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GDP Matters: Cost Effectiveness of Cochlear Implantation and Deaf Education in Sub-Saharan Africa

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Hypothesis: Cochlear implantation and deaf education are cost effective in Sub-Saharan Africa.
Background: Cost effectiveness of pediatric cochlear implantation has been well established in developed countries but is unknown in low resource settings, where access to the technology has traditionally been limited. With incidence of severe-to-profound congenital sensorineural hearing loss 5 to 6 times higher in low/middle-income countries than the United States and Europe, developing cost-effective management strategies in these settings is critical.
Methods: Costs were obtained from experts in Nigeria, South Africa, Kenya, Rwanda, Uganda, and Malawi using known costs and published data, with estimation when necessary. A disability adjusted life years (DALY) model was applied using 3% discounting and 10-year length of analysis. Sensitivity analysis was performed to evaluate the effect of device cost, professional salaries, annual number of implants, and probability of device failure. Cost effectiveness was determined using the WHO standard of cost-effectiveness ratio/gross domestic product per capita (CER/GDP) less than 3.
Results: Cochlear implantation was cost effective in South Africa and Nigeria, with CER/GDP of 1.03 and 2.05, respectively. Deaf education was cost effective in all countries investigated, with CER/GDP ranging from 0.55 to 1.56. The most influential factor in the sensitivity analysis was device cost, with the cost-effective threshold reached in all countries using discounted device costs that varied directly with GDP.
Conclusion: Cochlear implantation and deaf education are equally cost effective in lower-middle and upper-middle income economies of Nigeria and South Africa. Device cost may have greater impact in the emerging economies of Kenya, Uganda, Rwanda, and Malawi. **Key Words:** Cochlear implant—Deaf education—Cost effective—DALY—Sub-Saharan Africa—Pediatric.
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The World Health Organization estimates that 360 million individuals are living with disabling hearing loss worldwide (1). The societal impact of hearing loss is considerable at every life stage, with speech and language delays in early childhood (2–4), poor academic performance and decreased nonverbal intelligence in school-age (5–7), increased likelihood of unemployment and low income in adulthood (8,9), and accelerated cognitive decline in older adults (10,11). Severe-to-profound congenital hearing loss is of particular concern, given the lifelong impact (12,13). Cochlear implantation (CI) has become standard of care for these children in high resource

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settings (14,15), and the cost effectiveness of this approach has been well demonstrated in multiple studies (16–25).

With up to 80% of the global hearing loss burden falling in low-and middle-income countries, expanding the focus of management strategies to include low resource settings is critical (26,27). Traditionally, cochlear implantation has not been available in these environments, and assessments of cost effectiveness of cochlear implantation in low resource settings are currently lacking (27). The World Health Organization (WHO) advocates for policymakers and governments to consider the cost-effectiveness of health interventions that may reduce the burden of disease in low resource areas (28). Sub-Saharan Africa is the ideal setting to examine the cost-effectiveness of cochlear implantation and deaf education, as there is a range of economic development and existing CI infrastructure. Accessibility of services for prelingually deaf children continues to be lacking in this region of the world, where hearing aids are often not provided even when appropriate and enrollment into deaf schools is frequently delayed (29). This study compares the cost effectiveness of managing prelingually deaf children with a national cochlear implantation program and mainstream education versus deaf education with sign language across 6 Sub-Saharan African countries, evaluating cost effectiveness within the context of each country's economic environment.

MATERIALS AND METHODS

Costs were derived from published data and estimates specific to each country. Kenya, Malawi, Nigeria, Rwanda, South Africa, and Uganda participated in the study, with the lead author from each country responsible for gathering cost data from that location. The model assumed deaf children were identified with failed auditory brainstem evoked response, and treatment was initiated before 36 months of age. Decision tree analysis was used to estimate lifelong individual effects and costs for cochlear implantation, deaf education, and no intervention. Cost effectiveness was compared using incremental cost-effectiveness ratios (ICER). A 10-year length of analysis was used.

