Improving Child Survival Through Environmental and Nutritional Interventions
The Importance of Targeting Interventions Toward the Poor

Emmanuela Gakidou, PhD
Shefali Oza, SB
Cecilia Vidal Fuertes, MA
Amy Y. Li, AB
Diana K. Lee, BS
Angelica Sousa, MS
Margaret C. Hogan, AB
Stephen Vander Hoorn, MSc
Majid Ezzati, PhD

The United Nations Millennium Development Goals (MDGs) were established in 2000 in a declaration adopted unanimously by the member countries of the United Nations to focus resources and efforts toward the critical global poverty, health, and sustainability problems (http://millenniumindicators.un.org/unsd/mdg/Default.aspx). The MDGs set numerical targets to be achieved by 2015 and use socioeconomic, environmental, nutritional, and health indicators to monitor progress toward these targets. There are concerns that the progress toward some of the health-related MDGs has been slow in many countries, making it very difficult to achieve them by the target date.1–3 A crucial question for efficient allocation of resources is whether some interventions may help achieve targets related to multiple MDGs, or whether additional and/or separate interventions are needed.

A second characteristic of the current MDG-related policies, programs, and monitoring is that they do not explicitly take into account within-context

The Millennium Development Goals (MDGs) were established in 2000 in a declaration adopted unanimously by the member countries of the United Nations to focus resources and efforts toward the critical global poverty, health, and sustainability problems. A critical but underinvestigated question for planning and allocating resources toward the MDGs is how interventions related to one MDG might affect progress toward other goals.

Objectives To estimate the reduction in child mortality as a result of interventions related to the environmental and nutritional MDGs (improving child nutrition and providing clean water, sanitation, and fuels) and to estimate how the magnitude and distribution of the effects of interventions vary based on the economic status of intervention recipients.

Design, Setting, and Population Population-level comparative risk assessment modeling the mortality effects of interventions on child nutrition and environmental risk factors, stratified by economic status. Data on economic status, child underweight, water and sanitation, and household fuels were from the nationally representative Demographic and Health Surveys for 42 countries in Latin America and the Caribbean, South Asia, and sub-Saharan Africa. Data on disease-specific child mortality were from the World Health Organization. Data on the hazardous effects of each MDG-related risk factor were from systematic reviews and meta-analyses of epidemiological studies.

Main Outcome Measure Child mortality, stratified by comparable international quintiles of economic status.

Results Implementing interventions that improve child nutrition and provide clean water and sanitation and clean household fuels to all children younger than 5 years would result in an estimated annual reduction in child deaths of 49,700 (14%) in Latin America and the Caribbean, 0.80 million (24%) in South Asia, and 1.47 million (31%) in sub-Saharan Africa. These benefits are equivalent to 30% to 48% of the current regional gaps toward the MDG target on reducing child mortality. Fifty percent coverage of the same environmental and nutritional interventions, as envisioned by the MDGs, would reduce child mortality by 26,900, 0.51 million, and 1.02 million in the 3 regions, respectively, if the interventions are implemented among the poor first. These reductions are 30% to 75% larger than those expected if the same 50% coverage first reached the wealthier households, who nonetheless are in need of similar interventions.

Conclusions Interventions related to nutritional and environmental MDGs can also provide substantial gains toward the MDG of reducing child mortality. To maximize the reduction in childhood mortality, such integrated management of interventions should prioritize the poor.

JAMA. 2007;298(16):1876-1887

Author Affiliations: Initiative for Global Health, Harvard University, Cambridge, Massachusetts (Drs Gakidou and Ezzati and Ms Oza, Vidal Fuertes, Li, Lee, and Sousa); Institute for Health Metrics and Evaluation, University of Washington, Seattle (Ms Hogan); School of Population Health, University of Queensland, Brisbane, Australia (Ms Hogan); Clinical Trials Research Unit, University of Auckland, Auckland, New Zealand (Mr Vander Hoorn); and Harvard School of Public Health, Boston, Massachusetts (Dr Ezzati). Dr Gakidou is now with the Institute for Health Metrics and Evaluation, University of Washington.

Corresponding Author: Majid Ezzati, PhD, Harvard School of Public Health, 665 Huntington Ave, Boston, MA 02115 (majid_ezzati@harvard.edu).
country disparities in intervention needs and coverage. However, there are at least 2 compelling reasons to examine how the factors that comprise the MDGs and the related interventions are distributed within countries: first, better nutritional, environmental, and health outcomes are important for improving the welfare of the poor and, therefore, can complement the broader, explicitly stated MDG of reducing poverty; and second, the absolute health benefits from specific nutritional and environmental interventions may depend on which segment of the population receives the interventions.

We evaluated how programs and policies related to 2 MDGs and their specific indicators—eradicating extreme poverty and hunger (goal 1) and ensuring environmental sustainability (goal 7)—affect a third MDG, reducing child mortality (goal 4). Specifically, we estimated (1) to what extent interventions related to children’s nutritional and environmental status are expected to reduce child mortality and (2) how the total benefits, as well as the distribution of benefits, from these interventions are expected to vary based on economic status of the intervention recipients. We evaluated these integrated interventions in 3 regions: Latin America and the Caribbean, South Asia, and sub-Saharan Africa. To examine the role of economic status of intervention recipients, we compared 2 hypothetical ways of implementing programs and policies: improving nutritional and environmental MDG indicators equally across all levels of economic status vs giving priority to either poorer or wealthier households.

