Assessing the value of human papillomavirus vaccination in Gavi-eligible low-income and middle-income countries

Jessica Ochalek, Kaja Abbas, Karl Claxton, Mark Jit, James Lomas

ABSTRACT

Introduction. Estimating the value of providing effective healthcare interventions in a country requires an assessment of whether the improvement in health outcomes they offer exceeds the improvement in health that would have been possible if the resources required had, instead, been made available for other healthcare activities in that country. This potential alternative use of the same resources represents the health opportunity cost of providing the intervention. Without such assessments, there is a danger that blanket recommendations made by international organisations will lead to the adoption of healthcare interventions that are not cost effective in some countries, even given existing donor mechanisms intended to support their affordability.

Methods. We assessed the net health impact to 46 Gavi-eligible countries of achieving one of the WHO’s proposed 90-70-90 targets for cervical cancer elimination, which includes 90% coverage of human papillomavirus (HPV) vaccination among girls by 15 years of age, using published estimates of the expected additional benefits and costs in each country and estimates of the marginal productivity of each healthcare system. We calculated the maximum price each country could afford to pay for HPV vaccination to be cost effective by assessing the net health impact that would be expected to be generated at different potential prices.

Results. At Gavi negotiated prices, HPV vaccination offers net health benefits across most Gavi-eligible countries included in this study. However, if Gavi-eligible countries faced the average price faced by non-Gavi eligible countries, providing HPV vaccination would result in reduced overall population health in most countries.

Conclusion. Estimates of the net health impact of providing a healthcare intervention can be used to assess the benefit (or lack of) to countries of adhering to global guidance, inform negotiations with donors, as well as pricing negotiations and the value of developing new healthcare interventions.

INTRODUCTION

In 2019, donors funded 27% of healthcare provided in low-income countries and 3% in lower middle income countries.1 How donors make decisions around which interventions to fund is unclear.5 Funding may be tied to a donor’s strategic mission or aligned to international guidance or recommendations. Estimating the value of providing effective

Key questions

What is already known?

► Human papillomavirus (HPV) vaccination is considered cost effective in almost every country when compared against a threshold of 1× gross domestic product (GDP) per capita.
► GDP per capita-based thresholds are no longer recommended for judging the value for money of healthcare interventions.
► Country-specific health opportunity costs enable the estimation of the impact of an intervention in terms of the population net health benefits.

What are the new findings?

► Health opportunity costs in Gavi-eligible low-income and middle-income countries can be used to estimate the scale of the expected net impact on population health of HPV vaccination.
► At Gavi negotiated prices, HPV vaccination offers positive net health benefits in most of the Gavi-eligible countries included in this study.
► If Gavi-eligible countries faced the same price as non-Gavi eligible countries, providing HPV vaccination would improve overall population health in 13 countries and reduce overall population health in 33 countries imposing a net burden of 38 million disability-adjusted life years.

What do the new findings imply?

► Gavi’s negotiations on behalf of countries eligible for its support have succeeded in making adhering to the WHO guidance around HPV vaccination a beneficial aim for most countries.
► Determining prices using these methods, which account for country-specific health opportunity costs, offers an opportunity to ensure that all countries can benefit from adopting HPV vaccination or other recommendations made by global bodies.
► Assessing the likely scale and distribution of the impact of potential new interventions on net population health, at a particular price, are valuable for informing priorities in developing new healthcare interventions.
interventions in a country—including vaccines, drugs, and diagnostics, as well as prioritising the development of new ones—requires an assessment of whether the improvement in health outcomes they offer exceeds the improvement in health that would have been possible if the resources required had, instead, been made available for other healthcare activities in that country. This potential alternative use of the same resources represents the health opportunity cost of providing the intervention. Without such assessments, there is a danger that blanket recommendations made by international organisations will lead to the adoption of healthcare interventions that are not cost effective in some countries, even given existing donor mechanisms intended to support their affordability.

To assess the health opportunity cost of providing an intervention in a given country, an assessment of the health effects if the additional resources required had, instead, been made available to other healthcare activities is needed. This requires country-specific estimates of the health effects of changes in healthcare expenditure. Such estimates are now available for a limited number of high-income countries based on within-country data and a wider range of high-income as well as low-/middle-income countries (LMICs) based on country-level data. These are typically reported as a cost per quality-adjusted life year (QALY) gained or disability-adjusted life years (DALY) averted.3–13

Comparing the additional cost per QALY gained or DALY averted by an intervention with a binary assessment of whether the intervention produces health at a better (worse) rate than interventions already funded by the healthcare system (HCS)—that is, is below (above) the estimate of cost per QALY gained or DALY averted that reflects health opportunity costs. However, binary assessments such as these obscure valuable information about the scale of the net benefits (or losses) associated with providing or developing an intervention, and other local context-specific important criteria of affordability, budget impact, fairness, and feasibility.14 This is particularly important when assessments of value are made across countries; an intervention may be expected to generate a net benefit in some, but a net loss in others.

Explicit consideration of the trade-offs between, for example, providing an intervention in all versus some countries requires quantifying the scale of the benefits (or losses) across countries. The scale of potential net benefits (or losses) associated with providing an intervention in a country can be measured by the net health impact of the intervention; that is the health that is generated by it minus its health opportunity cost. The health opportunity costs associated with additional healthcare expenditure in each HCS differs depending on for example, the budget for healthcare, efficiency of current spending, demographic structure and epidemiology. As such, the health opportunity cost of providing the same intervention at the same price, even to the same sized population, will be different in different HCS.

To illustrate this, we assess the net health impact to countries of achieving one of the WHO’s proposed 90-70-90 targets for cervical cancer elimination, which includes 90% coverage of human papillomavirus (HPV) vaccination among girls by 15 years of age.15 This paper shows how estimates of the expected additional benefits and costs of HPV vaccination and health opportunity costs can be used to assess the expected net health impact for each country and across countries associated with adhering to the WHO guidance. We also show how these metrics can inform pricing negotiations (eg, between Gavi, the Vaccine Alliance (hereafter Gavi) and manufacturers), and discuss how they may be used to inform the development of new healthcare interventions.

METHODS

Assessing the expected net health impact for each country and across countries requires data on the additional costs and benefits of HPV vaccination for each country and an estimate of the health opportunity costs faced by each country’s HCS. We consider countries that were Gavi eligible in 2019 (the most recent year for which a list of eligible countries is publicly available).16 Estimates of the additional health benefits of HPV vaccination over the period 2020–2029 come from the Papillomavirus Rapid Interface for Modelling and Economics (PRIME) model developed by Jit et al (2014) and recently updated by Abbas et al (2020).17 18 PRIME assumes lifelong vaccine protection, no indirect (herd) effects and no changes to screening programmes.