DALY Cost-Effectiveness Analysis

Disability adjusted life years (DALYs) are the time-based measure of health recommended by the WHO for cost-effectiveness analysis (28). DALYs consist of a combination of years of life lost and years lived with disability, which represent the number of years lived with a nonfatal health condition, weighted by the severity of that condition (disability weight). Effectiveness is measured by the number of DALYs averted as a result of a health intervention (30).

Disability weight estimates from the 2000 Report of the Global Burden of Disease (GBD) Project were used for this analysis (31). Combining the GBD assessment of hearing aids with the equivalent hearing loss concept described by Snik and colleagues, we set the disability weight for cochlear implantation to that of a mild hearing loss (32,33). The same disability weights were applied to both deaf education and cochlear implantation due to lack of deaf education-specific data. The resulting cost-effectiveness ratios (CERs) were divided by the gross domestic product (GDP) per capita of each country per WHO protocol (28). CER/GDP less than 3 was considered cost effective and CER/GDP less than 1 very cost effective.

Demographics

Gross domestic product (GDP) represents the 2012 GDP per capita based on international dollars (34). Number of surviving infants in each country was estimated from United Nations World Population Prospects 2012 data (35). Based on Olusanya and Newton's estimates of hearing impairment in developing countries, annual incidence of congenital hearing loss was estimated to be 6 per 1000 live births (26). Smith and colleagues estimate that 4 in 10,000 cases of congenital hearing loss are profound, representing 20% to 40% of 0.001 to 0.002 incidence of congenital hearing loss in the United States and Europe (36). Extrapolating from these data, we conservatively estimated that 25% of congenital hearing loss cases in Sub-Saharan Africa would be profound, yielding an annual incidence of profound SNHL of 0.0015.

Cochlear Implant Costs

Training costs were considered systems-level marginal costs because of the need to build capacity. These costs were allocated over the total number of implants performed during the 10-year length of analysis. Country-specific training costs and estimates for average surgeon, audiology, and speech therapy salaries were used. Personnel and equipment costs of hearing aid trials that do not lead to implantation were incorporated into the analysis.

Auditory brainstem evoked response, operating microscope, facial nerve monitor, mastoid drill, and audiology mapping equipment were considered fixed costs. The costs for needed equipment were incorporated on a country-specific basis depending on the needs assessment by each lead author. Needed equipment was included as a one-time expense and allocated over the total number of implants performed during the 10-year period. An amplification trial cost of $150 was included for each child (37).

Surgical costs were estimated from actual CI surgeries in the 3 countries with existing implant programs (South Africa, Nigeria, and Kenya). For the remaining countries, costs were estimated from a 3-hour surgery. Current device cost was used for the 3 countries with existing CI programs. As South Africa was the only participating country that uses devices from 3 manufacturers, the average cost from the middle-priced manufacturer was used in the primary analysis (M. Smith, personal communication). This mid-range South African cost ($22,523) was used to estimate device cost in countries without CI programs.

Average maintenance costs were provided by the lead authors in each country with existing CI programs. Maintenance included annual rechargeable battery replacement, annual external repairs, and external device replacement every 10 years and was calculated across the lifetime of the individual based on life expectancy in each country. In countries without data, external repairs and external device replacement were estimated to be $250 and 20% of implant cost, respectively (38).

Rehabilitation costs included mapping and speech therapy sessions. One hour was allotted for each mapping session, with a tapered mapping schedule across the life span. A 6-year speech therapy taper was included for 80% of children, with an extended 8-year therapy schedule for the remaining 20%. Mainstream education costs were included in the cochlear implant cost analysis. Four hours weekly of educational support for 5 years were also included for 29% of CI recipients in all countries except South Africa, where no educational support is currently provided (39).

Device failures requiring reimplantation (including device, CT, and OR costs) were included in the analysis. The observed probability of device failure in South Africa and Nigeria was used in those respective countries. Probability of device failure ranges widely in the literature, from 2.3% to 6.8%, and tends to be higher in children than adults (40–47). Conservatively assuming that device failures will be higher in low resource settings, an estimated failure probability of 7% was applied to the countries without existing CI data. We assumed that failures would occur at an average age of 10 years, with each affected child being reimplanted and resuming use of the device and associated costs. To account for the possibility of nonuse, the 1.2% probability of nonuse observed in the South African national implant program was applied to each country, assuming that these children would be lost to follow-up and thus not accrue additional costs after 8 years of age (M. Smith, unpublished data). Decision tree analysis was used to account for failure and nonuse costs in the model. Indirect costs were not included.