**METHODS**

**Overview**

We conducted a population-level comparative risk assessment (CRA) using data that were defined and measured consistently and comparably across countries for the following indicators related to the aforementioned 3 MDGs: economic status, child mortality (mortality rate in children younger than 5 years), child nutrition as measured by anthropometry (prevalence of underweight children younger than 5 years, an indicator for the MDG of eradicating extreme poverty and hunger), water and sanitation (proportion of population with sustainable access to an improved water source and with access to improved sanitation, indicators for the MDG of ensuring environmental sustainability), and household fuel use (proportion of population using solid fuels, another indicator for the MDG of ensuring environmental sustainability) (Table 1). The CRA estimates the number of child deaths that would be prevented if exposures to the MDG-related risk factors were reduced through effective interventions. Inputs to the CRA are (1) risk factor exposure, based on Demographic and Health Surveys (DHS), (2) relative risks for each disease outcome caused by risk factor exposure, based on systematic reviews conducted in the World Health Organization (WHO) CRA project,6,7 and (3) total number of child deaths from each disease based on the WHO databases and the Child Health Epidemiology Reference Group.

To consider the role of the economic status of intervention recipients, all analyses were conducted stratified on a comparable measure of wealth (described below) and repeated for each of the intervention scenarios in Table 2.

To take into account country-specific epidemiological characteristics (eg, the diseases that contribute to child mortality), we conducted all calculations separately for each country, following the steps in Figure 1. All analyses were conducted using Stata statistical software, version 9.2 (Stata Corp, College Station, Texas).

**Data Sources**

Demographic and Health Surveys. The DHS program, which was established in the 1980s, is a nationally representative household survey program that primarily focuses on maternal and child health in developing countries. The survey instruments are extensively validated through pretesting and are standardized across countries. The DHS constitutes one of the largest consistent and comparable health survey programs in the world and is used in many analyses related to maternal and child health including those performed by WHO, the United Nations Children’s Fund, and the United Nations Population Division. (For detailed information on DHS design, instruments, and implementation and access to the data sets, see http://www.measuredhs.com and http://www.statcompiler.com.) In each country, the DHS questionnaire is
administered to a nationally representative sample of women aged 15 to 49 years and includes questions on basic sociodemographic characteristics; household asset ownership; water sources and sanitation facilities; fuel use; complete birth history and children’s survival; contraception use; antenatal, delivery, and postpartum care; breastfeeding and nutrition; and children’s health. Each DHS includes measured weight and height data for children born in the 3 or 5 years preceding the interview.

The DHS surveys use a multistage cluster design. The sample sizes for all but 2 surveys used in our analysis ranged from more than 5000 to more than 90 000; 2 surveys from smaller countries had sample sizes of more than 3000. The response rates for all but 3 of the DHS surveys used in our analysis were greater than 95%; 2 other surveys had response rates greater than 93% and 1 survey had a response rate of 88% (see aforementioned Web sites). We used the most recent DHS survey data (surveys conducted before 1990 were not used) from 42 countries in the 3 regions, Latin America and the Caribbean, South Asia, and sub-Saharan Africa, for estimating risk factor exposure and child mortality (these 42 surveys were among the 144 used for estimating economic status). We did not use surveys that included only preliminary data. The countries with surveys covered 58% of the regional population younger than 5 years in Latin America and the Caribbean, 96% in South Asia, and 83% in sub-Saharan Africa (listed in eTable 1, available online at http://www.jama.com).

CRA Project Reviews of Risk Factor Epidemiology. The CRA project was coordinated at WHO between 1999 and 2002. For each risk factor, an expert working group conducted a comprehensive review of the published literature as well as other sources (government reports, international databases, etc) to obtain data on effects size (relative risk [RR]). The work included a number of reanalyses of original data, systematic reviews, and meta-analyses of randomized intervention studies and observational epidemiological studies. There was particular emphasis on ensuring that the bias due to confounding in RRs was adequately dealt with by using RRs from randomized studies or studies with adjustment for multiple covariates. Each risk factor chapter was anonymously peer-reviewed by external reviewers (more than 160 peer reviews plus multiple rereviews as appropriate), by the CRA editorial group, and in the process of publication in scientific journals. Data sources and methods are described in detail in individual risk factor chapters and summarized elsewhere. All chapters are available online at http://www.who.int/publications/cra/en/. The CRA framework, data, and estimates formed the technical basis of the World Health Report 2002.

WHO and Child Health Epidemiology Reference Group Mortality Data. WHO reports child mortality by disease for each of its 193 member states. The 2004 disease-specific mortality rates were based on the work of the Child Health Epidemiology Reference Group (CHERG), established in 2001 to develop estimates of the proportion of deaths in children younger than 5 years (including separate estimates for causes of death in the first 28 days of life). For countries without a vital registration system, CHERG used a 2-step approach: in the first step, all available historical data were used to divide total deaths (from demographic methods) into 3 broad groups: communicable, noncommunicable, and injuries. This step also used information on the country’s economic development and regional characteristics. In the next step, CHERG used single-cause and multicause proportionate mortality models, together with all available population- or community-based epidemiological data, to divide deaths into specific diseases. Estimates for human

<table>
<thead>
<tr>
<th>Table 2. Intervention Scenarios Used in the Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scenario</strong></td>
</tr>
<tr>
<td><strong>Equal Implementation of Interventions</strong></td>
</tr>
<tr>
<td>“Equal-100” (full [100%] reduction)</td>
</tr>
<tr>
<td>“Equal-50” (50% reduction)</td>
</tr>
<tr>
<td><strong>Differential-Coverage Implementation of Interventions</strong></td>
</tr>
<tr>
<td>50% “Pro-poor” reduction</td>
</tr>
<tr>
<td>50% “Pro-wealthy” reduction</td>
</tr>
</tbody>
</table>

This scenario is more ambitious than the Millennium Development Goal (MDG) targets. We used this scenario because it demonstrates the theoretical maximum reduction in child mortality that can be achieved by addressing the other environmental and nutritional MDG-related risks and interventions.
immunodeficiency virus/AIDS, tuberculosis, and vaccine-preventable diseases also used data and epidemiological and natural history models from UNAIDS and WHO technical groups. This effort has led to better estimates of the causes of death in children than ever before—arguably substantially better estimates than for causes of death in adults. Further details of the methods are described elsewhere.12–15