The additional (ie, net) cost of vaccination ($\Delta C_i$) is made up of the cost of procurement ($\Delta C_p^i$), which is a function of the per dose procurement price and number of doses, the cost of delivering the vaccine in a country ($\Delta C_d^i$), and the cost savings that result from cervical cancers averted ($\Delta C_c^i$)

$$\Delta C_i = \Delta C_p^i + \Delta C_d^i - \Delta C_c^i$$

The market price for HPV vaccine doses in countries not eligible for Gavi support is on average US$25 per dose.19 Below private market rate procurement prices were negotiated by Gavi with HPV vaccine manufacturers, enabling Gavi eligible countries to purchase vaccines through United Nations organisations at US$4.50 per dose.20 21 Countries purchase a share of the vaccines provided while Gavi purchases the remainder. The share funded by Gavi is based on the Gavi cofinancing mechanism depending on the funding phase the country is in.22 We assume two doses per vaccinated girl in line with the WHO recommended schedule for HPV vaccination, and that the per dose price remains constant in real terms over the period 2020–2029.23 Delivery costs are assumed to be US$1.76 per dose (2019 US$) for low-income countries and US$3.87 per dose (2019 US$) for middle-income countries24 (originally in 2013 US$, scaled up...
using gross domestic product (GDP) deflator 2011 Q1 to 2019 Q3 for USA from the US Federal Reserve https://fred.stlouisfed.org/series/GDPDEF). In combination with published estimates of the health opportunity costs faced by different HCS from Ochalek et al (2018), the scale of the net health impact of HPV vaccination by HCS, measured in DALYs averted (net DALYs averted, NDA, where the i subscript denotes each HCS) can be estimated for each HCS. No estimates of the health opportunity costs associated with additional healthcare expenditure are available for 12 countries, limiting our analysis to 46 Gavi-eligible countries.

\[ NDA_i = \Delta DALY_Si - \frac{\Delta C_i}{k_i} \]  

(2)

Net DALYs averted (NDA) for a given HCS is the difference between DALYs averted by an intervention (\(DALY_Si\)) and DALYs that could have been averted with the additional HCS resources required to implement it (\(\frac{\Delta C_i}{k_i}\)) (net of any additional cost savings), where \(k_i\) is the country-specific estimate of health opportunity cost to avert a single DALY. Note that if the net effect of the intervention saves HCS costs, that is, \(\Delta C_i < 0\), then the net DALYs averted is the DALYs averted by the intervention plus the additional DALYs that can also be averted with the cost savings offered.

The scale of the value of the impact can also be reported in terms of the amount of additional healthcare resources which would be required to deliver similar net health impacts (net dollar value, \(NSV\)).

\[ NSV_i = k_i \cdot \Delta DALY_Si - \Delta C_i \]  

(3)

The aggregate net effects of providing the HPV vaccine in a group of countries (eg, all countries in a given income category) can be calculated by summing the estimated net health impact or net dollar value by HCS. For example, where HPV is provided in a group, \(g\), of \(N\) HCS, these can be calculated as follows:

\[ NDA_g = \sum_{i=1}^{N} \Delta DALY_Si - \frac{\Delta C_i}{k_i} \]  

(4)

\[ NSV_g = \sum_{i=1}^{N} k_i \cdot \Delta DALY_Si - \Delta C_i \]  

(5)

An estimate of the health opportunity costs faced by the HCS also enables the calculation of the maximum per dose procurement price, which is calculated by dividing the maximum procurement cost (\(C^P_i\)) by the number of required doses (two doses are required for each person in the cohort), that each HCS could afford to pay for HPV vaccine to ensure that the health lost from the money required to fund it is not greater than the benefit it offers (ie, the cost at which the net dollar value to the HCS would be zero).

\[ \Delta C^P_i = \Delta DALY_Si \cdot k_i - \Delta C^D_i + \Delta C^C_i \]  

(6)

This can be used to inform pricing negotiations between Gavi and manufacturers in a way that ensures that global access could be provided with no net losses for any HCS.

We illustrate how these assessments can be used to inform global guidance or recommendations and pricing negotiations by assessing four potential policy options:

1. Achieving the WHO recommendation of 90% coverage of HPV vaccination in Gavi-eligible countries at the average market per dose procurement prices (US$25 per dose).
2. Informing country-specific per dose procurement prices that would ensure that HPV vaccination generates a net health benefit in each Gavi-eligible country.
3. Informing per dose procurement prices for country groups (ie, low-income and lower middle income) that would ensure that HPV vaccination generates a net health benefit in each Gavi-eligible country.
4. Achieving the WHO recommendation of 90% coverage of HPV vaccination in all Gavi-eligible countries at current Gavi-negotiated per dose procurement prices (US$4.50 per dose) first assuming current levels of support for procurement (option 4a) and second, assuming no procurement support (option 4b).

Policy option 1 reflects the implementation of blanket recommendations for providing an intervention for an entire set of countries (see, eg, World Health Organization, 2020). Policy option 4 reflects the practice of negotiating prices to support countries in complying with recommendations. Policy options 2 and 3 reflect potential methods for determining prices.

While all Gavi funded countries face the same per dose price (US$4.50) for HPV vaccines, most Gavi-funded countries pay for only a portion of the vaccines they purchase while the remainder are funded by Gavi. The share funded by Gavi is based on a co-financing mechanism, and differs for each country depending on the funding phase the country is in and its per capita income. In the first instance, we assume current Gavi-negotiated per dose procurement prices and with current levels of support (policy option 4a). Since data on the proportion of vaccines purchased by Gavi are not publicly available, we have calculated them based on the number of years a country has been a Gavi funding recipient and the countries’ gross national income (GNI) per capita in each of those years (see online supplemental appendix 1). Second, we assess this scenario assuming that countries pay 100% of the vaccine procurement costs (ie, US$4.50 per dose; which we term policy option 4b). Delivery costs are the same for each option and are current delivery costs.

We also undertake sensitivity analyses around discount rates and the estimates of the marginal productivity of HCSs used. Global guidance recommends that where country guidance is lacking either 0% for health benefits and 3% for costs or 3% for both are used as discount rates. Following common practice, our base case for each policy option applies a discount rate of 3% to both costs and benefits and we assess the results where 0% is applied to health benefits in sensitivity analysis. Our base case uses the central estimate of health opportunity cost for each country from Ochalek et al. We...
also assess each policy option using the minimum and maximum estimates of cost per DALY for each country from Ochalek et al (2018) as a sensitivity analysis. The total net health impact across all countries for the first policy option, where HPV vaccination is implemented in all countries at current market prices, is calculated by aggregating the NDA for each country from equation 2.

The second policy option entails calculating the maximum price each HCS could afford to pay for HPV vaccination to be a cost-effective use of resources in that HCS if it is not already cost effective at average market price (US$25 per dose). This is calculated by determining the maximum total vaccination procurement cost a country can afford to pay, which is the monetary value of the expected health gains of HPV vaccination net of the difference between the delivery costs and cancer treatment costs averted (as set forth in equation 6).

The third policy option, to set a price by HCS group (eg, income group) rather than by country, is also informed by equation 6, but the lowest maximum price affordable from among a group of countries is applied to all countries in the group.

The fourth policy option reflects the total net health impact of implementing HPV vaccination in all countries at Gavi negotiated prices and with current levels of Gavi support (policy option 4a) or at Gavi negotiated prices without procurement support (policy option 4b) and is calculated by aggregating the NDA for each country from equation 2.

RESULTS
Figure 1A plots the health gains from the vaccine against the health opportunity cost for each country of achieving the WHO recommendation of 90% coverage of HPV vaccination in all Gavi-eligible countries at average market per dose procurement prices (US$25 per dose) and given current delivery costs (policy option 1). The diagonal line indicates zero net health impact, and (black) points that fall above it refer to countries which have a positive net health impact while (grey) points that fall below it refer to countries which have a negative net health impact.