Deaf Education Costs

Deaf education costs were gathered by the lead author from each country. Years of schooling varied by country, ranging from 14 to 17. Transition to mainstream education occurs regularly only in Malawi. Transition costs were accounted for by incorporating interpreter salary, training, and mainstream education costs into the analysis. For the remaining 5 countries, costs included deaf educator training, salaries, residential costs, and after school programs, when relevant.

Sensitivity Analysis

A sensitivity analysis was conducted to assess the impact of 4 key factors: 1) device cost, 2) professional salaries, 3) number of implants per year, and 4) probability of device failure (Table 4). These factors were selected based on contribution to overall costs and uncertainty in the estimates.

For South Africa, the average device cost for each of the 3 manufacturers was used in the sensitivity analysis, with the middle cost ($22,523) applied in the primary analysis (M. Smith, personal communication). The current device costs in Nigeria ($29,411) and Kenya ($25,400) were used for the primary analysis, with minimum and maximum scenarios representing 25% below and above the current device cost, respectively. In the remaining countries where CI cost estimates were required, the South African cost of $22,523 was applied to the primary analysis, and the minimum and maximum scenarios represented 25% below and above the mid-range estimate. Minimum and maximum salaries represented 25% below and above the average salaries provided by the lead author from each country with the exception of South Africa, where middle, minimum, and maximum salaries were provided directly by the lead author. The number of annual implants in the primary analysis was based on 30% accessibility of cochlear implant services. The minimum scenario was based on 20% accessibility and the maximum on 40% accessibility. Lastly, device failure probabilities were based on observed data in South Africa (2%, 1% minimum, and 3% maximum) and Nigeria (20%, 15%, and 25%) and an estimated 7% failure in the other countries (5% minimum and 9% maximum).

Device cost where the cost-effective threshold (CER/GDP <3) was reached was determined in each country by graphing the CER/GDP by progressively decreasing device cost from US $22,000 to $1,000 (Fig. 1).

RESULTS

Demographics

Demographic information for participating countries is listed in Table 1. GDP per capita ranged from 12,258 in South Africa to 753 in Malawi. As the most populous Sub-Saharan African nation, Nigeria had the highest estimated annual number of infants with profound hearing loss (9,156). The number of potential annual implants, calculated based on 30% accessibility of CI services, ranged from 2,747 in Nigeria to 174 in Rwanda. Three participating countries have existing cochlear implant programs, including South Africa (230 implants per year), Nigeria (5 per year), and Kenya (6 per annum).

Cochlear Implant Capacity and Training

All countries except South Africa would require training of additional personnel to serve 30% of potential implant candidates. There are 21 CI-trained surgeons working in South Africa: 6 in Nigeria; 4 in Kenya; and none in Rwanda, Uganda, or Malawi, where implant programs have not yet been established (Table 2). Applying the assumption of 192 new implant patients as the annual maximum for one surgeon full-time equivalent (4 CI surgeries per week, 48 weeks per year), we estimate that 4 of 6 countries will require training of additional surgeons. Increased audiology capacity is needed in Nigeria and Uganda. Speech therapists represent the largest personnel gap across countries, with all countries but South Africa requiring increased workforce in this area.

Cochlear Implant Costs

Individual cochlear implant costs are listed by country in Table 3. These costs represent the total cost for cochlear implantation across the lifetime of the individual and include mainstream education costs and educational support. Total individual CI costs ranged from $118,317 in South Africa to $64,310 in Malawi. Discounted 3% costs include device failures requiring reimplantation and the 1.2% probability of nonuse estimated from South African data. Discounted individual costs ranged from $80,853 in South Africa to $45,584 in Uganda. Four variables that contributed substantially to cochlear implantation costs and were associated with uncertainty in estimation were included in a nonrandom sensitivity analysis described in Table 4.

