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Moving Beyond GDP: Cost Effectiveness of Cochlear Implantation and Deaf Education in Latin America

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Hypothesis: Cochlear implantation (CI) and deaf education are cost effective management strategies of childhood profound sensorineural hearing loss in Latin America.
Background: CI has been widely established as cost effective in North America and Europe and is considered standard of care in those regions, yet cost effectiveness in other economic environments has not been explored. With 80% of the global hearing loss burden existing in low- and middle-income countries, developing cost effective management strategies in these settings is essential. This analysis represents the continuation of a global assessment of CI and deaf education cost effectiveness.
Methods: Brazil, Colombia, Ecuador, Guatemala, Paraguay, Trinidad and Tobago, and Venezuela participated in the study. A Disability Adjusted Life Years model was applied with 3% discounting and 10-year length of analysis. Experts from each country supplied cost estimates from known costs and published data. 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 World Health Organization standard of cost effectiveness ratio/gross domestic product per capita (CER/GDP)<3.
Results: Deaf education was very cost effective in all countries (CER/GDP 0.07–0.93). CI was cost effective in all countries (CER/GDP 0.69–2.96), with borderline cost effectiveness in the Guatemalan sensitivity analysis (Max CER/GDP 3.21).
Conclusion: Both cochlear implantation and deaf education are widely cost effective in Latin America. In the lower-middle income economy of Guatemala, implant cost may have a larger impact. GDP is less influential in the middle- and high-income economies included in this study. **Key Words:** Cochlear implantation—Cost effectiveness—DALY—Deaf education—Hearing loss—Latin America—Pediatric.

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There are an estimated 1.1 billion people in the world living with hearing loss, including 8.2 million with profound losses (1). The World Health Organization estimates that 80% of these individuals are from low- and middle-income countries (2). The consequences of hearing loss are lifelong and include impaired speech and language development in early childhood, decreased academic performance in school-aged children, increased likelihood of school dropout in adolescence, higher likelihood of being low income, unemployed, or

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underemployed in adulthood, and cognitive decline in older adults (3–10). Cochlear implantation (CI) has become standard of care for children born with profound hearing loss, improving language outcomes, increasing the likelihood of transition to mainstream education, raising academic performance, and expanding employment opportunities (11–16).

The cost effectiveness of cochlear implantation has been well established in high resource settings such as North America and Europe (17–24). Little is known about cost effectiveness in other regions of the world, however, where access to the technology has traditionally been limited. With the global burden of hearing loss disproportionately affecting low- and middle-income countries, it is essential that we expand management strategies to incorporate the full breadth of global economic development. We have recently studied cochlear implant and deaf education cost effectiveness in Nicaragua and Sub-Saharan Africa (25,26). We now seek to expand on these studies by evaluating cost effectiveness in Latin America. This study compares the cost effectiveness of managing prelingually deaf children with a national cochlear implant program and mainstream education versus deaf education with sign language across seven Latin American countries with a wide range of economic development and population size, representing the diversity of countries in this region of the world.

METHODS

Methods for this study have been previously described (26). Briefly, data were gathered from experts in each country using known costs and published data (27,28). A disability-adjusted life years (DALY) model was used to assess cost effectiveness based on WHO recommendations (29). DALYs are a measure of years of life lost and years lived with disability, with effectiveness of an intervention described as the number of DALYs averted (30). Disability weight estimates from the 2013 Global Burden of Disease Study were applied (1). As in previous analyses, equivalent disability weights were used for cochlear implantation and deaf education because of a dearth of deaf education-specific data (25,26). Ten-year length of analysis and 3% discounting were used. The model assumed diagnosis and initiation of treatment would occur by 36 months of age. As previously described, we estimated an annual incidence of profound sensorineural hearing loss of 0.0015 (26). Individual lifelong costs for cochlear implantation, deaf education, and no intervention were estimated using decision tree analysis. Cost effectiveness was compared with incremental cost effectiveness ratios (ICER) and cost effectiveness ratios per gross domestic product (CER/GDP) using 2014 GDP per capita based on purchasing power parity in international dollars (28). The WHO threshold of CER/GDP less than 3 was considered cost effective and less than 1 very cost effective (29).