What is evident is that at this price HPV vaccine results in net health losses in most countries. More countries are below the zero net impact line than above it. The distance between a point above (below) the line and the line is the net health gain (loss) that would result from providing the intervention. There are net health gains in some countries (totalling 2 million DALYS averted); however, these are offset by the net health losses in others (totalling –40 million DALYS averted (see table 1 column 1).

If HPV vaccination were provided only in those countries where it does not reduce overall net health at current average market price, it would be implemented in only 2 of 22 low-income countries and 11 of 24 lower middle income countries where it would generate a net health benefit. While there is a clear benefit to this policy option (ie, it would ensure that overall health across the countries increases as a result of the recommendation, and health is not reduced anywhere), it unlikely to be politically feasible or appealing to restrict access in this way. It may also not be seen as equitable to provide vaccination only to countries that can afford to pay a uniform price for it.

Pricing arrangements that ensure that HPV vaccine generates a net health benefit for each country requires calculating the per dose price at which HPV vaccination would be cost effective in each HCS for which it is not at US$25 per dose (policy option 2). This is visualised in figure 1B, where all of the countries that previously had negative net health impact (as denoted by grey points in figure 1A) are now on the zero net impact line.

Table 2 reports the per dose price at which HPV vaccination would be cost effective in each HCS for which it

Figure 1  (A) Net health impact in Gavi-eligible countries. (B) Net health impact in Gavi-eligible countries after country-specific subsidies. DALYs, disability-adjusted life years; HPV, human papillomavirus; MICs, middle-income countries.
Table 1  Net health impact and net monetary impact at three prices