Deaf Education Costs

Individual deaf education costs for public, sign-based residential education are listed by country in Table 5. Total years of education varied across countries, from 17 in Nigeria to 14 in South Africa. Only Malawi regularly transitions deaf students to mainstream schools, typically around age 8. Special education teachers act as sign language interpreters in Malawi, and they do not receive special training for this role. Training costs are similarly negligible in South Africa, where deaf educators are trained in informal programs by existing deaf educators. Training is otherwise accounted for by country, and the deaf educator salary represents total salary per pupil for the length of deaf education in that country. Total individual and discounted costs ranged from $132,433 and $99,184 in South Africa to $4,480 and $3,450 in Malawi, respectively.

Cost Effectiveness

Total program and individual costs, DALYs averted, incremental costs per DALY averted, and cost-effectiveness

TABLE 1. *Country demographics and estimates of congenital profound sensorineural hearing loss*

Demographic	South Africa	Nigeria	Kenya	Rwanda	Uganda	Malawi
GDP per capita[a]	12,258	5,386	2,675	1,426	1,358	753
Population	51,452,000	159,708,000	40,909,000	10,837,000	33,987,000	15,014,000
Life expectancy	52	50	57	60	57	52
Crude birth rate[b]	22	42	38	38	46	42
Total annual live births	1,131,944	6,707,736	1,554,542	411,806	1,563,402	630,588
Infant mortality rate[c]	52	90	60	60	67	95
Surviving infants	1,073,083	6,104,040	1,461,269	387,098	1,458,654	570,682
Estimated annual number of infants with profound HL[d]	1,610	9,156	2,192	581	2,188	856
Potential annual implants[e]	483	2,747	658	174	656	257
Actual annual implants	230	5	6	0	0	0

Vital statistics are based on United Nations World Population Prospects 2012 data.
[a]2012 GDP per capita in international dollars.
[b]Average annual live births per 1,000 population.
[c]Average annual deaths (between birth and age 1) per 1,000 live births.
[d]Based on 0.0015 estimated incidence of profound congenital HL.
[e]Assuming 30% accessibility of cochlear implant services.

ratios (CER/GDP) are summarized by country in Table 6. CER/GDP less than 3 is considered cost effective and less than 1 very cost effective based on the WHO standard.

The incremental cost per DALY averted in South Africa is $19,111 for deaf education and –$15,025 for cochlear implantation (minimum and maximum sensitivity analysis: −$20,671, −$9,376), indicating that CI is less expensive per DALY averted than deaf education in the South African economy. The South African CER/GDP is 1.03 (0.94, 1.12) for cochlear implantation and 1.56 for deaf education. In Nigeria, the incremental cost per DALY averted is $3,700 for deaf education and $42,405 ($34,503, $52,512) for cochlear implantation. The CER/GDP in Nigeria is 2.05 (1.77, 2.41) for CI and 0.69 for deaf education. Incremental cost per DALY averted in Kenya is $2,425 for deaf education and $36,735 ($30,363, $44,429) for cochlear implantation. The CER/GDP in Kenya is 3.27 (2.83, 3.80) for CI and 1.11 for deaf education.

In Rwanda, the incremental cost per DALY averted is $769 for deaf education and $35,242 ($29,995, $41,336) for cochlear implantation. The Rwanda CER/GDP is 4.89 (4.23, 5.66) for CI and 0.55 for deaf education. The incremental cost per DALY averted in Uganda is $1,766 for deaf education and $31,149 ($25,753, $37,668) for cochlear implantation. The CER/GDP in Uganda is 5.43 (4.67, 6.35) for CI and 1.30 for deaf education. Lastly, the incremental cost per DALY averted in Malawi is $673 for deaf education and $35,589 ($30,581, $41,385) for CI. The CER/GDP in Malawi is 9.62 (8.37, 11.07) and 0.89 for cochlear implantation and deaf education, respectively.

Given the substantial influence of device cost in our model, the effect of discounted device cost on CER/GDP was further explored and is displayed graphically in Figure 1. The discounted device cost required to reach the WHO cost-effectiveness threshold of CER/GDP less than 3 varies directly with GDP, with $22,000 meeting this criteria in Kenya (GDP per capita 2,675), $10,000 in Rwanda (GDP 1,426), $8,500 in Uganda (GDP 1,358), and $1,100 in Malawi (GDP 753). Cochlear implantation is cost effective at all device costs in South Africa and Nigeria, the 2 countries with the highest GDP per capita in the study (12,258 and 5,386, respectively).