Cochlear Implant Costs

Country-specific training, personnel, surgical, maintenance, rehabilitation, and education costs were used. The required number of CI-trained personnel was estimated from 30% accessibility of implant services, assuming an annual maximum number of new implant patients per otolaryngology, audiology, and speech therapy full-time equivalent of 192, 60, and 15, respectively (26). Training and equipment costs were allocated over the total number of implants performed in the 10-year length of analysis. Labor and equipment for hearing aid trials not leading to implantation were included. Equipment costs, including auditory brainstem-evoked response, operating microscope, facial nerve monitor, mastoid drill, and audiology mapping equipment, were included based on a needs assessment by each participating country. Lifetime maintenance costs were calculated based on the life expectancy in each country and included country-specific estimates for annual rechargeable battery replacement, annual external repairs, and external device replacement every 10 years. Surgical costs were estimated by each country based on the cost of a CI surgery at a private hospital. Rehabilitation costs included hour-long mapping sessions across the lifespan and a 6-year speech therapy taper for 80% of children, with the remaining 20% receiving an extended 8-year taper (26). Education costs included parental cost of mainstream education and the cost of educational support. Each country supplied an estimate of the percentage of implanted children requiring support and length of time this support was provided. The cost of device failure, including a replacement device, reimaging, and operating room costs, was included based on country-specific probabilities of device failure. An estimated 3% device failure was applied to Trinidad and Tobago, as they do not currently have an active implant program. We assumed failures would occur at an average of 10 years of age, with each failure addressed by reimplantation and resumed use of the device with all associated costs. Country-specific probabilities of nonuse were applied, assuming that these children would be lost to follow up and therefore no longer accrue additional costs beyond 8 years of age (26). Estimated nonuse of 7% was applied to Trinidad and Tobago, as a country-specific estimate was not available without an active implant program. Failure and nonuse costs were incorporated through decision tree analysis. Indirect costs were not included.

Deaf Education Costs

Country-specific deaf education costs were provided by the lead author from each location. Deaf educator training, salaries, parental education and residential costs, and other educational costs such as afterschool programs were included for each country when relevant. No participating countries regularly transition students from deaf education to mainstream, so mainstream education costs, interpreter training, and salary were not included.

Sensitivity Analysis

A sensitivity analysis was performed to evaluate the impact of factors that contributed substantially to overall costs or contained uncertainty in the estimates, including device cost, professional salaries, number of implants per year, and probability of device failure. The device cost provided by the lead author in each country was used for the primary analysis, with minimum and maximum scenarios representing 25% below and above the current device cost, respectively. Venezuela was the only country to provide a range for device cost, so the upper and lower limits of this range were used for the maximum and minimum scenarios, with the mid-range estimate used in the primary analysis representing an average of these two costs. Minimum and maximum salaries represented 25% below and above the country-specific estimates. Annual number of implants was based on 30% accessibility of services, with minimum and maximum representing 20% and 40%, respectively. Minimum and maximum probabilities of device failure represented 25% below and above the country-specific estimate.

RESULTS

Demographics

Demographics are listed by country in Table 1. GDP per capita ranged from 30,285 in Trinidad and Tobago to 7,454 in Guatemala. Brazil was the most populous country in the study, with a population of over 207 million and an estimated 4614 infants born annually with profound hearing loss. All countries except Trinidad and Tobago have active implant programs in place. Brazil performs the largest total number of implants at 1,200 annually. Colombia's 500 annual implants represents the highest accessibility of CI services, reaching an estimated 43% of infants born with profound hearing loss annually. Probability of device failure ranged from 0.6% in Ecuador to 8% in Venezuela. Probability of nonuse also varied by country, from 0.5% in Paraguay to 11% in Brazil.

Cochlear Implant Capacity and Training

Current and goal capacity, along with training costs to reach goal capacity, are listed by country in Table 2. Brazil, Colombia, and Ecuador have already reached goal capacity, defined as having sufficient CI-trained otolaryngologists, audiologists, and speech therapists to provide cochlear implant services for 30% of children born with profound hearing loss. Speech therapy represents the primary gap in capacity, with Guatemala, Paraguay, Trinidad and Tobago, and Venezuela each requiring additional trained personnel. Increased audiology capacity is also required in Guatemala, Paraguay, and Venezuela. Trinidad and Tobago is the only country that requires additional surgeon training.