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Benin</td>
<td>Low income</td>
<td>-222</td>
<td>-47212</td>
<td>98</td>
<td>20749</td>
<td>42</td>
<td>8965</td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>Low income</td>
<td>-232</td>
<td>-37900</td>
<td>526</td>
<td>85735</td>
<td>394</td>
<td>64298</td>
</tr>
<tr>
<td>Burundi</td>
<td>Low income</td>
<td>-164</td>
<td>-19599</td>
<td>453</td>
<td>54223</td>
<td>346</td>
<td>41423</td>
</tr>
<tr>
<td>Chad</td>
<td>Low income</td>
<td>-576</td>
<td>-85115</td>
<td>120</td>
<td>17705</td>
<td>-1</td>
<td>-123</td>
</tr>
<tr>
<td>Democratic Republic of the Congo</td>
<td>Low income</td>
<td>-7746</td>
<td>-495691</td>
<td>975</td>
<td>62387</td>
<td>-537</td>
<td>-34377</td>
</tr>
<tr>
<td>Eritrea</td>
<td>Low income</td>
<td>-114</td>
<td>-15648</td>
<td>21</td>
<td>2854</td>
<td>-3</td>
<td>-354</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>Low income</td>
<td>-1944</td>
<td>-397625</td>
<td>1049</td>
<td>214497</td>
<td>530</td>
<td>108363</td>
</tr>
<tr>
<td>Gambia</td>
<td>Low income</td>
<td>-12</td>
<td>-3732</td>
<td>35</td>
<td>10652</td>
<td>27</td>
<td>8158</td>
</tr>
<tr>
<td>Guinea</td>
<td>Low income</td>
<td>-276</td>
<td>-36630</td>
<td>294</td>
<td>39031</td>
<td>195</td>
<td>25912</td>
</tr>
<tr>
<td>Guinea Bissau</td>
<td>Low income</td>
<td>-151</td>
<td>-9399</td>
<td>27</td>
<td>1701</td>
<td>-4</td>
<td>-223</td>
</tr>
<tr>
<td>Haiti</td>
<td>Low income</td>
<td>-216</td>
<td>-38111</td>
<td>53</td>
<td>9297</td>
<td>6</td>
<td>1077</td>
</tr>
<tr>
<td>Madagascar</td>
<td>Low income</td>
<td>-1012</td>
<td>-82141</td>
<td>822</td>
<td>66750</td>
<td>504</td>
<td>40934</td>
</tr>
<tr>
<td>Malawi</td>
<td>Low income</td>
<td>163</td>
<td>24257</td>
<td>896</td>
<td>133320</td>
<td>769</td>
<td>114410</td>
</tr>
<tr>
<td>Mali</td>
<td>Low income</td>
<td>-1085</td>
<td>-89221</td>
<td>458</td>
<td>37691</td>
<td>191</td>
<td>15666</td>
</tr>
<tr>
<td>Mozambique</td>
<td>Low income</td>
<td>38</td>
<td>9024</td>
<td>836</td>
<td>196248</td>
<td>698</td>
<td>163786</td>
</tr>
<tr>
<td>Nepal</td>
<td>Low income</td>
<td>-172</td>
<td>-46634</td>
<td>217</td>
<td>58934</td>
<td>150</td>
<td>40630</td>
</tr>
<tr>
<td>Niger</td>
<td>Low income</td>
<td>-1,505</td>
<td>-157478</td>
<td>69</td>
<td>7267</td>
<td>-204</td>
<td>-21298</td>
</tr>
<tr>
<td>Rwanda</td>
<td>Low income</td>
<td>-55</td>
<td>-14362</td>
<td>207</td>
<td>54440</td>
<td>162</td>
<td>42511</td>
</tr>
<tr>
<td>Sierra Leone</td>
<td>Low income</td>
<td>-320</td>
<td>-39693</td>
<td>23</td>
<td>2802</td>
<td>-37</td>
<td>-4566</td>
</tr>
<tr>
<td>Togo</td>
<td>Low income</td>
<td>-250</td>
<td>-35745</td>
<td>64</td>
<td>9176</td>
<td>10</td>
<td>1387</td>
</tr>
<tr>
<td>Uganda</td>
<td>Low income</td>
<td>-454</td>
<td>-64882</td>
<td>1523</td>
<td>217831</td>
<td>1180</td>
<td>168813</td>
</tr>
<tr>
<td>Yemen</td>
<td>Low income</td>
<td>-627</td>
<td>-157748</td>
<td>-37</td>
<td>-9388</td>
<td>-125</td>
<td>-31390</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>Lower middle income</td>
<td>-3,406</td>
<td>-504494</td>
<td>301</td>
<td>44653</td>
<td>-309</td>
<td>-45704</td>
</tr>
<tr>
<td>Cambodia</td>
<td>Lower middle income</td>
<td>-197</td>
<td>-50702</td>
<td>63</td>
<td>16229</td>
<td>20</td>
<td>5079</td>
</tr>
<tr>
<td>Cameroon</td>
<td>Lower middle income</td>
<td>-736</td>
<td>-94408</td>
<td>373</td>
<td>47898</td>
<td>228</td>
<td>29285</td>
</tr>
<tr>
<td>Comoros</td>
<td>Lower middle income</td>
<td>6</td>
<td>1861</td>
<td>21</td>
<td>6122</td>
<td>19</td>
<td>5565</td>
</tr>
<tr>
<td>Côte d’Ivoire</td>
<td>Lower middle income</td>
<td>-346</td>
<td>-85109</td>
<td>239</td>
<td>58651</td>
<td>152</td>
<td>37331</td>
</tr>
<tr>
<td>Ghana</td>
<td>Lower middle income</td>
<td>3</td>
<td>1344</td>
<td>276</td>
<td>127469</td>
<td>276</td>
<td>127469</td>
</tr>
<tr>
<td>India</td>
<td>Lower middle income</td>
<td>-8,392</td>
<td>-2814745</td>
<td>2888</td>
<td>968749</td>
<td>2368</td>
<td>794116</td>
</tr>
<tr>
<td>Kenya</td>
<td>Lower middle income</td>
<td>307</td>
<td>188020</td>
<td>744</td>
<td>455613</td>
<td>673</td>
<td>412218</td>
</tr>
<tr>
<td>Kyrgyzstan</td>
<td>Lower middle income</td>
<td>17</td>
<td>14386</td>
<td>50</td>
<td>43895</td>
<td>44</td>
<td>38919</td>
</tr>
<tr>
<td>Continued</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Country</td>
<td>Income category</td>
<td>US$25 per dose (options 1 and 2)</td>
<td>Gavi procurement support (per dose price differs by country, all ≤US$4.50, option 4a)</td>
<td>US$4.50 per dose (option 4b)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------</td>
<td>----------------------------------</td>
<td>---------------------------------------------------------------------------------</td>
<td>------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lesotho</td>
<td>Lower middle income</td>
<td>22</td>
<td>15009</td>
<td>34</td>
<td>23484</td>
<td>32</td>
<td>22375</td>
</tr>
<tr>
<td>Mauritania</td>
<td>Lower middle income</td>
<td>-11</td>
<td>-3685</td>
<td>61</td>
<td>20443</td>
<td>50</td>
<td>16865</td>
</tr>
<tr>
<td>Nicaragua</td>
<td>Lower middle income</td>
<td>36</td>
<td>97972</td>
<td>44</td>
<td>118524</td>
<td>44</td>
<td>118524</td>
</tr>
<tr>
<td>Nigeria</td>
<td>Lower middle income</td>
<td>-2783</td>
<td>-724904</td>
<td>979</td>
<td>255030</td>
<td>979</td>
<td>255030</td>
</tr>
<tr>
<td>Pakistan</td>
<td>Lower middle income</td>
<td>-6147</td>
<td>-999875</td>
<td>-174</td>
<td>-28328</td>
<td>-1085</td>
<td>-176560</td>
</tr>
<tr>
<td>Republic of Congo</td>
<td>Lower middle income</td>
<td>9</td>
<td>13848</td>
<td>26</td>
<td>39162</td>
<td>26</td>
<td>39162</td>
</tr>
<tr>
<td>Republic of Sudan</td>
<td>Lower middle income</td>
<td>-555</td>
<td>-206489</td>
<td>-42</td>
<td>-15482</td>
<td>-42</td>
<td>-15482</td>
</tr>
<tr>
<td>Senegal</td>
<td>Lower middle income</td>
<td>79</td>
<td>28645</td>
<td>335</td>
<td>121002</td>
<td>300</td>
<td>108298</td>
</tr>
<tr>
<td>South Sudan</td>
<td>Lower middle income</td>
<td>-39</td>
<td>-14613</td>
<td>122</td>
<td>45478</td>
<td>96</td>
<td>35491</td>
</tr>
<tr>
<td>Tajikistan</td>
<td>Lower middle income</td>
<td>-104</td>
<td>-43036</td>
<td>12</td>
<td>4919</td>
<td>-7</td>
<td>-2272</td>
</tr>
<tr>
<td>Tanzania</td>
<td>Lower middle income</td>
<td>751</td>
<td>212282</td>
<td>1989</td>
<td>562400</td>
<td>1775</td>
<td>502045</td>
</tr>
<tr>
<td>Uzbekistan</td>
<td>Lower middle income</td>
<td>-7</td>
<td>-8595</td>
<td>74</td>
<td>96739</td>
<td>74</td>
<td>96739</td>
</tr>
<tr>
<td>Vietnam</td>
<td>Lower middle income</td>
<td>-32</td>
<td>-52974</td>
<td>109</td>
<td>181915</td>
<td>109</td>
<td>181915</td>
</tr>
<tr>
<td>Zambia</td>
<td>Lower middle income</td>
<td>356</td>
<td>190274</td>
<td>527</td>
<td>281374</td>
<td>525</td>
<td>280238</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>Lower middle income</td>
<td>129</td>
<td>33316</td>
<td>446</td>
<td>115670</td>
<td>395</td>
<td>102315</td>
</tr>
<tr>
<td><strong>Low-income countries</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total net benefits</td>
<td></td>
<td>201</td>
<td>33281</td>
<td>8766</td>
<td>1303289</td>
<td>5203</td>
<td>846353</td>
</tr>
<tr>
<td>Total net losses</td>
<td></td>
<td>-17134</td>
<td>-1874568</td>
<td>-37</td>
<td>-9388</td>
<td>-909</td>
<td>-92332</td>
</tr>
<tr>
<td>Total net impact</td>
<td></td>
<td>-16932</td>
<td>-1841287</td>
<td>8728</td>
<td>1293901</td>
<td>4294</td>
<td>754021</td>
</tr>
<tr>
<td><strong>Lower middle income countries</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total net benefits</td>
<td></td>
<td>1715</td>
<td>797406</td>
<td>9714</td>
<td>3635420</td>
<td>8185</td>
<td>3209078</td>
</tr>
<tr>
<td>Total net losses</td>
<td></td>
<td>-22755</td>
<td>-5603628</td>
<td>-216</td>
<td>-43809</td>
<td>-1442</td>
<td>-240472</td>
</tr>
<tr>
<td>Total net impact</td>
<td></td>
<td>-21041</td>
<td>-4806222</td>
<td>9498</td>
<td>3591610</td>
<td>6743</td>
<td>2966006</td>
</tr>
<tr>
<td><strong>All countries</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total net benefits</td>
<td></td>
<td>1916</td>
<td>830687</td>
<td>18479</td>
<td>4938709</td>
<td>13388</td>
<td>4055431</td>
</tr>
<tr>
<td>Total net losses</td>
<td></td>
<td>-39889</td>
<td>-7478196</td>
<td>-253</td>
<td>-53198</td>
<td>-2351</td>
<td>-332803</td>
</tr>
<tr>
<td>Total net impact</td>
<td></td>
<td>-37973</td>
<td>-6647509</td>
<td>18226</td>
<td>485511</td>
<td>11036</td>
<td>3722627</td>
</tr>
<tr>
<td>Country</td>
<td>Income group</td>
<td>Per dose price reduction required (2019 US$)</td>
<td>Cohort size (1000s)</td>
<td>Total reduction using country-specific price (1000s, 2019 US$, option 2)</td>
<td>Total reduction using country income group price (1000s, US$1 for low-income countries, US$0 for lower middle income countries, 2019 US, option 3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>--------------</td>
<td>---------------------------------------------</td>
<td>---------------------</td>
<td>---------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benin</td>
<td>Low</td>
<td>18</td>
<td>1567</td>
<td>57749</td>
<td>80661</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>Low</td>
<td>10</td>
<td>2851</td>
<td>57074</td>
<td>146744</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burundi</td>
<td>Low</td>
<td>9</td>
<td>1703</td>
<td>31075</td>
<td>87647</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chad</td>
<td>Low</td>
<td>21</td>
<td>2372</td>
<td>101129</td>
<td>122104</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Democratic Republic of the Congo</td>
<td>Low</td>
<td>23</td>
<td>12881</td>
<td>582915</td>
<td>663039</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eritrea</td>
<td>Low</td>
<td>22</td>
<td>425</td>
<td>18430</td>
<td>21877</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethiopia</td>
<td>Low</td>
<td>17</td>
<td>14104</td>
<td>491992</td>
<td>725995</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gambia</td>
<td>Low</td>
<td>9</td>
<td>332</td>
<td>5981</td>
<td>17090</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guinea</td>
<td>Low</td>
<td>14</td>
<td>1744</td>
<td>48351</td>
<td>89790</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guinea Bissau</td>
<td>Low</td>
<td>22</td>
<td>256</td>
<td>11104</td>
<td>13159</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haiti</td>
<td>Low</td>
<td>21</td>
<td>1088</td>
<td>45173</td>
<td>55990</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Madagascar</td>
<td>Low</td>
<td>15</td>
<td>3434</td>
<td>105294</td>
<td>176781</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Malawi</td>
<td>Low</td>
<td>0</td>
<td>2510</td>
<td>0</td>
<td>129186</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mali</td>
<td>Low</td>
<td>19</td>
<td>2927</td>
<td>108948</td>
<td>150676</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mozambique</td>
<td>Low</td>
<td>2</td>
<td>4319</td>
<td>20123</td>
<td>222326</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nepal</td>
<td>Low</td>
<td>13</td>
<td>2418</td>
<td>62126</td>
<td>124454</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Niger</td>
<td>Low</td>
<td>24</td>
<td>3811</td>
<td>183674</td>
<td>196160</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rwanda</td>
<td>Low</td>
<td>8</td>
<td>1587</td>
<td>25035</td>
<td>81666</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sierra Leone</td>
<td>Low</td>
<td>24</td>
<td>978</td>
<td>46162</td>
<td>50321</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Togo</td>
<td>Low</td>
<td>21</td>
<td>1034</td>
<td>42623</td>
<td>53232</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uganda</td>
<td>Low</td>
<td>8</td>
<td>6512</td>
<td>108355</td>
<td>335200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yemen</td>
<td>Low</td>
<td>26</td>
<td>3515</td>
<td>180923</td>
<td>180923</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bangladesh</td>
<td>Lower middle</td>
<td>23</td>
<td>12719</td>
<td>592799</td>
<td>645928</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cambodia</td>
<td>Lower middle</td>
<td>20</td>
<td>1549</td>
<td>61602</td>
<td>78677</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cameroon</td>
<td>Lower middle</td>
<td>17</td>
<td>3447</td>
<td>119244</td>
<td>175050</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comoros</td>
<td>Lower middle</td>
<td>0</td>
<td>103</td>
<td>0</td>
<td>5236</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Côte d’Ivoire</td>
<td>Lower middle</td>
<td>16</td>
<td>3418</td>
<td>110006</td>
<td>173553</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ghana</td>
<td>Lower middle</td>
<td>3</td>
<td>3511</td>
<td>23785</td>
<td>178321</td>
<td></td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>Lower middle</td>
<td>18</td>
<td>100082</td>
<td>3511214</td>
<td>5082526</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kenya</td>
<td>Lower middle</td>
<td>0</td>
<td>6225</td>
<td>0</td>
<td>316137</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kyrgyzstan</td>
<td>Lower middle</td>
<td>0</td>
<td>669</td>
<td>0</td>
<td>33951</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lesotho</td>
<td>Lower middle</td>
<td>0</td>
<td>205</td>
<td>0</td>
<td>10408</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mauritania</td>
<td>Lower middle</td>
<td>7</td>
<td>573</td>
<td>7837</td>
<td>29105</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nicaragua</td>
<td>Lower middle</td>
<td>0</td>
<td>570</td>
<td>0</td>
<td>28958</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nigeria</td>
<td>Lower middle</td>
<td>17</td>
<td>27327</td>
<td>922743</td>
<td>1387758</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pakistan</td>
<td>Lower middle</td>
<td>25</td>
<td>22940</td>
<td>1164963</td>
<td>1164963</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Republic of Congo</td>
<td>Lower middle</td>
<td>0</td>
<td>705</td>
<td>0</td>
<td>35787</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Republic of Sudan</td>
<td>Lower middle</td>
<td>23</td>
<td>5322</td>
<td>244785</td>
<td>270266</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Senegal</td>
<td>Lower middle</td>
<td>0</td>
<td>2219</td>
<td>0</td>
<td>112695</td>
<td></td>
<td></td>
</tr>
<tr>
<td>South Sudan</td>
<td>Lower middle</td>
<td>9</td>
<td>1399</td>
<td>24665</td>
<td>71023</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tajikistan</td>
<td>Lower middle</td>
<td>23</td>
<td>1125</td>
<td>51199</td>
<td>57107</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tanzania</td>
<td>Lower middle</td>
<td>0</td>
<td>8087</td>
<td>0</td>
<td>410661</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uzbekistan</td>
<td>Lower middle</td>
<td>5</td>
<td>2929</td>
<td>29386</td>
<td>148753</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vietnam</td>
<td>Lower middle</td>
<td>8</td>
<td>6530</td>
<td>99216</td>
<td>331607</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Continued
is not at US$25 per dose. That is the maximum that the country could afford to pay per dose for HPV vaccination to generate zero net benefit (ie, no net loss in overall population health, but also no net benefit). Among countries where a price reduction is required, the price reduction ranges from US$2 to US$26 (2019 US). If the vaccine manufacturer and/or a global donor were to fund the difference for both doses for all eligible girls for each country, it would cost US$9.3 billion (2019 US). The same money could avert 49 million DALYs if spent on existing interventions in these countries instead.