DISCUSSION

Cochlear implantation has been widely shown to be cost effective in high-income settings and is regarded the

TABLE 2. *Current cochlear implant capacity and goal capacity by country*

Type of capacity	South Africa	Nigeria	Kenya	Rwanda	Uganda	Malawi
Current capacity						
CI-trained otolaryngologists	21	6	4	0	0	0
Audiologists	376	29	7	3	4	7
Speech therapists	745	10	16	3	10	1
Goal capacity[a]						
CI-trained otolaryngologists	3	14	3	1	3	1
Audiologists	8	46	11	3	11	4
Speech therapists	32	183	44	12	44	17
Training costs (US$)[b]						
Otolaryngologist	$0	$80,000	$0	$10,000	$30,000	$10,000
Audiologist	$0	$300,050	$56,000	$0	$70,000	$0
Speech therapist	$0	$2,035,345	$112,000	$90,000	$204,000	$80,000

Training costs represent the cost in US$ to train the additional personnel required to meet goal capacity.
[a]Goal capacity estimated using potential annual implants from Table 1 and an annual maximum number of new implant patients per otolaryngology, audiology, and speech therapy full-time equivalent of 192, 60, and 15, respectively.
[b]Training costs are listed as zero when a country has already met capacity.

TABLE 3. *Individual cochlear implant costs (US$) by country*

Cost Category	South Africa	Nigeria	Kenya	Rwanda	Uganda	Malawi
Amortized training costs[a]						
Otolaryngology	0	3	0	6	5	4
Audiology	0	11	9	0	11	0
Speech therapy	0	74	17	52	31	31
Amortized equipment[a]	0	11	0	9	6	4
Lifetime maintenance						
CI batteries	12,360	2,675	5,904	3,244	3,074	2,789
External repairs	13,243	4,113	13,500	14,250	13,500	12,250
External device replacement	40,613	53,444	27,432	25,676	24,325	22,073
Implant cost	22,523	29,411	25,400	22,523	22,523	22,523
Surgery costs						
CT scan	901	352	60	150	94	500
Surgeon labor	674	184	260	78	82	62
Facility and OR costs	3223	617	345	330	332	1400
Anesthesia	541	295	70	100	377	500
Postoperative meds	1613	411	30	15	19	50
Private vs. public	Private	Private	Public	Public	Private	Public
Lifetime mapping and therapy						
Speech therapy	10,995	2,732	4,018	1,822	2,578	380
Audiology	1,379	343	1,381	229	431	86
Hearing aid trial	150	150	150	150	150	150
Mainstream education and support	10,101	1,515	5,207	1,911	1,132	1,508
Total individual CI costs	**118,317**	**96,341**	**83,783**	**70,544**	**68,669**	**64,310**
Discounted (3%) individual CI costs	**80,853**	**66,895**	**56,472**	**46,496**	**45,584**	**45,801**

[a]Amortized over the total number of implants in the 10-year length of analysis.

standard of care for severe-to-profound sensorineural hearing loss (14–25). With more than two-thirds of the global hearing loss burden falling in low- and middle-income countries, expanding the scope of management strategies to include low resource settings is essential (12,27). This paper is the first to examine cost effectiveness of pediatric cochlear implantation and deaf education in the context of Sub-Saharan Africa, where economic and political stability, health infrastructure, and resources differ substantially from those of the United States and Europe. Six countries with a wide range of economic development and breadth of existing CI infrastructure were included in the study. Our analyses demonstrate that cochlear implantation and deaf education are both cost effective in the upper-middle and lower-middle income economies of South Africa and Nigeria. In the low-income economies of Kenya, Rwanda, Uganda, and Malawi, cochlear implantation reaches the same cost-effective threshold as deaf education by using discounted device costs that vary directly with GDP.