Cochlear Implant Costs

Costs of cochlear implantation across the lifetime of an individual are summarized by country in Table 3. Total costs include training of personnel, purchase of necessary equipment, lifetime maintenance, implant and surgical costs, mapping and speech therapy costs, preoperative hearing aid trial, and the parental cost of mainstream education and educational support. Total individual CI costs varied from $91,742 in Brazil to $265,989 in Venezuela. Discounted CI costs included device failures requiring reimplantation and the probability of nonuse. Discounted costs ranged from $47,547 in Brazil to $126,419 in Trinidad and Tobago. The effect of device cost, professional salaries, number of annual implants, and probability of device failure were evaluated in a nonrandom sensitivity analysis described in Table 4.

Deaf Education Costs

Individual costs for deaf education are listed by country in Table 5. Years of deaf education ranged from 9 in Venezuela to 14 in Ecuador. None of the participating countries routinely transitions students from deaf education to mainstream schools. In Brazil, Colombia, and Paraguay, there is no cost to the parent for deaf education, and schools are not residential. This section of the table is therefore left blank for those countries. Additional educational costs such as afterschool programs, tutoring, and supplies are included when applicable. Total and discounted deaf education costs range from $4,367 and $3,491, respectively, in Colombia to $144,667 and $111,058 in Trinidad and Tobago.

TABLE 1. *Demographics by country with estimates of congenital profound hearing loss*

Demographic	Brazil	Colombia	Ecuador	Guatemala	Paraguay	Trinidad and Tobago[f]	Venezuela
GDP per Capita[a]	15,838	13,357	11,350	7,454	8,894	30,285	17,558
Population	207,848,000	48,229,000	16,144,000	16,343,000	6,639,000	1,360,000	31,108,000
Life expectancy	74	73	76	71	73	70	74
Crude birth rate[b]	15	16	21	28	22	15	20
Total annual live births	3,138,505	781,310	342,253	452,701	144,066	19,992	622,160
Infant mortality rate[c]	20	18	21	23	29	25	14
Surviving infants	3,075,735	767,246	335,065	442,289	139,888	19,492	613,450
Estimated annual number of infants with profound HL[d]	4,614	1,151	503	663	210	29	920
Potential annual implants[e]	1,384	345	151	199	63	9	276
Actual annual implants	1,200	500	50	5	3	0	120
Device failure (%)	1.2	1	0.6	3	2.5	3	8
Nonuse (%)	11	7	4.6	7	0.5	7	9

Vital statistics are based on United Nations World Population Prospects 2015 data.
[a]2014 GDP per capita, purchasing power parity, 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 hearing loss.
[e]Assuming 30% accessibility of cochlear implant services.
[f]Device failure and nonuse were estimated from other participating countries, as there is no active implant program in Trinidad and Tobago.

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

	Brazil	Colombia	Ecuador	Guatemala	Paraguay	Trinidad and Tobago	Venezuela
Current capacity							
Otolaryngologists	110	30	7	2	1	0	12
Audiologists	240	50	5	1	1	1	4
Speech therapists	150	100	20	2	1	0	7
Goal capacity[a]							
Otolaryngologists	8	2	1	1	1	1	2
Audiologists	24	6	3	4	2	1	5
Speech therapists	93	23	11	14	5	1	19
Training costs (USD) to reach capacity[b]							
Otolaryngologist	$0	$0	$0	$0	$0	$10,000	$0
Audiologist	$0	$0	$0	$120,000	$40,000	$0	$3,000
Speech therapist	$0	$0	$0	$480,000	$160,000	$7,300	$30,000

Training costs represent the cost in USD to train the additional personnel required to meet goal capacity.
[a]Goal capacity was 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.

Cost Effectiveness

Total program and individual costs, DALYs averted, cost and incremental costs per DALY averted, and cost effectiveness ratio per gross domestic product (CER/GDP) are described by country in Table 6. CER/GDP of less than 3 was considered cost effective and less than 1 very cost effective (29). In Brazil, the incremental cost per DALY averted was $40,433 for CI (minimum and maximum sensitivity analysis: $24,377, $60,313) and $8,767 for deaf education. Both CI and deaf education were very cost effective in Brazil, with CER/GDP of 0.69 (0.62, 0.78) and 0.55, respectively. The incremental cost per DALY averted in Colombia was $98,338 ($88,796, $110,726) for CI and $871 for deaf education. Similar to Brazil, both CI and deaf education were very cost effective in Colombia, with CER/GDP of 0.83 (0.76, 0.93) and 0.07, respectively.