Alternatively, prices might be negotiated by country groups, such as income category if it is not possible to have country-specific pricing arrangements (policy option 3). In order to ensure providing HPV vaccination in all countries within an income group (or any group for that matter) generates a net benefit, or at minimum no net loss in overall population health, requires applying the lowest price required for HPV vaccination to be cost effective in any of the countries in the group to all countries in the group. This would be US$−1 per dose (2019 US) in low-income countries and US$0 per dose (2019 US) in lower middle-income countries. If the manufacturer and/or a global donor were to fund the difference for each country, it would cost US$14.7 billion (2019 US). More net health benefits would be generated across countries than from option 2; however, the same money could avert 70 million DALYs if spent on existing interventions in these countries instead.

The net health impact and net monetary impact of achieving the WHO recommendation of 90% coverage of HPV vaccination in all Gavi-eligible countries at current Gavi-negotiated prices (US$4.50 per dose, 2019 US), with current delivery costs and existing levels of Gavi procurement support, where many countries pay below US$4.50 per dose, are presented in Table 1 (columns 3 and 4). This represents existing policy (policy option 4a) and offers positive net health impact for all but three countries, implying that at current prices and levels of Gavi support HPV vaccination generates a health benefit over and above any loss incurred as a result of the money required to fund it not being available to fund other healthcare interventions for most countries. Without the Gavi procurement support (ie, at a per dose price of US$4.50 (2019 US) for all countries, option 4b), HPV vaccination generates a net health loss in eight more countries than it would with the Gavi procurement support (see Table 1 columns 5 and 6).