Cost-effectiveness of other surgical interventions has been previously investigated in low resource settings, including circumcision (48–50), ophthalmologic procedures (51–55),

TABLE 4. *Sensitivity analysis evaluating the effect of device cost, professional salaries, number of annual implants, and probability of device failure*

	South Africa			Nigeria			Kenya		
Factor	Mid	Min	Max	Mid	Min	Max	Mid	Min	Max
Device cost[a]	$22,523	$18,018	$25,049	$29,411	$22,058	$36,764	$25,400	$19,050	$31,750
Salaries[a]									
Otolaryngology	$75,887	$129,700	$167,056	$35,400	$26,550	$44,250	$50,000	$37,500	$62,500
Audiology	$21,834	$28,973	$36,223	$7,200	$5,400	$9,000	$29,000	$21,750	$36,250
Speech therapy	$21,834	$28,973	$36,223	$7,200	$5,400	$9,000	$10,588	$7,941	$13,235
Annual implants[b]	483	322	644	2,747	1,831	3,662	658	438	877
Device failure	2%	1%	3%	20%	15%	25%	7%	5%	9%

	Rwanda			Uganda			Malawi		
Factor	Mid	Min	Max	Mid	Min	Max	Mid	Min	Max
Device cost[a]	$22,523	$16,892	$28,154	$22,523	$16,892	$28,154	$22,523	$16,892	$28,154
Salaries[a]									
Otolaryngology	$15,000	$11,250	$18,750	$15,849	$11,887	$19,811	$12,000	$9,000	$15,000
Audiology	$4,800	$3,600	$6,000	$9,057	$6,793	$11,321	$1,800	$1,350	$2,250
Speech therapy	$4,800	$3,600	$6,000	$6,792	$5,094	$8,490	$1,000	$750	$1,250
Annual implants[b]	174	116	232	656	438	875	257	171	342
Device failure	7%	5%	9%	7%	5%	9%	7%	5%	9%

[a]US$.
[b]Mid-range analysis based on 30% accessibility of implant services. Minimum and maximum based on 20% and 40%, respectively.

TABLE 5. *Individual deaf education costs (US$) by country*

Variable	South Africa	Nigeria	Kenya	Rwanda	Uganda	Malawi[a]
Years of deaf education	14	17	16	16	15	3
Years of mainstream	0	0	0	0	0	13
Children per deaf educator	4	15	12	13	15	10
Children per interpreter	—	—	—	—	—	10
Deaf education training per student	$0	$867	$813	$385	$226	$100
Total deaf educator salary	$56,757	$1,591	$8,320	$2,215	$1,811	$540
Total interpreter salary	—	—	—	—	—	$2,340
Total residential facility costs	$75,676	$23,868	$8240	$3,120	$10,189	$1,500
Other educational costs (supplies and afterschool expenses)	0	0	$216	0	0	0
Total individual cost of deaf education	**$132,433**	**$26,326**	**$17,589**	**$5,720**	**$12,226**	**$4,480**
Discounted (3%) individual deaf education cost	**$99,184**	**$18,129**	**$12,757**	**$4,206**	**$8,828**	**$3,450**

[a]There is no specific cost associated with sign language interpreter training in Malawi, where the interpreter role is filled by special education teachers. All mainstream educational costs are covered by the Malawian government. Residential facility costs were only required in Malawi for the 3 years of deaf education before transition to mainstream.

cleft lip and palate repair (56–58), general surgery procedures (59–61), orthopedic repairs (62,63), and caesarian deliveries (64). Nearly all procedures studied were found to be very cost effective (CER/GDP <1) by WHO standards (65,66). Overall costs were higher for cochlear implantation than other procedures previously studied (65,66). This is not surprising, however, given the device cost, lifetime maintenance, and inclusion of education, speech therapy, and audiology mapping in our model. The only directly comparable study in the literature is an evaluation of the cost-effectiveness of cochlear implantation in Nicaragua, where CI was found to be cost effective (CER/GDP 1.31) (67). Nicaragua has a lower-middle income economy most similar in GDP to Nigeria, which demonstrated similar CI cost-effectiveness (CER/GDP 2.05).