Measuring Economic Status

There are several ways of measuring economic status in household surveys, including monetary measures (eg, self-reported income and expenditure) and nonmonetary indices derived from information on ownership of household assets (eg, television, radio, car, motorcycle). Asset-based approaches use the information content in the set of assets owned by a given household to estimate a “wealth index” for that household and are therefore based on a long-term conceptualization of wealth, one that is arguably more relevant as a determinant of health. Asset-based approaches are also more robust to common reporting biases that make monetary income and expenditure at the lower end of the spectrum especially problematic.16,17 Asset-based indices have been widely used in equity analyses in low- and middle-income countries, including analyses of the DHS, the World Health Surveys, and several country health surveys.3,8,18–20

The asset-based index used in this analysis (step 1 in Figure 1) was developed by Ferguson et al20 and has been applied in several other studies, especially ones that required cross-population comparability.18,19,21,23,24,26 The method of Ferguson et al20 is conceptually similar to other commonly used asset-based approaches and is ideal for comparative cross-country analysis because (1) it incorporates both asset ownership and household sociodemographic characteristics that are related to household wealth, such as the education, age, and sex of the household head and urban-rural residence and (2) the wealth indices from all DHS surveys are placed on the same international scale.

The effects of asset ownership and household characteristics on household wealth were simultaneously estimated using a random-effects probit model, with the hierarchical error term at the household level. The output of the model is a set of covariate coefficients and asset cut points. The covariate coefficients represent the underlying relationship between each sociodemographic predictor and the “latent wealth variable.” The asset cut points represent the point or threshold on the (latent) wealth scale above which a household is more likely to own a particular asset. This “asset ladder” was then applied to every household in each survey to produce adjusted estimates of household wealth.

To obtain measures of wealth that are comparable across countries, we first set a single international scale for wealth, then rescaled all country-specific results to this scale. The international scale refers to all developing countries for which DHS data were available at the time of analysis; this includes 44+ DHS surveys in 66 countries between 1985 and 2005. To set the international wealth scale, we calculated international asset cut points as the weighted means of the compiled country-specific ones (weights account for the sample sizes for surveys from each country and the population of each country). Rescaling to the common international scale used a simple linear transformation. For each country, the country-specific cut points were regressed against the international cut points. The coefficients were applied to the estimates of wealth for each household, resulting in estimates on the international scale while preserving within-country rank order.

To estimate international wealth quintiles, rescaled estimates of wealth from individual surveys were appended and quintile cutoffs were set using appropriate sample weights. These weights represent the probability of choosing the household from the international population (note that “international” refers to all country-years represented by the 44 surveys used in the analysis). To convert sample weights for each household from individual surveys into an “international” weight, we multiplied the former by the ratio of the country population to the total population of all countries with a survey. The results of this analysis provide estimates of average economic status at the country level that are highly correlated with gross domestic product per capita (correlation coefficient = 0.83) (data available on request), supporting that the index can be used for cross-country comparative analysis. Copies of statistical programs to replicate the analysis are available from the authors.

Because the quintiles of wealth index are international, in countries with very high poverty, most people fall in the poorest quintile(s) and few in the wealthiest. For example, 60% or more of the populations of the Central African Republic, Chad, Ethiopia, Madagascar, and Niger lived in the poorest quintile vs 5% or less

Figure 1. Analysis Steps

1. Construct comparable quintiles of wealth (data source: DHS)

2. Estimate all-cause child mortality by wealth quintile (data source: DHS)

3. Estimate disease-specific child mortality by wealth quintile (data source: WHO)

4. Extract risk factor exposure by wealth quintile (data source: WHO)

5. Estimate disease-specific PAF for individual risks by wealth quintile

6. Estimate disease-specific PAF for all 3 risks by wealth quintile

7. Estimate disease-specific preventable deaths by wealth quintile

8. Estimate all-cause preventable deaths by wealth quintile

To take into account country-specific epidemiological characteristics, these steps were conducted for each country in each region. Regional PAF estimates of preventable deaths for each quintile were aggregated from the estimates for individual countries and applied to regional disease-specific deaths. DHS indicates Demographic and Health Surveys; PAF, population-attributable fraction; WHO, World Health Organization. aThe 3 risk factors are child undernutrition (underweight), unsafe water and sanitation, and indoor air pollution from solid fuels (Table 1).
in the wealthiest quintile. In contrast, some countries in Latin America and the Caribbean had no or few households in the poorest quintile, with 10% and 7% of the regional population in the poorest 2 quintiles vs 34% and 37% in the wealthiest 2 quintiles (eTable 2, available online at http://www.jama.com).

**Child Mortality and Risk Factor Exposure by Economic Status**

We used total and disease-specific mortality among children younger than 5 years for each country from the WHO databases. We divided disease-specific deaths for each country into wealth quintiles using weights that were proportional to the total number of under-5 deaths in the quintile, \( n_i \), as given by equation 1 (step 3 in Figure 1):

\[
\text{w}_i = \frac{n_i}{\sum n_i}
\]

The number of under-5 deaths in each wealth quintile, \( n_i \), is a product of 2 factors: (1) the population younger than 5 years in the quintile and (2) the annual mortality rate in the quintile, \( r_i \). To calculate annual mortality rate by wealth quintile, we used the DHS data. We applied standard demographic techniques\(^{31} \) to information on complete birth histories from the DHS data, described in detail in the DHS supporting documentation,\(^{32} \) to estimate the probability of death between birth and the fifth birthday, \( s_{5q0} \), for the 5-year period prior to the survey (step 2 in Figure 1). The probability \( s_{5q0} \) was converted to annual mortality rates using the relationship shown in equation 2, a common demographic relationship.\(^{31} \) The denominator of equation 2 represents the total number of person-years lived between birth and age 5 years, which is the sum of the years lived by those who survived to age 5 years (first term) plus the years lived by those who died during the interval (second term). The number 5 in the first term of the denominator is included because those who survive to age 5 years contribute 5 person-years. The value of 0.8 is the estimated average number of years lived by those who died before age 5 years, because child mortality declines rapidly with age, with most deaths occurring during the first month and a large proportion during the first year of life.

\[
r = \frac{s_{5q0}}{\left[\left(1000 - s_{5q0}\right) \times 5 + \left(s_{5q0} \times 0.8\right)\right]}\]

The levels of risk factors for child mortality (Table 1) by wealth quintile for each country were calculated directly from the DHS data (step 4 in Figure 1; national data provided in eTable 2).