**Sensitivity analyses**

Our analysis used a discount rate of 3% for costs and benefits following common practice. While this is in line with the WHO guidance, the guidance also recommends a sensitivity analysis where health is undiscounted but costs are discounted at 3%. The resulting net health impact estimates for this sensitivity analysis are reported against the base case in online supplemental appendix table 1 and the price reductions required are reported against the base case in online supplemental appendix table 2. The health benefits of HPV vaccination often occur in future years (eg, cancer cases are averted up to decades after the vaccine has been administered). Since greater weight is attached to future health outcomes when they are undiscounted, discounting the health benefits from HPV vaccination has the effect of reducing their net present value. Therefore, HPV vaccination appears better value when no discounting is applied to health benefits. The per dose price reduction required in order for HPV vaccination to generate zero net benefit (ie, no net loss in overall population health, but also no net benefit) in countries where it generates a net loss at average market price are also lower (and more often zero or not required at all) than when a 3% discount rate is used for health benefits. If country-specific pricing were possible, the total price reduction required (ie, for all doses for all eligible girls across all countries where a price required is required) would be less than a third of that required when a 3% discount rate is applied to health benefits. Where country income-group pricing is applied, the difference in funding required is lower at US$11.6 billion (compared with US$14.7 billion when a 3% discount rate is applied to health benefits). The price for low-income countries would be US$2 per dose and for lower middle income countries it would be US$6 per dose (2019 US).

<table>
<thead>
<tr>
<th>Country</th>
<th>Income group</th>
<th>Per dose price reduction required (2019 US$)</th>
<th>Cohort size (1000s)</th>
<th>Total reduction using country-specific price (1000s, 2019 US$)</th>
<th>Total reduction using country income group price (1000s, US$1−1 for low-income countries, US$0 for lower middle income countries, 2019 US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zambia</td>
<td>Lower middle</td>
<td>0</td>
<td>2506</td>
<td>0</td>
<td>127.288</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>Lower middle</td>
<td>0</td>
<td>1911</td>
<td>0</td>
<td>97.035</td>
</tr>
<tr>
<td>Low-income countries</td>
<td></td>
<td>2334238</td>
<td></td>
<td>3725020</td>
<td></td>
</tr>
<tr>
<td>Lower middle income countries</td>
<td></td>
<td>6963445</td>
<td></td>
<td>10972795</td>
<td></td>
</tr>
<tr>
<td>All countries</td>
<td></td>
<td>9297682</td>
<td></td>
<td>14697815</td>
<td></td>
</tr>
</tbody>
</table>
Our analysis uses the central estimate of the marginal productivity of each HCS from the range estimated by Ochalek et al. As a sensitivity analysis, we use the minimum and maximum from the ranges for each country. Using the minimum (maximum) estimate for each country will tell us the maximum (minimum) health opportunity cost expected from adopting HPV vaccination and therefore lowest (highest) estimate of net health benefit from it for each country. The results of this sensitivity analysis are reported in online supplementary appendix tables 3 and 4. Using the minimum or maximum makes little overall difference to the number of countries for which HPV vaccination would be expected to generate a net health benefit. Among low-income countries, at market price (US$25 per dose) one fewer low-income country would be estimated to have a net health benefit from adopting HPV vaccination when the minimum estimate of the marginal productivity of each HCS is used. Results do not change when current per dose procurement prices are used (as in option 4a), but when the price is US$4.50 per dose (option 4b) three additional low-income countries would expect a net health benefit when the maximum estimate of the marginal productivity of each HCS is used while one fewer would expect a net health benefit when the minimum is used (compared with the central estimate). Among lower middle income countries adopting HPV vaccination would be estimated to generate a net health benefit in one fewer (more) country when the minimum (maximum) estimate of the marginal productivity of each HCS is used at market price (US$25 per dose), but results do not change when current per dose procurement prices (as in policy option 4a) or US$4.50 per dose (policy option 4b) are used. Even when introducing HPV vaccination would result in net health benefit for the same number of countries regardless of whether the minimum, central or maximum estimate is used, the magnitude of the net health benefit differs. The estimated net health benefits (losses) are greatest (lowest) when using the maximum estimate of health opportunity cost from the range. The price reduction required for HPV vaccination to generate a net health benefit in all countries is higher (lower) when using the minimum (maximum) estimate of health opportunity costs. When the minimum estimate is used the per dose price reduction required in both low-income and lower middle income countries is US$26 (2019 US; ie, the maximum that the country that can least afford to adopt HPV vaccination can afford to pay is US$1–1 per dose). When the maximum estimates of health opportunity cost are used, the price reductions required for low-income and lower middle-income countries are US$26 and US$25 (2019 US), respectively, which is the same as the base case (ie, when the central estimate is used). When country-specific pricing is used (as in policy option 2), this amounts to a total of US$8.6 billion to US$9.9 billion in funding required when the maximum and minimum estimates are used, respectively. When country income group pricing is used (as in policy option 3), this amounts to a total of US$14.5 billion to US$14.8 billion in funding required when the maximum and minimum estimates are used, respectively.

**DISCUSSION**

The analysis undertaken enables an assessment of blanket recommendations (in order to, eg, inform whether, at current prices, they would be expected to improve health in all countries); an assessment of the price reduction (if any) required for a healthcare intervention to generate at minimum no net health loss; and the value of developing new healthcare interventions.

Previous analyses have used a GDP per capita threshold to judge the cost effectiveness of adopting HPV vaccination and eliminating cervical cancer. The GDP per capita threshold originates from human capital arguments made by the WHO Commission on Macroeconomics and Health around the value of a year of life. However, WHO no longer recommends it for country evaluations on the basis that it may not reflect country priorities and decision-making processes. Estimates of the marginal productivity of HCSs reflect health opportunity cost and tend to be lower than GDP per capita, and so using a GDP per capita threshold to make decisions can lead to net health losses. Indeed, in practice, low-income countries’ actual decisions to introduce HPV vaccination, or not, reveal an implicit cost-effectiveness threshold of 30%–35% of GDP per capita. Reassuringly, our results show that HPV vaccination remains cost-effective for most countries at current Gavi negotiated prices when a threshold that reflects the health opportunity cost faced by the country is used (rather than human capital arguments about the value of health spending). Although there is uncertainty around existing estimates of the marginal productivity of HCSs, using the minimum or maximum from the range of estimates from Ochalek et al (2018) has little impact on the results.

A blanket recommendation to introduce HPV vaccination in LMICs would result in net health losses in most countries in the absence of Gavi support. This was analysed under the assumption that these countries would face the average market price faced by countries not eligible for Gavi support. Manufacturers might be able to price discriminate (ie, using tiered pricing policy), reducing prices for these countries. However, there is no guarantee that in the absence of pooled procurement and market shaping efforts by organisations like Gavi lower-income countries would pay lower prices. The extent to which prices would be lower than the average market price among high-income countries in the absence of Gavi support is unclear but would result in better net health impacts, while higher prices would result in worse net health impacts. It is worth noting that our estimate for policy option 1 being conservative or optimistic has no implications for comparisons between policy options 2, 3, 4a and 4b.
The current reality of vaccine procurement prices paid by countries likely falls somewhere between policy options 2 and 4. Policy option 4 assumed all countries pay S$4.50 per dose or less (as countries purchase a share of the vaccines provided while Gavi purchases the remainder). The share funded by Gavi is based on the Gavi cofinancing mechanism depending on the funding phase the country is in (based on country income level and years of funding) rather than reflecting health opportunity costs as in policy option 2. However, in practice, countries may not meet their cofinancing requirements. Gavi funding a greater proportion of vaccines would have the effect of reducing the per dose price below the prices used in 4a, and all else the same the vaccine would generate a more positive net impact in those countries. Determining prices using a more systematic method of accounting for opportunity costs, as illustrated in policy option 2, offers an opportunity to ensure that countries that do not benefit from adopting HPV vaccination at current prices would be able to introduce it without facing a reduction in population health. Future research could seek to establish the best way for donors to support the affordability of interventions, which would require information on the opportunity cost of donor financial support and the loss of revenue for the manufacturers of vaccine, in addition to the transaction costs associated with implementing donor support mechanisms.