In Ecuador, the incremental cost per DALY averted was $175,664 ($165,741, $189,695) for CI and $2,808 for deaf education. CI was cost effective in Ecuador, with

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

	Brazil	Colombia	Ecuador	Guatemala	Paraguay	Trinidad and Tobago	Venezuela
Amortized training costs[a]							
Otolaryngology	0	0	0	0	0	111	0
Audiology	0	0	0	60	63	0	1
Speech therapy	0	0	0	241	254	81	11
Amortized equipment[a]	0	0	11	1	12	22	9
Lifetime maintenance							
CI batteries	11,190	21,222	29,016	8,673	6,974	8,741	53,213
External repairs	7,105	5,659	108,085	34,235	34,870	127,756	85,140
External device replacement	41,446	49,518	90,675	61,623	55,792	67,240	67,403
Implant cost	16,000	16,000	21,000	26,700	29,000	23,000	21,550
Surgery costs[b]							
CT scan	300	140	170	275	100	350	18
Surgeon labor	187	156	175	624	1,040	416	14
Facility and OR	4,000	2,225	543	2,000	1,400	2,500	1,700
Anesthesia	2,000	500	200	0	2,500	1,999	790
Postop meds	100	20	50	0	300	200	12
Lifetime mapping and therapy							
Speech therapy	4,554	3,795	5,009	1,139	30,360	18,216	463
Audiology	678	571	628	1,143	3,809	2,381	71
Hearing aid trial	150	150	150	150	150	150	150
Mainstream education and support	4,032	9,408	1,728	42,476	25,920	1,210	35,444
Total individual CI costs	91,742	109,364	257,440	179,339	192,544	254,373	265,989
Discounted (3%) individual CI costs	47,547	49,710	109,799	97,196	105,799	126,419	116,724

[a]Amortized over the total number of implants in the 10-year length of analysis.
[b]Estimated based on the cost of a CI surgery at a private hospital.
CI indicates cochlear implantation.

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

	Brazil			Colombia			Ecuador			Guatemala		
Factor	Mid	Min	Max	Mid	Min	Max	Mid	Min	Max	Mid	Min	Max
Device cost[a]	$16,000	$12,000	$20,000	$16,000	$12,000	$20,000	$21,000	$15,750	$26,250	$26,700	$20,025	$33,375
Salaries[a]												
Otolaryngology	$36,000	$27,000	$45,000	$30,000	$22,500	$37,500	$33,600	$25,200	$42,000	$120,000	$90,000	$150,000
Audiology	$14,236	$10,677	$17,795	$12,000	$9,000	$15,000	$13,200	$9,900	$16,500	$24,000	$18,000	$30,000
Speech Therapy	$12,000	$9,000	$15,000	$10,000	$7,500	$12,500	$13,200	$9,900	$16,500	$3,000	$2,250	$3,750
Annual implants[b]	1384	923	1845	345	230	460	151	101	201	199	133	265
Device failure	1.2%	0.9%	1.5%	1%	0.8%	1.3%	0.6%	0.4%	0.7%	3%	2%	4%

	Paraguay			Trinidad and Tobago			Venezuela		
Factor	Mid	Min	Max	Mid	Min	Max	Mid	Min	Max
Device cost[a]	$29,000	$21,750	$36,250	$23,000	$17,250	$28,750	$21,550	16,600	26,500
Salaries[a]									
Otolaryngology	$200,000	$150,000	$250,000	$80,000	$60,000	$100,000	$2,680	$2,010	$3,350
Audiology	$80,000	$60,000	$100,000	$50,000	$37,500	$62,500	$1,500	$1,125	$1,875
Speech Therapy	$80,000	$60,000	$100,000	$48,000	$36,000	$60,000	$1,220	$915	$1,525
Annual Implants[b]	63	42	84	9	6	12	276	184	368
Device Failure	2.5%	2%	3%	3%	2%	4%	8%	6%	10%

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

CER/GDP of 2.09 (1.98, 2.24), and deaf education was very cost effective (CER/GDP 0.25). The incremental cost per DALY averted in Guatemala was $154,845 ($140,870, $172,826) for CI and $6,198 for deaf education. CER/GDP was 2.96 (2.76, 3.21) for CI and 0.83 for deaf education, indicating that CI was cost effective in Guatemala in the primary analysis and borderline cost effective in the sensitivity analysis. Deaf education was very cost effective in Guatemala.