**Mortality Prevented Through Risk Factor Interventions**

To estimate the child mortality effects of interventions for nutritional and environmental MDGs at the population level, we used the disease-specific mortality and risk factor exposure by wealth quintile in each country, as calculated above, together with data on the hazardous effects of each risk (measured by RR). The RRs for each risk factor came from systematic reviews and meta-analyses of the epidemiological literature in the CRA project (Table 3).

The proportional reduction in mortality that would be achieved by decreasing exposure to a risk factor from its current level to some alternative postintervention scenario can be estimated using the population-attributable fraction (PAF) relationship in equation 3 (also known as the potential impact fraction relationship).\(^{6,34,35} \)

\[
\text{PAF} = \frac{\sum_{i=1}^{n} P_i R_i - \sum_{i=1}^{n} P_i' R_i}{\sum_{i=1}^{n} P_i R_i}
\]

where \( n \) is the number of exposure categories (\( n = 4 \) for undernutrition and unsafe water and sanitation and \( n = 3 \) for fuel use) (Table 3); \( P_i \) is the proportion of population currently in the \( i \)th exposure category; \( P_i' \) is the proportion of population in the

---

**Table 3. Relative Risks of Disease-Specific Child Mortality Associated With Nutritional and Environmental Health Risks**

<table>
<thead>
<tr>
<th>Disease</th>
<th>Undernutrition (SD of Weight for Age)</th>
<th>Unsafe Water and Sanitation</th>
<th>Indoor Air Pollution From Solid Fuels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Very High</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Diarrhea</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diarrhea</td>
<td>&lt;−3</td>
<td>−3 to 2</td>
<td>−2 to 1</td>
</tr>
<tr>
<td>Malaria</td>
<td>0.49</td>
<td>4.48</td>
<td>2.12</td>
</tr>
<tr>
<td>Measles</td>
<td>0.22</td>
<td>3.01</td>
<td>1.73</td>
</tr>
<tr>
<td>Lower respiratory tract infection</td>
<td>0.09</td>
<td>4.03</td>
<td>2.01</td>
</tr>
<tr>
<td>Selected other infectious diseases</td>
<td>0.72</td>
<td>4.24</td>
<td>2.06</td>
</tr>
</tbody>
</table>

\(^{a}\)The lowest exposure category for each risk factor is the reference category, with a relative risk of 1.0.

\(^{b}\)Based on a meta-analysis of 10 cohort studies of mortality to obtain hazard in 1-SD increments.\(^{36} \) In addition to these infectious diseases, some children die directly as a result of severe undernutrition. These deaths are coded directly as protein-energy malnutrition according to the International Classification of Diseases, 10th Revision.

\(^{c}\)Based on a systematic review of multicountry randomized intervention studies and observational studies.\(^{37} \) We excluded 1 additional exposure category (an ideal situation in which there was complete absence of pathogen transmission) that was included in the comparative risk assessment project\(^{16} \) because it does not correspond to any known or even hypothetical water and sanitation intervention that can be implemented in achieving the Millennium Development Goals. All relative risks were recalculated relative to the lowest fecal-oral pathogen transmission exposure category that corresponds to water and sanitation interventions.

\(^{d}\)Based on a systematic review and meta-analysis of epidemiological studies of solid fuel use\(^{17} \) and an exposure-response relationship study in Kenya that included multiple exposure categories and quantified the beneficial effects of charcoal relative to wood.\(^{18} \)
ith exposure category in alternative exposure scenarios, as defined in the intervention scenarios in Table 2; and

\[ RR_i \] is the RR of disease-specific mortality for the ith exposure category.

For each disease caused by exposure to these risk factors, we first computed PAFs for individual risks using equation 3 (step 5 in Figure 1). Disease-specific deaths may be caused by multiple risk factors acting simultaneously and, hence, can be prevented by intervening on each of the risks. For example, some deaths from childhood pneumonia may be prevented by removing exposure to indoor air pollution from solid fuels or by improving child nutrition.\(^9\) As a result of multicausality, the PAFs for interventions related to multiple risk factors overlap and cannot be combined by simple addition.\(^9\) Under specific assumptions, described below, the combined (joint) PAF that avoids double-counting the overlap of interventions on multiple risk factors is given by equation 4.\(^9,35,36\) In equation 4, the proportion of the disease that can be prevented by reducing exposure to the ith risk factor equals PAF\(_i\), and (1 – PAF\(_i\)) is the proportion that is not preventable by intervention on the ith factor. The second term in the right-hand side of equation 4 (ie, the product of all \([1 – PAF_i]\) terms) is the fraction of disease that is not preventable through interventions on any of the n risk factors. One minus this term is the fraction attributable to the combined effects of interventions on the n risk factors.

\[
PAF = 1 - \prod_{i=1}^{n} (1 – PAF_i)
\]

where PAF\(_i\) is the PAF of the ith individual risk factors.