This type of analysis can also help to inform the value of developing a new healthcare intervention that does not yet exist. For example, the Bill and Melinda Gates Foundation funds the development of new healthcare interventions targeted towards the leading causes of death and disability in LMICs. While a more uncertain prospect at this earlier stage, estimating the price at which a healthcare intervention would have a positive net health impact in each HCS (as in policy option 2) can help to inform whether it should be considered for development by the foundation, through comparison with the cost of the intervention to the provider. Using the expected net health impact of different potential healthcare interventions (and how this is distributed across countries) to rank potential investments would ensure that new healthcare interventions which are likely to generate the greatest health gains offered at affordable prices are prioritised over others. Value of information analysis provides a means to prioritise future research to resolve uncertainties with the new healthcare interventions under consideration for development. However, the development of a new healthcare intervention may be seen to address multiple objectives in addition to improving overall population health. This framework could be extended to incorporate other objectives, such as equity, following, for example, extended or distributional cost-effectiveness analysis methods. In fact, prioritisation decisions for both vaccine research and development (eg, the Vaccine Innovation Prioritisation Strategy) and financing for adoption (eg, the Gavi Investment Strategy) use a kind of multicriteria decision analysis that considers cost effectiveness alongside multiple other criteria.

Equity concerns may also be relevant for interventions for which a net health benefit is generated in some, but not all, countries in which it is recommended. The benefit associated with providing HPV vaccination in some countries may outweigh the losses in other countries if, for example, to reflect equity being another objective in decision-making more weight is given to gains in low-income countries and this is where the bulk of the gains are. Assessing the net health impact of providing a healthcare intervention for each country enables decision-makers to be explicit about the trade-offs being made if, for example, net health losses were incurred in some low-income countries but no lower middle income countries. If more weight was put on outcomes in low-income countries, a blanket recommendation of providing the healthcare intervention would appear to be less favourable as policy choice if the price was the same in all countries as this is where a disproportionately larger amount of the overall losses in net health would be incurred.

The results are sensitive to the discount rate used. The WHO recommends initially using the discount rate used in the country, and where national guidelines do not exist recommends two scenarios: our base case (ie, 3% discounting for both health and consumption) and sensitivity analysis (ie, 3% and 0% discounting for consumption and health, respectively). However, application of the same discount rates for all countries is unlikely to be appropriate. Where the objective is improving population health, for example, the appropriate discount rate for health for each country should depend on the rate at which the principal can borrow and save and the expected growth in the marginal productivity of the HCS — both of which would be expected to vary by country. To date, there are no data on the expected growth in the marginal productivity of the HCS, and this should be a priority for future research.

CONCLUSION

This paper illustrates how estimates of the net health impact or, equivalently, net monetary value of providing a healthcare intervention can be used to estimate the expected effect to overall population health in a country of adhering to global guidance and inform negotiations with donors, as well as informing pricing negotiations and the value of developing new healthcare interventions. At Gavi negotiated prices, HPV vaccination generates net health benefits across nearly all Gavi-eligible countries included in this study. However, if Gavi-eligible countries faced the same price as non-Gavi eligible countries, providing HPV vaccination would reduce overall population health in all but two low-income and nearly half of lower middle income countries and impose a net DALY burden of 38 million DALYs globally. This suggests that Gavi’s negotiations on behalf of countries eligible for its support have succeeded in making adhering to the
WHO guidance around HPV vaccination a worthy aim for most countries. Assessing the likely scale and distribution of the impact of potential new interventions on net population health, at a particular price, can also inform priorities in developing new technologies. The maximum price each country could afford to pay for HPV vaccination to be cost effective can be calculated as can the net health benefit that would be expected to be generated at different potential prices. Determining prices using these methods, which account for country-specific opportunity costs, offers an opportunity to ensure that all countries can benefit from adopting HPV vaccination or other recommendations made by global bodies. Finally, the methods used here can be applied to assess the value of developing a new technology. It will also depend on not only the expected costs and benefits of the new technology for each country in which it may be implemented, but as well the likely health opportunity costs in those countries.

Contributors J0 undertook the analysis and wrote the initial draft. KA, KC, MJ and JL contributed equally to developing the analysis plan, the review and interpretation of results and the final drafting of the manuscript.

Funding This study is funded by Vaccine Impact Modelling Consortium (OPP1157270), Bill and Melinda Gates Foundation (OPP1165566).

Competing interests None declared.

Patient and public involvement Patients and/or the public were not involved in the design, conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Not required.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available in a public, open access repository. Data on the costs and benefits of HPV vaccination across countries are output from the PRIME Tool, which can be accessed at https://github.com/lshtm-prime/prime. Country-specific estimates of the health effects of changes in health care expenditure can be accessed at https://www.york.ac.uk/che/research/tehtta/health-opportunity-costs/estimating-health-opportunity-costs-for-lmics/#tab-4.

Open access This is an open access article distributed in accordance with the Creative Commons Attribution 4.0 Unported (CC BY 4.0) license, which permits others to copy, redistribute, remix, transform and build upon this work for any purpose, provided the original work is properly cited, a link to the licence is given, and indication of whether changes were made. See: https://creativecommons.org/licenses/by/4.0/.

ORCID iDs
Jessica Ochalek http://orcid.org/0000-0003-0744-1178
Kaja Abbas http://orcid.org/0000-0003-0563-1576
Karl Claxton http://orcid.org/0000-0003-2002-4694
Mark Jit http://orcid.org/0000-0001-6658-8255
James Lomas http://orcid.org/0000-0002-2478-7018

REFERENCES

21 Gavi The Vaccine Alliance. HPV supply and procurement roadmap: the market shaping goal shape vaccine markets to ensure adequate supply of appropriate, quality vaccines at low and sustainable prices for developing countries. human papilloma virus vaccine, 2017.
22 Gavi The Vaccine Alliance. Application guidelines: gavi’s support to countries, 2019.


Supplementary Appendix 1. Calculated per dose price

Estimates of the additional cost of HPV vaccination reflect the three phases of the Gavi co-financing mechanism: 1) initial self-financing, 2) preparatory transition, and 3) accelerated transition. Countries in the first phase co-finance a portion of the HPV vaccines equivalent to $0.20 per dose (or 4.4% of the cost of a dose). Countries remain in the first phase until their gross national income (GNI) per capita exceeds $1,005.

Countries with a GNI per capita above $1,005 and up to $1,580 per capita are in the second phase (i.e., the preparatory transition phase), and pay 15% more for each dose each year. If HPV vaccination is introduced when countries are already in this phase, we calculate the price per dose as:

$$HPV\ vaccine\ price\ per\ dose\ (phase\ 2) = 4.50 - \frac{0.20}{4.50} \times 1.15^t$$

where $t$ is the number of years the country has been in the preparatory transition phase.