Several important themes emerge from our data. Cochlear implantation is highly cost effective in South Africa, the one country with a robust national CI program in this region. With the most developed economy of the 6 countries studied and the largest existing infrastructure for cochlear implantation, South Africa demonstrates that a highly cost-effective cochlear implant program is an achievable and realistic goal in Sub-Saharan Africa. Recognizing that CI cost effectiveness is not geographically driven is essential in expanding global access to this technology. Second, Nigeria demonstrates that cochlear implantation can meet the cost effective threshold even when substantial growth of infrastructure and capacity are required. With a mere 5 implants per year, the current Nigerian implant program needs to grow by more than 500% to reach 30% of the estimated children in need. Our analyses indicated that cochlear implantation is cost effective in Nigeria even while accounting for the cost of this tremendous growth. The remaining countries in the study demonstrate the opportunity to expand CI programs to areas that traditionally have not had access to this technology. Kenya, Rwanda, Uganda, and Malawi highlight the role for philanthropic, university, and business collaborations in building capacity for robust national cochlear implant programs. Device cost and the associated maintenance are particularly influential in these emerging economies. Each country is able to reach the cost-effective

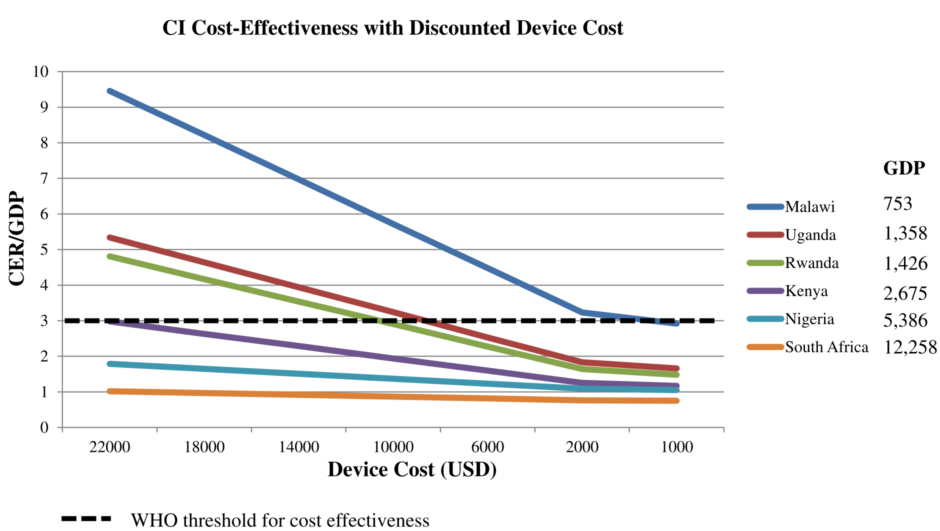

FIG. 1. Variation in CER/GDP with discounted device cost by country. Maximum device cost that achieves WHO cost-effectiveness criteria of CER/GDP less than 3 is $22,000 in Kenya, $10,000 in Rwanda, $8,500 in Uganda, and $1,100 in Malawi. Cochlear implantation is cost effective at all device costs in South Africa and Nigeria. GDP represents 2012 GDP per capita in international dollars.

TABLE 6. *Discounted costs (US$) and cost-effectiveness ratios for cochlear implantation and deaf education by country*