For diseases affected by multiple risk factors (diarrhea and lower respiratory tract infections), we estimated the combined PAFs using equation 4 (step 6 in Figure 1). This provided the proportional reduction in deaths from each disease as a result of the combined effects of intervention on all 3 risks and properly accounted for multicausality. The proportional reduction was used in equation 5 to calculate the number of deaths from each disease that would be prevented by interventions on all 3 risk factors (step 7 in Figure 1).

\[
AM_j = PAF_j \times M_j
\]

where AM\(_j\) is deaths from disease j prevented as a result of interventions on all 3 risk factors:

PAF\(_j\) is the PAF for disease j from interventions on all 3 risk factors combined; and

M\(_j\) is total deaths from disease j.

The preventable deaths were then summed across diseases to obtain the total (all-cause) mortality that would be prevented through interventions on all 3 risks (step 8 in Figure 1). Preventable deaths from different diseases can be added because in cause-of-death statistics, following the International Classification of Diseases system, each death is categorically assigned to a single underlying cause (disease) and, unlike risk factors, there is no overlap between disease-specific deaths.

There are 2 key assumptions when using equation 4. First, exposures to these risks are uncorrelated. Environmental and nutritional risk factors for child mortality may be correlated because undernutrition, unsafe water and sanitation, and use of solid fuels are more common among the poor. Positive correlation among risk factors in relation to economic status is accounted for by conducting all analyses stratified on wealth quintiles. We examined whether there was within-quintile correlation of risk factors using data from 6 large DHS and found that there was little remaining correlation beyond what was accounted for by stratification on the wealth quintiles (data available on request). Because positive correlation between risks increases the estimated PAFs, remaining correlation between risks would strengthen the findings of our analysis.

The second assumption is that the hazardous effects of one risk are not mediated through other risks. Child growth (eg, weight for age) may be affected by diet (eg, protein-energy consumption) as well as previous infections.\(^37-39\) Therefore, some of the hazardous effects of indoor air pollution from solid fuels and unsafe water and sanitation (which result in lower respiratory tract infections and diarrhea, respectively) may be mediated through low weight for age. To account for potential mediated effects in a sensitivity analysis, we repeated all the analysis assuming that 50% of the excess risk (RR – 1) from indoor air pollution from solid fuels and unsafe water and sanitation are mediated through underweight, based on reviews of epidemiological studies reported elsewhere.\(^9\) The results of this sensitivity analysis for TABLE 4 are shown in eTable 3 (available online at http://www.jama.com).

RESULTS

Child Mortality and Risk Factor Exposure by Economic Status

An estimated 0.36 million, 3.38 million, and 4.79 million children younger than 5 years died in Latin America and the Caribbean, South Asia, and sub-Saharan Africa in 2004, respectively (Table 4), with corresponding annual mortality rates of 6.5, 19.9, and 39.1 per 1000 children. Child mortality declined with increasing wealth in all regions (Figure 2). In South Asia, child mortality declined across all quintiles, with the greatest decline between quintiles 2 and 4. In Latin America and the Caribbean and in sub-Saharan Africa, the differences in child mortality were smaller in the first 3 quintiles, but there was a sharp decline in the higher wealth levels. This may reflect more demarcated inequalities in socioeconomic status and in access to preventive and clinical services in these 2 regions compared with those in South Asia. Beyond the economic gradient within each region, Figure 2 illustrates that child mortality among the poor was substantially higher in sub-Saharan Africa (46.9 and 42.7 deaths per 1000 children in quintiles 1 and 2, respectively) than in Latin America and the Caribbean (9.6 and 10.2 deaths per 1000 children), with South Asia having levels between these 2 regions. Our analysis also re-
revealed significant variation in mortality across countries in each region. Countries with the highest mortality rate among the poor were Niger (75.6 per 1000 children), Mali (58.6), and Nigeria (58.1); those with the lowest mortality among the poor were the Dominican Republic (6.0 per 1000 children), Paraguay (8.3), and Peru (10.3) (data available on request).

Child mortality varied less for households in the wealthiest quintiles, ranging from 21.5 per 1000 children in sub-Saharan Africa to 4.4 per 1000 children in Latin America and the Caribbean in quintile 5. In other words, children in wealthier households had more similar (and better) survival across nations and regions compared with children in poor households, whose survival varied enormously. For example, in the poorest quintile, the child mortality rate varied between 6.0 per 1000 children (Dominican Republic) and 31.1 (Haiti) in Latin America and the Caribbean, between 20.4 (Nepal) and 27.2 (Pakistan) in South Asia, and between 15.5 (Namibia) and 75.6 (Niger) in sub-Saharan Africa. The larger variation among the poor may be due to differential exposure to nutritional and environmental causes of child mortality and/or differential access to health care for treatment of childhood diseases (eg, oral rehydration therapy for diarrhea and antibiotics for pneumonia and other infections).

Based on DHS risk factor data (eTable 2), an estimated 56%, 87%, and 83% of the 339 million children in the three regions were exposed to preventable risks associated with undernutrition, unsafe water and sanitation, and indoor air pollution from solid fuels, respectively, and, hence, in need of interventions. The poor in every region had higher exposure to all 3 risks, but there was heterogeneity in regional and socioeconomic patterns of risk factor exposure (Figure 3, Figure 4, and Figure 5). Unlike child mortality, which was highest in sub-Saharan Africa, underweight was highest in South Asia in every wealth quintile. The poor in Latin America and the Caribbean had slightly worse access to safe water and sanitation than those in South Asia and sub-Saharan Africa, possibly reflecting a decade or longer of targeted water and sanitation interventions in the latter 2 regions. In all regions, the poor relied on solid fuels, while wealthier households (quintiles 4 and 5) in sub-Saharan Africa used solid fuels substantially more than households of the same affluence in the other 2 regions. This reflects nearly universal reliance on biomass fuels in both rural and urban parts of Africa.