In Paraguay, the incremental cost per DALY averted was $112,099 ($91,935, $135,708) for CI and $5,678 for deaf education. CI was cost effective in Paraguay (CER/GDP 2.50 [2.15, 2.91]), and deaf education was very cost effective (CER/GDP 0.64). The incremental cost per DALY averted in Trinidad and Tobago was $32,683 ($11,709, $59,034) for CI and $28,045 for deaf education. Both CI and deaf education were very cost effective in Trinidad and Tobago, with CER/GDP of 0.94 (0.87, 1.03) and 0.93, respectively. In Venezuela, the incremental cost per DALY averted was $235,408 ($222,764, $252,395) for CI and $6,198 for deaf education. CI was cost effective and deaf education very cost effective in Venezuela, with CER/GDP of 1.51 (1.44, 1.59) and 0.35, respectively.

DISCUSSION

This analysis demonstrates that cochlear implantation and deaf education are cost effective in all Latin American countries included in the study. Deaf education is

TABLE 5. *Individual deaf education costs (USD) by country*[a]

	Brazil	Colombia	Ecuador	Guatemala	Paraguay	Trinidad and Tobago	Venezuela
Years of deaf ed	13	13	14	10	12	13	9
Children per deaf educator	10	15	15	11	12	3	15
Deaf education training per student	$500	$640	$0	$0	$1,667	$1,667	$48
Total deaf educator salary	$45,500	$3,727	$10,080	$5,455	$6,500	$78,000	$900
Parental education costs, including residential facility fees	—	—	$5,040	$6,000	—	$65,000	$12,600
Other educational costs (supplies and afterschool expenses)	$0	$0	$0	$20,160	$21,600	$0	$32,000
Total individual cost of deaf education	$46,000	$4,367	$15,120	$31,615	$29,767	$144,667	$45,548
Discounted (3%) individual deaf education cost	$35,417	$3,491	$11,427	$24,419	$22,826	$111,058	$24,915

[a]Parental costs for deaf education are left blank in countries where the system is entirely public, with no cost to the family. The deaf education college training program in Guatemala closed, so training is now done informally within deaf schools. In Ecuador, training programs to become a deaf educator are public and free of charge.