Country	Intervention	Total program cost	Individual cost	Individual discounted DALY	DALYs averted	Cost per DALY averted	Incremental cost per DALY averted	Cost-effectiveness ratio per gross domestic product (CER/GDP)
South Africa	CI	$390,426,878 (238,110,864, 564,946,353)	$80,853 (73,965, 87,745)	2.57	6.41	$12,614 (11,539, 13,689)	-$15,025 (−20,671, −9,376)	**1.03 (0.94, 1.12)**
	Deaf Ed	$478,945,922	$99,184	3.79	5.19	$19,111	$19,111	**1.56**
	None	$0	$0	8.98	0	—	—	—
Nigeria	CI	$1,837,497,061 (1,058,585,640, 2,875,664,827)	$66,895 (57,808, 78,518)	2.49	6.05	$11,057 (9,555, 12,978)	$42,405 (34,503, 52,512)	**2.05 (1.77, 2.41)**
	Deaf Ed	$497,959,615	$18,129	3.64	4.9	$3,700	$3,700	**0.69**
	None	$0	$0	8.54	0	—	—	—
Kenya	CI	$371,341,635 (214,321,182, 575,396,292)	$56,472 (48,889, 65,627)	2.57	6.45	$8,755 (7,580, 10,175)	$36,735 (30,363, 44,429)	**3.27 (2.83, 3.80)**
	Deaf Ed	$83,884,540	$12,757	3.76	5.26	$2,425	$2,425	**1.11**
	None	$0	$0	9.02	0	—	—	—
Rwanda	CI	$80,992,482, (46,683,763, 124,976,438)	$46,496 (40,200, 53,809)	2.60	6.67	$6,971 (6,027, 8,067)	$35,242 (29,995, 41,336)	**4.89 (4.23, 5.66)**
	Deaf Ed	$7,326,654	$4,206	3.80	5.47	$769	$769	**0.55**
	None	$0	$0	9.27	0	—	—	—
Uganda	CI	$299,213,658 (171,612,788, 466,267,987)	$45,584 (39,217, 53,276)	2.53	6.18	$7,376 (6,346, 8,621)	$31,149 (25,753, 37,668)	**5.43 (4.67, 6.35)**
	Deaf Ed	$57,945,326	$8,828	3.71	5.00	$1,766	$1,766	**1.30**
	None	$0	$0	8.71	0	—	—	—
Malawi	CI	$117,620,136 (68,209,272, 180,442,174)	$45,803 (39,841, 52,698)	2.55	6.32	$7,247 (6,304, 8,338)	$35,589 (30,581, 41,385)	**9.62 (8.37, 11.07)**
	Deaf Ed	$8,860,548	$3,450	3.74	5.13	$673	$673	**0.89**
	None	$0	$0	8.87	0	—	—	—

Middle, minimum, and maximum costs are included from the CI sensitivity analysis. CER/GDP less than 3 is cost effective and less than 1 very cost effective.

threshold with discounted device costs that vary directly with GDP. In Kenya, where the GDP is 2,675 per capita, only a slightly discounted cost of $22,000 is required to reach cost effectiveness compared with the country's current device cost of $24,500. By contrast, the Malawian GDP of 753 necessitates a heavily discounted device cost of $1100 to achieve cost effectiveness. Partnerships with implant manufacturers that decrease the disproportionate impact of device and maintenance costs in these emerging economies will be essential for building cost-effective implant programs.

There are weaknesses in this study that should be discussed. Cost data could be obtained directly from countries with existing CI programs, whereas additional estimations were required in remaining countries (68). The costs associated with training surgeons, audiologists, and speech therapists in cochlear implantation were estimated by the lead author in each country. More data are needed on these training costs, as well improved methodology for determining the number of personnel already CI-trained in each location. Our estimates for CI-trained otolaryngologists represent the number of CI-trained surgeons, but audiology and speech therapy capacity represent the number of individuals practicing in each country and not necessarily those that are CI trained. Second, repairs and external device replacement had to be estimated for 4 countries, and the countries that did have estimates for these costs varied substantially from each other (69,70). Surgery costs also varied markedly between countries. Although some variation is expected because of cost discrepancies between public and private institutions, there were wide variations even between public estimates. Further evaluation is required to understand reasons for this variation and how it can be minimized to increase the opportunity for cost-effective CI programs in the lowest GDP countries. Lastly, DALY methodology requires the assignment of disability weights that represent the severity of a condition (71). There are no data on the effect of deaf education on the disability associated with deafness, and thus, we applied the same disability weight to both cochlear implantation and deaf education. Because this assumption would bias our results toward the null, we felt that this was the most conservative way to proceed in the absence of data.

This study highlights the opportunity to expand cochlear implantation to areas of the world where access to the technology has traditionally been limited. Quantifying the cost effectiveness of a health intervention within the context of the local economic environment is essential to understanding where resources and support are needed. Our analyses demonstrate that a cost-effective cochlear implant program is possible in the sub-Saharan Africa region and focuses attention on lower GDP countries where support is most needed to expand access to this technology. Partnerships between higher resource countries, universities, and implant manufacturers to build infrastructure and capacity in emerging economies will change the landscape of profound hearing loss management worldwide, shifting the focus from high resource environments to a truly global perspective.

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