### Total Health Benefits of Interventions

The MDG-4 target is to reduce the mortality rate of children younger than 5 years by two-thirds between 1990 and 2015. Between 1990 and 2004, child mortality declined by 39%, 28%, and 9% in Latin America and the Caribbean, South Asia, and sub-Saharan Africa, respectively. To estimate the total health benefits of interventions, we used DHS risk factor data (eTable 2) to estimate the number of deaths attributable to each risk factor and the number of deaths that would be prevented by implementing specific interventions. The results are presented in Table 4 for Latin America and the Caribbean, South Asia, and sub-Saharan Africa.

<table>
<thead>
<tr>
<th>Wealth Quintile</th>
<th>No. of Children, Millions</th>
<th>No. of Child Deaths (×1000)</th>
<th>No. of Avoided Deaths (×1000) by Intervention Scenario</th>
<th>Wealth Quintile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>&quot;Equal-100&quot;</td>
<td>&quot;Equal-50&quot;</td>
</tr>
<tr>
<td>Latin America and the Caribbean</td>
<td>4.2</td>
<td>42.5</td>
<td>3.8</td>
<td>4.2</td>
</tr>
<tr>
<td>2</td>
<td>2.6</td>
<td>27.4</td>
<td>5.4</td>
<td>2.7</td>
</tr>
<tr>
<td>3</td>
<td>4.7</td>
<td>46.8</td>
<td>8.1</td>
<td>4.1</td>
</tr>
<tr>
<td>4</td>
<td>19.5</td>
<td>131.1</td>
<td>21.7</td>
<td>10.8</td>
</tr>
<tr>
<td>5 (Wealthiest)</td>
<td>25.5</td>
<td>117.0</td>
<td>9.0</td>
<td>4.5</td>
</tr>
<tr>
<td>All combined</td>
<td>56.5</td>
<td>364.8</td>
<td>49.7</td>
<td>24.9</td>
</tr>
<tr>
<td>South Asia</td>
<td>25.2</td>
<td>631.5</td>
<td>159.0</td>
<td>79.5</td>
</tr>
<tr>
<td>2</td>
<td>25.2</td>
<td>591.9</td>
<td>144.0</td>
<td>72.0</td>
</tr>
<tr>
<td>3</td>
<td>44.1</td>
<td>891.7</td>
<td>241.1</td>
<td>120.5</td>
</tr>
<tr>
<td>4</td>
<td>35.0</td>
<td>600.8</td>
<td>130.5</td>
<td>65.2</td>
</tr>
<tr>
<td>5 (Wealthiest)</td>
<td>39.9</td>
<td>669.7</td>
<td>126.5</td>
<td>63.2</td>
</tr>
<tr>
<td>All combined</td>
<td>169.3</td>
<td>3375.5</td>
<td>801.1</td>
<td>400.5</td>
</tr>
<tr>
<td>Sub-Saharan Africa</td>
<td>39.0</td>
<td>1841.0</td>
<td>649.2</td>
<td>324.6</td>
</tr>
<tr>
<td>2</td>
<td>18.2</td>
<td>785.4</td>
<td>237.4</td>
<td>118.7</td>
</tr>
<tr>
<td>3</td>
<td>22.9</td>
<td>992.6</td>
<td>300.8</td>
<td>150.4</td>
</tr>
<tr>
<td>4</td>
<td>22.8</td>
<td>757.2</td>
<td>198.2</td>
<td>99.1</td>
</tr>
<tr>
<td>5 (Wealthiest)</td>
<td>19.6</td>
<td>416.9</td>
<td>69.5</td>
<td>34.7</td>
</tr>
<tr>
<td>All combined</td>
<td>122.5</td>
<td>4793.2</td>
<td>1470.7</td>
<td>735.4</td>
</tr>
</tbody>
</table>

*Discrepancies between the sum of individual quintiles and the results for all quintiles combined are a result of rounding. See eTable 3 and eTable 4 for sensitivity analyses.

A portion of deaths in each group are neonatal deaths (deaths in the first 4 weeks of life), which are primarily affected by pregnancy-related/perinatal exposures and maternal health services.40 Only a small proportion of these deaths would be preventable by the nutritional and environmental risk factors in this analysis.

*Results by specific disease are available from the authors.

**See Table 2 for definitions of each intervention scenario.**
spective (see Figure 1 in Lopez et al for 1990 levels). To achieve the MDG target, the reduction required as a proportion of 2004 mortality rates would be approximately 45% in Latin America and the Caribbean, 53% in South Asia, and 63% in sub-Saharan Africa. If interventions for the 3 nutritional and environmental MDGs reached all children who need them (“equal-100” scenario), an estimated 49,700 annual child deaths in Latin America and the Caribbean (14%), 0.80 million in South Asia (24%), and 1.47 million in sub-Saharan Africa (31%) would be prevented (Table 4). These effects are equivalent to 30% to 48% of the regional gaps between mortality levels in 2004 and the MDG target (Table 4 and Figure 2). Excluding deaths during the neonatal period, which can be prevented primarily through better antenatal, maternal, and neonatal health services,40 the corresponding proportional reductions in mortality would be 22% in Latin America and the Caribbean, 39% in South Asia, and 39% in sub-Saharan Africa (data available on request). The benefits of these environmental and nutritional interventions are smallest in Latin America and the Caribbean, in both absolute and relative terms, because the majority of the population of this region is in the wealthier quintiles and has already achieved low levels of child mortality and improved environmental and nutritional status. The 14% reduction in child mortality in this region would nonetheless contribute substantially to achieving the MDG target. The benefits would be larger in poorer countries in the region such as Haiti (28%) and Nicaragua (24%) (data available on request).

