	2.05	2.53
0.9	0.4	2.87	2.92	2.59	2.64	2.42	2.85
0.9	0.6	2.71	2.92	2.71	2.51	2.51	2.83
1	0.1	2.88	2.97	2.56	2.67	2.36	2.95
1	0.7	3.08	3.16	2.89	3.04	2.72	3.12
1	0.8	3.42	3.21	3.07	3.05	3.02	3.35
1	1	3.65	3.59	3.44	3.30	3.35	3.63
1.1	0.1	2.86	2.95	2.58	2.57	2.4	2.98
1.1	0.6	2.7	2.93	2.72	2.59	2.39	2.98
1.1	0.7	2.84	2.7	2.26	2.36	2.26	2.56
1.1	0.9	3.35	3.46	3.31	3.07	3.12	3.44
1.1	1	3.66	3.59	3.42	3.29	3.33	3.64
1.1	1.1	3.7	3.67	3.48	3.43	3.43	3.69

Abbreviations: VA = visual acuity on a scale of 0.1–1.1; Read = reading newspaper; Face = recognize faces; Shopping = seeing prices when shopping; Walk = walking; Hobby = participating in a hobby; TV = watching TV.

CONCLUSIONS

The index approach described can provide valuable information regarding the loss of daily activities for individuals suffering from an eye disease. For example, results from this

Table 3. Estimated Index Score of Benefit

Best eye (VA)	Worst eye (VA)	Index score
0.1	0.1	0.58
0.4	0.1	0.64
0.6	0.1	0.69
0.8	0.1	0.70
0.6	0.4	0.72
0.7	0.1	0.72
0.9	0.6	0.73
1.0	0.1	0.73
1.0	0.7	0.76
0.8	0.7	0.77
0.9	0.4	0.78
1.1	0.1	0.78
1.1	0.6	0.78
0.8	0.4	0.79
1.0	0.8	0.83
1.1	0.7	0.84
1.1	0.9	0.86
1.0	1.0	0.88
1.1	1.0	0.92
1.1	1.1	0.93

Abbreviations: VA = visual acuity on a scale of 0.1–1.1; index score = index of benefits for each level of eyesight on a scale of 0.0–1.0, with the capability set for the highest level of visual acuity as a starting point.

simulation of successive reductions in eyesight in patients with cataract showed that loss of benefits during progression to blindness was not proportional to decreases in visual acuity. Such information concerning changes in daily activities is critical if the demand for, and potential gains from, treatment are to be understood. Treatment may be characterized by improvement in visual acuity and in daily activity or as gains accrued from preventing or delaying a further progression of the disease. Such information can have policy implications for allocating healthcare resources and managing eye disease.

An advantage of the suggested index approach is that it takes into account both clinical measures and the effect of eye disease on an individual's living conditions, while at the same time acknowledging that the effect of eye disease on daily life may vary between individuals. From a practical viewpoint, the approach using the linear programming technique has several strengths: a) it does not *a priori* require weights for the summation of variables into an overall index number; b) indexes can be estimated using variables measured in different units; and c) the method is based on distance functions, which are well recognized in economic theory and applied economics.

Results of the present analysis showed a loss of benefits for patients suffering from cataract. Potential therapeutic gains were also easily calculated using the model. It also may be possible to test whether treatment outcomes depend on factors such as general health, personal characteristics, and individual lifestyles, in addition to visual acuity, or to analyze the benefits of new medical technologies in different types of individuals, with special regard to their effects on health, other eye diseases, and lifestyles. In addition, the expected benefits of new treatments can be compared with those achieved using current technology.

Finally, the index may prove useful in studies of the progression of visual loss to blindness in a variety of patient populations, including those suffering from AMD or open-angle glaucoma. It should be borne in mind, however, that when individuals with different eye diseases are compared, the rate of development of each disease could restrict possible gains from treatment with available technology. Furthermore, it may be necessary in some conditions to broaden the description of eyesight to include additional measures of visual resolution.

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