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

Country	Treatment Type	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)
Brazil	CI	$658,050,390 (394,399,622, 987,275,257)	$47,547 (42,730, 53,511)	1.74	4.34	$10,956 (9846, 12,330)	40,433 (24,377, 60,313)	0.69 (0.62, 0.78)
	Deaf Ed	$490,177,173	$35,417	2.04	4.04	$8,767	$8,767	0.55
	None	$0	$0	6.08	0	—	—	—
Colombia	CI	$171,500,179 (104,018,097, 255,446,381)	$49,710 (45,491, 55,352)	1.56	4.48	$11,096 (10,095, 12,396)	$98,338 (88,796, 110,726)	0.83 (0.76, 0.93)
	Deaf Ed	$12,044,695	$3,491	2.03	4.01	$871	$871	0.07
	None	$0	$0	6.04	0	—	—	—
Ecuador	CI	$165,797,061 (105,284,071, 236,487,636)	$109,799 (104,242, 117,656)	1.48	4.63	$23,715 (22,514, 25,412)	$175,664 (165,741, 189,695)	2.09 (1.98, 2.24)
	Deaf Ed	$17,254,284	$11,427	2.04	4.07	$2,808	$2,808	0.25
	None	$0	$0	6.11	0	—	—	—
Guatemala	CI	$193,419,589, (120,535,809, 279,963,390)	$97,196 (90,628, 105,647)	1.55	4.41	$22,040 (20,551, 23,956)	$154,845 (140,870, 172,826)	2.96 (2.76, 3.21)
	Deaf Ed	$48,593,224	$24,419	2.02	3.94	$6,198	$6,198	0.83
	None	$0	$0	5.96	0	—	—	—
Paraguay	CI	$66,640,577 (38,160,531, 103,529,732)	$105,779 (90,858, 123,250)	1.29	4.76	$22,222 (19,088, 25,893)	$112,099 (91,935, 135,708)	2.50 (2.15, 2.91)
	Deaf Ed	$14,380,630	$22,826	2.03	4.02	$5,678	$5,678	0.64
	None	$0	$0	6.05	0	—	—	—
Trinidad and Tobago	CI	$11,377,679 (6,993,642, 16,656,495)	$126,419 (116,561, 138,804)	1.56	4.43	$28,537 (26,312, 31,333)	$32,683 (11,709, 59,034)	0.94 (0.87, 1.03)
	Deaf Ed	$9,995,183	$111,058	2.03	3.96	$28,045	$28,045	0.93
	None	$0	$0	5.99	0	—	—	—
Venezuela	CI	$322,157,750 (205,699,112, 453,923,145)	$116,724 (111,793, 123,349)	1.65	4.41	$26,468 (25,350, 27,970)	$235,408 (222,764, 252,395)	1.51 (1.44, 1.59)
	Deaf Ed	$68,764,616	$24,915	2.04	4.02	$6,198	$6,198	0.35
	None	$0	$0	6.06	0	—	—	—

Mid-, minimum-, and maximum costs are included from the CI sensitivity analysis. CER/GDP <3 is cost effective and <1 very cost effective.

very cost effective, with CER/GDPs ranging from 0.07 to 0.93. Cochlear implantation is very cost effective in Brazil (CER/GDP 0.69), Colombia (0.83), and Trinidad and Tobago (0.94) and cost effective in Ecuador (2.09), Guatemala (2.96), Paraguay (2.50), and Venezuela (1.51). Guatemala was the only participating country with borderline cost effectiveness in the CI sensitivity analysis (2.76, 3.21). The relatively high device cost of $26,700 in Guatemala ($20,025, $33,375) may have a larger effect in this lower middle-income economy than in the other countries in the study.

These results are consistent with our previous analyses in Sub-Saharan Africa and Nicaragua (25,26). Cochlear implantation and deaf education were previously found to be cost effective in the upper middle-income economy of South Africa and lower middle-income economies of Nigeria and Nicaragua, with borderline cost effectiveness in the lower middle-income economy of Kenya. CI was not yet cost effective in the emerging economies of Rwanda, Uganda, and Malawi, but by decreasing implant cost in direct proportion to GDP, each country was able to meet the WHO cost effectiveness threshold. The range of economic development in countries participating in this study is generally higher than the Sub-Saharan African analysis, spanning the lower middle-income of Guatemala to the upper middle-income economies of Brazil, Colombia, Ecuador, and Paraguay and high-income economies of Trinidad and Tobago and Venezuela. It is therefore not surprising that cochlear implantation and deaf education would be cost effective in all countries studied.

This study of primarily middle-income countries provides valuable insight into factors that contribute to a particularly cost effective national cochlear implant program. Brazil and Colombia have the most cost effective programs despite not having the highest GDP per capita of participating Latin American countries. They are the highest volume countries in the study, with 1,200 implants occurring annually in Brazil and 500 in Colombia. This represents an estimated 26% and 43% accessibility of CI services, respectively, compared with the next highest volume country of Venezuela, where 120 implants are performed annually to reach an estimated 13% of children born with profound hearing loss. Total individual cochlear implant costs are lower in Brazil and Colombia than the other participating countries. In particular, the cost of the device, annual repairs, and external device replacement is lowest in Brazil and Colombia. Lifetime external repairs in these two countries range from $5,659 to $7,105, whereas the remaining countries range from $34,325 to $127,756. Lifetime cost of external device replacement every 10 years follows the same pattern, with Brazil and Colombia ranging from $41,446 to $49,518, compared with $55,792 to $90,675 in the remaining countries. Device cost is notably lower in Brazil and Colombia as well, with both countries paying an average of $16,000 per device, compared with $21,000 to $29,000 elsewhere. Interestingly, CI batteries did not follow the same pattern, as Paraguay and Trinidad and Tobago pay less for lifetime annual battery replacement ($6,974 to $8,741) than Brazil and Colombia ($11,190 to $21,222). Improved negotiating capacity from higher volume of services may be contributing to the observed decreased cost of the device, external repairs, and external device replacement.