If environmental and nutritional risks are reduced by 50%, as envisioned by the MDGs, and if the reductions are distributed proportionally to current exposures across all wealth quintiles (“equal-50” scenario), there would be an estimated 24,900 (7%), 0.40 million (12%), and 0.74 million (15%) fewer child deaths in Latin America and the Caribbean, South Asia, and sub-Saharan Africa, respectively. If the same interventions were delivered preferentially to the poor (“pro-poor” scenario), the estimated total number of preventable deaths would be 26,900 (7%) in Latin America and the Caribbean, 0.51 million (15%) in South Asia, and 1.02 million (21%) in sub-Saharan Africa. These reductions are 8% to 39% higher than those expected in the “equal-50” scenario. These “pro-poor” programs would reduce the remaining gap toward the child mortality MDG target by 16% to 34%. In contrast, the aggregate benefits would be 19,000 (5%), 0.39 million

![Figure 2. Annual Child Mortality Rate by Quintile of Wealth in Latin America and the Caribbean, South Asia, and Sub-Saharan Africa](image-url)
(12%), and 0.58 million (12%) averted deaths if the 50% interventions first reached the wealthier households (“pro-wealthy” scenario).

**Health Benefits of Interventions by Economic Status**

Because the poor have higher environmental and nutritional risk exposures and intervention needs, all intervention scenarios except the “pro-wealthy” scenario would also reduce the disparity in child mortality between poor and wealthier families. For example, the difference in mortality rate between quintiles 1 and 5 would be reduced from 5.2 to 3.8 per 1000 children in Latin America and the Caribbean, from 8.6 to 5.4 per 1000 children in South Asia, and from 25.4 to 12.8 per 1000 children in sub-Saharan Africa in the “equal-100” scenario (100% reduction; Figure 2). The equity benefits would be even larger if the interventions prioritized the poor (“pro-poor” scenario), reducing the difference in mortality rate between quintiles 1 and 5 to 3.5 per 1000 children in Latin America and the Caribbean, 2.4 per 1000 children in South Asia, and 10.1 per 1000 children in sub-Saharan Africa (Figure 2).

**COMMENT**

The results of our analysis demonstrate that complete coverage of effective interventions that address child undernutrition and provide clean water and sanitation and clean household fuels would reduce child mortality by an estimated 14% to 31% in Latin America and the Caribbean, South Asia, and sub-Saharan Africa. These benefits would close 30% to 48% of the current regional gaps toward the MDG target for reducing child mortality. These interventions would also be expected to reduce the absolute disparity in child mortality between poor and better-off households. The poor have a larger proportional reduction in child mortality because they currently have higher exposure; they also have larger absolute benefits (ie, greater reductions in mortality rate) because of both larger proportional benefits and larger initial mortality levels (ie, a greater percentage reduction of a larger total number of deaths). Fifty percent coverage of the same environmental and nutritional interventions, as envisioned by the MDGs, would have 30% to 75% larger benefits for reducing child mortality if the interventions were targeted to the poor first than if the interventions benefited wealthier households, who nonetheless are also in need of MDG-related interventions. In other words, pro-poor nutritional and environmental interventions not only reduce within-population child mortality disparities but also are significantly more effective in achieving the aggregate MDG target of reducing child mortality. This effect is strongest in sub-Saharan Africa, where child mortality is farthest from the MDG target. Pro-poor interventions have larger aggregate benefits, especially in sub-Saharan Africa, because they deliver environmental and nutritional interventions to children who are most susceptible to dying of such exposures, possibly because of limited access to medical services.

Our results are based on population-level analyses, in relation to economic status. Economic status is multifaceted and its measurement is complex. Asset-
based methods provide a robust approach to comparable measurements. For this reason, the DHS wealth index is commonly used. However, the DHS were not explicitly designed to measure economic status and it is possible that the full set of asset items does not fully differentiate households throughout the distribution of income in a country. As a result, the true gradient in child mortality and risk factors might be even steeper than observed in our results, which would strengthen our findings. More detailed measurement of economic status and the identification of the absolute poor are necessary for better reporting toward the MDGs. Risk assessment analytics used in our work apply relative risks from meta-analyses of epidemiological studies to population-level exposure and disease-specific mortality data. Although this is necessary to develop evidence for population-level effects of risk factors, programs, and policies based on epidemiological evidence, the results, by definition, are estimates (vs direct measurement). Related to this, while interventions for the risk factors considered in our analysis are available, the implementation scenarios are, by definition, hypothetical. Therefore, our analyses and results are intended to draw attention to the important issues of integrated intervention programs and the poverty status of intervention recipients in future efforts.

Beyond these issues that enter all population-level analyses of poverty, risk factors, and mortality, there are a number of limitations and sources of uncertainty specific to the data used in our analysis. The DHS constitutes the largest international survey program, with implementation procedures, sample sizes, and response rates that are comparable with or better than those in many high-income countries. To obtain data directly from as many countries as possible, we have used the most recent survey for each country, for years after 1990. The fact that surveys were implemented in different years might affect comparability across countries. To test how sensitive our results are to the year of the survey, we repeated all of our analyses excluding surveys that were older than 10 years. Although the number of preventable deaths changed (by 2%-3% in sub-Saharan Africa, 6%-9% in South Asia, and 18%-27% in Latin America and the Caribbean for different scenarios; data available on request), there were no changes in the ordering of scenarios in terms of their benefits or in any of the conclusions made based on the results.

The most important source of uncertainty in our estimates is likely to be the use of disease-specific child death estimates in countries without complete vital statistics. Considering the full range of uncertainties for all-cause and disease-specific deaths, Mathers et al estimated that regional uncertainties in deaths from diarrhea, lower respiratory tract infection, malaria, and measles were about 11% in Latin America and the Caribbean, 10% to 17% in South Asia, and 20% to 23% in sub-Saharan Africa (some of this uncertainty is in the total number of deaths and some is in the distribution of deaths across diseases; in the second component, deaths from these diseases cannot be simultaneously underestimated or overestimated). The re-
cent work of the Child Health Epidemiology Reference Group has led to better data and more consistent models for these estimates. Therefore, while uncertainty in actual death numbers remains an attribute of all quantitative analyses in global health, the overall conclusions of our analyses on the benefits of pro-poor integrated interventions are unlikely to be simply an artifact of disease-specific mortality methods.

The disease-specific quintile weights that we used were based on all-cause mortality (equation 1) and reflect the empirical finding that most under-5 deaths in developing countries are due to neonatal conditions and a small number of infectious diseases. These diseases (eg, diarrhea, lower respiratory tract infections, and malaria) are the same as those affected by the environmental and nutritional risk factors considered in this article. To examine the sensitivity of our results to this assumption, we repeated the analysis using a model in which the proportional share of diseases in each quintile was related to the quintiles’ total mortality level (empirically, the proportional share of infectious diseases like diarrhea and lower respiratory tract infections is larger when total mortality is higher). Our conclusions on the effects of pro-poor programs were strengthened in this alternative analysis, presented in eTable 4 (available online at http://www.jama.com). This is because when disease composition depends on total mortality, an even larger share of infectious disease deaths occurs among the poor, which in turn leads to higher absolute benefits of risk factor interventions.

The Millennium Declaration of the United Nations has provided the motivation, framework, and resources to initiate policies and programs to achieve specific development goals in a sustainable manner. Although the interdependence of multiple MDGs is broadly and qualitatively recognized, there has been little systematic effort to integrate the design, implementation, and evaluation of programs across goals and across the sectors that are responsible for them. Halfway through their intended timeline, however, the slow rate of progress toward the MDGs has led to increasing concerns about whether they will be achieved by 2015 and has created an imperative for identifying effective programs. The results of our analysis demonstrate a real opportunity for leveraging the linkages between multiple MDGs to substantially increase the possibility of achieving them. In addition to highlighting the need for funding, implementing, and monitoring such integrated intervention programs, our analysis demonstrates that the health benefits would be largest if the MDG-related nutritional and environmental interventions systematically and preferentially reach the poor. It has also been argued that the absence of pro-poor programs are driven by political and institutional factors rather than by considerations about their feasibility or costs. Above and beyond their aggregate effectiveness, equity considerations in our analysis provide an ethical imperative for pro-poor programs and should motivate progressive intervention programs that index recipient communities and households based on their level of poverty as well as on exposure to nutritional and environmental risks (eg, poor rural communities, urban slums). In par-

Figure 5. Levels of Fuel Use by Quintile of Wealth in Latin America and the Caribbean, South Asia, and Sub-Saharan Africa

Exposures are measured using the variables described in Table 1. Regional estimates for each quintile are weighted averages of those for individual countries in the same quintile, with weights for each country proportional to the number of children in the quintile in that country. See eTable 2 for exposure data from individual countries.
ticular, to increase the accountability of both national governments and interna-
tional donors, monitoring progress toward the MDGs should also be based on report-
ing multiple environmental, health, and nutritional indicators together with the
economic status of the recipient house-
holds and communities.

Author Contributions: Dr Ezzati had full access to all of the
data in the study and takes responsibility for the in-
tegrity of the data and the accuracy of the data analysis.
Study concept and design: Gakidou, Ezzati.
Acquisition of data: Gakidou, Ezzati.
Analysis and interpretation of data: Gakidou, Oza, Vidal
Fuentes, Li, Lee, Sousa, Hogan, Vander Hoorn, Ezzati.
Drafting of the manuscript: Gakidou, Ezzati.
Critical revision of the manuscript for important in-
tellectual content: Oza, Vidal Fuentes, Lee, Sousa,
Hogan, Vander Hoorn, Ezzati.
Statistical analysis: Gakidou, Oza, Vidal Fuentes, Lee,
Sousa, Hogan, Vander Hoorn, Ezzati.
Obtained funding: Gakidou, Ezzati.
Study supervision: Gakidou, Ezzati.
Financial Disclosures: None reported.
Funding/Support: This work was sponsored by Na-
ton Foundation grant 0027536, by the Grand Challenges in Global Health, and by the Center for In-
ternational Development at Harvard University.
Role of the Sponsor: The sponsors had no role in the design and conduct of the study; collection, manage-
ment, analysis, and interpretation of the data; prepa-
ration, review, or approval of the manuscript; or de-
cision to submit the manuscript.

Supplemental Information: eTables 1-4 are avail-
able online at http://www.jama.com.

Additional Contributions: We thank Kenneth Hill, PhD,
Harvard University, and Kevin Thomas, PhD, Penn-
sylvania State University, for discussion on demo-
graphic methods; Colin Mathers, PhD, World Health
Organization, and Robert Black, MD, Johns Hopkins
University, for discussion on disease-specific child mor-
tality data and methods; Kenneth Hill and Barry Bloom,
PhD, Harvard University, for comments on the manu-
script; and Stanislava Nikolaeva, AB, Harvard Univer-
sity, for editorial help. None of those acknowledged
received compensation for their contributions.

REFERENCES

1. Sachs JD, McArthur JW. The Millennium Project: a plan for
the achievement of the Millennium Development Goals.
2. Travis P, Bennett S, Haines A, et al. Overcoming health-
systems constraints to achieve the Millennium
Making Services Work for Poor People. New York, NY:
4. Gwatkin DR. How much would poor people gain
from faster progress towards the Millennium Devel-
5. Fishman SM, Caufield LE, de Onis M, et al. Child-
hood and maternal underweight. In: Ezzati M, Lopez
AD, Rodgers A, Murray CJL, eds. Comparative Quan-
tification of Health and Disease Global and Regional Bur-
den of Disease Attributable to Selected Major Risk
Factors. Geneva, Switzerland: World Health Organi-
tation; 2004:39-161.
Cultural and nutritional interventions and child survival.