While appreciating the increased cost effectiveness achieved in Brazil and Colombia with high volumes and relatively lower costs, it is equally important to recognize that national programs with lower volumes in countries with less robust economies can still be cost effective. Ecuador, Guatemala, and Paraguay each exemplify this principal, as they respectively perform 50, 5, and 3 implants per year and have cost effectiveness ratios ranging from 2.10 to 2.96. Of these three countries, Guatemala and Paraguay both require training of additional personnel and purchase of equipment, yet still fall below the cost effective threshold in the primary analysis. This finding highlights that countries requiring substantial growth to develop robust implant programs can still achieve cost effectiveness even when taking the cost of this growth into account.

There are weaknesses in this study that should be discussed. The DALY measure recommended by the WHO for cost effectiveness analysis is dependent on standardized disability weights assigned to quantify the severity of a condition (30). These weights are revised periodically by the Global Burden of Disease working group. There was a substantial change in the hearing loss disability weights from 2000 to 2010 (31,32). The 2010 weights were considered highly controversial, as the revised method for determining disability weights that involved asking survey respondents to make pairwise comparisons between health states described hearing impairment in isolation without known sequelae such as delayed speech and language development, depression, and social isolation (32–35). Our previous analyses therefore used the 2000 disability weights to avoid this controversy. The Global Burden of Disease group revised the 2010 disability weights in their 2013 study by incorporating social isolation into the lay descriptions of hearing loss presented to survey respondents (36,37). These disability weights are considered more valid for sensory deficits than 2010, and we therefore based the current analysis on the 2013 revision (38). This results in the CER/GDP ratios in this analysis not being directly comparable to our previous studies. We nevertheless thought it was important to recognize the recent revision of disability weights and thus maintain the modernity of our analyses.

Cost estimation remains a challenge, as our model requires country-specific cost estimates for a large number of variables, many of which are not published or readily available. Particularly for high-volume countries, cost estimates from a single collaborator are assumed to apply universally to programs across that country. In reality, variation likely exists from program to program. There is also wide variation in select costs between countries, notably CI maintenance and education costs. Some variation in maintenance costs may reflect varying negotiating capacity between countries with larger CI volumes, although other factors may also affect these observed differences. Quantifying the cost of education has proven difficult for both mainstream and deaf education. Our reported costs represent the cost to the parent, including fees, afterschool activities, uniforms, and educational support, when applicable. We incorporated educator training and salary to account for institutional costs, but ultimately there are likely costs associated with mainstream and deaf education born by the government that we were unable to assess. More data on education costs would be valuable for future studies evaluating CI and deaf education.

Lastly, although our model provides a comparison of cost effectiveness of cochlear implantation and deaf education, it is unable to account for long-term differences in economic productivity between the two intervention strategies. Preliminary studies of long-term outcomes in cochlear implantation suggest that implant recipients routinely complete secondary and postsecondary education and become productive members of the workforce in early adulthood (13–16). Longitudinal studies that prospectively evaluate academic and economic outcomes of hearing loss management with CI and mainstream education versus deaf education are needed to further delineate these findings. It would be particularly valuable to study these outcomes across a spectrum of economic environments, including low- and middle-income countries alongside the more commonly studied high-income settings.

This study demonstrates that cochlear implantation and deaf education are widely cost effective in Latin America. It extends our previous evaluation of cost effectiveness in Sub-Saharan Africa to an additional region of the world, providing much needed data on CI cost effectiveness across a variety of geographic and economic contexts that are more reflective of the global distribution of hearing loss than the previous concentration of studies in North America and Europe. The ultimate goal is to broaden management strategies for profound childhood hearing loss to include low- and middle-income countries, where the majority of the global hearing loss burden is located. The Latin American countries in this study exemplify the feasibility of expanding access to cochlear implantation and deaf education so that children born with profound hearing loss can reach their full potential.

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