Countries move from the second transition phase into the third phase once their GNI per capita is above $1,580, and can remain in this phase for five years, at which point they graduate from Gavi funding to become fully self-financing. For countries in the first year of this phase in 2020, price per dose increases 15% and is calculated as:

$$HPV\ vaccine\ price\ per\ dose\ (phase\ 3\ year\ 1\ of\ 5) = 4.50 - \frac{0.20}{4.50} \times 1.15^{t+1}$$

In the following four years, the co-financed share increases linearly to reach $4.50.
### Supplementary Appendix Table 1. Sensitivity analysis around discount rates: Net health impact (NHI) and net monetary impact (NMI)

A: Base case (discount rate of 3% for health and 3% for costs)
B: Discount rate of 0% for health and 3% for costs

<table>
<thead>
<tr>
<th></th>
<th>$25 per dose</th>
<th>Gavi procurement support (per dose price differs by country, all &lt;= $4.50)</th>
<th>$4.50 per dose</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td><strong>Low-income</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net health benefits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of countries</td>
<td>2</td>
<td>13</td>
<td>21</td>
</tr>
<tr>
<td>Total +ive NHI (1,000s)</td>
<td>201</td>
<td>16,104</td>
<td>8,766</td>
</tr>
<tr>
<td>Total +ive NMI (1,000s 2019 US$)</td>
<td>33,281</td>
<td>2,671,456</td>
<td>1,327,194</td>
</tr>
<tr>
<td>Net health losses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of countries</td>
<td>20</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>Total -ive NHI (1,000s)</td>
<td>-17,134</td>
<td>-6,118</td>
<td>-37</td>
</tr>
<tr>
<td>Total -ive NMI (1,000s 2019 US$)</td>
<td>-2,331,849</td>
<td>-797,328</td>
<td>-9,388</td>
</tr>
<tr>
<td>Net health impact</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of countries</td>
<td>22</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Total NHI (1,000s)</td>
<td>-16,932</td>
<td>9,986</td>
<td>8,728</td>
</tr>
<tr>
<td>Total NMI (1,000s 2019 US$)</td>
<td>-2,298,568</td>
<td>1,874,127</td>
<td>1,317,805</td>
</tr>
<tr>
<td><strong>Lower middle-income</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net health benefits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of countries</td>
<td>12</td>
<td>20</td>
<td>22</td>
</tr>
<tr>
<td>Total +ive NHI (1,000s)</td>
<td>1,781</td>
<td>28,844</td>
<td>9,646</td>
</tr>
<tr>
<td>Total +ive NMI (1,000s 2019 US$)</td>
<td>819,677</td>
<td>12,087,170</td>
<td>3,609,966</td>
</tr>
<tr>
<td>Net health losses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of countries</td>
<td>12</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Total -ive NHI (1,000s)</td>
<td>-23,277</td>
<td>-6,033</td>
<td>-216</td>
</tr>
<tr>
<td>Total -ive NMI (1,000s 2019 US$)</td>
<td>-5,798,249</td>
<td>-962,153</td>
<td>-43,809</td>
</tr>
<tr>
<td>Net health impact</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of countries</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Total NHI (1,000s)</td>
<td>Total NMI (1,000s 2019 US$)</td>
<td>All countries</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>--------------------</td>
<td>-------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td></td>
<td>-21,496</td>
<td>11,105,017</td>
<td># of countries</td>
</tr>
<tr>
<td></td>
<td>22,811</td>
<td>11,105,017</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>9,431</td>
<td>11,105,017</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>53,350</td>
<td>11,105,017</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>6,610</td>
<td>11,105,017</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>50,594</td>
<td>11,105,017</td>
<td>45</td>
</tr>
<tr>
<td>Net health benefits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total +ive NHI (1,000s)</td>
<td>1,983</td>
<td>44,498</td>
<td></td>
</tr>
<tr>
<td></td>
<td>44,948</td>
<td>44,498</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18,412</td>
<td>44,498</td>
<td></td>
</tr>
<tr>
<td></td>
<td>88,996</td>
<td>44,498</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13,315</td>
<td>44,498</td>
<td></td>
</tr>
<tr>
<td></td>
<td>81,856</td>
<td>44,498</td>
<td></td>
</tr>
<tr>
<td>Net health losses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total -ive NHI (1,000s)</td>
<td>-40,411</td>
<td>-12,151</td>
<td># of countries</td>
</tr>
<tr>
<td></td>
<td>-12,151</td>
<td>-12,151</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>-253</td>
<td>-12,151</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>-12,151</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>-2,410</td>
<td>-12,151</td>
<td>12</td>
</tr>
<tr>
<td>Net health impact</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total NHI (1,000s)</td>
<td>-38,428</td>
<td>32,797</td>
<td># of countries</td>
</tr>
<tr>
<td></td>
<td>32,797</td>
<td>32,797</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>32,797</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>32,797</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>32,797</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>32,797</td>
<td>46</td>
</tr>
<tr>
<td>Total NMI (1,000s 2019 US$)</td>
<td>-6,819,860</td>
<td>13,258,353</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13,258,353</td>
<td>13,258,353</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4,860,057</td>
<td>13,258,353</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3,672,652</td>
<td>13,258,353</td>
<td></td>
</tr>
</tbody>
</table>
### Supplementary Appendix Table 2. Sensitivity analysis around discount rates: Pricing arrangements

A: Base case (discount rate of 3% for health and 3% for costs)
B: Discount rate of 0% for health and 3% for costs

<table>
<thead>
<tr>
<th>Country</th>
<th>Income group</th>
<th>Per dose price reduction required (2019 US$)</th>
<th>Total reduction using country specific price (1,000s 2019 US$, option 2)</th>
<th>Total reduction using country income group price (1,000s, $2 for low-income countries, $6 for lower middle-income countries, 2019 US$, option 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benin</td>
<td>Low</td>
<td>18</td>
<td>57,749</td>
<td>0</td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>Low</td>
<td>10</td>
<td>57,074</td>
<td>0</td>
</tr>
<tr>
<td>Burundi</td>
<td>Low</td>
<td>9</td>
<td>31,075</td>
<td>0</td>
</tr>
<tr>
<td>Chad</td>
<td>Low</td>
<td>21</td>
<td>101,129</td>
<td>37,013</td>
</tr>
<tr>
<td>Democratic Republic of the Congo</td>
<td>Low</td>
<td>23</td>
<td>582,915</td>
<td>348,943</td>
</tr>
<tr>
<td>Eritrea</td>
<td>Low</td>
<td>22</td>
<td>18,430</td>
<td>6,879</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>Low</td>
<td>17</td>
<td>491,992</td>
<td>0</td>
</tr>
<tr>
<td>Gambia</td>
<td>Low</td>
<td>9</td>
<td>5,981</td>
<td>0</td>
</tr>
<tr>
<td>Guinea</td>
<td>Low</td>
<td>14</td>
<td>48,351</td>
<td>0</td>
</tr>
<tr>
<td>Guinea Bissau</td>
<td>Low</td>
<td>22</td>
<td>11,104</td>
<td>5,759</td>
</tr>
<tr>
<td>Haiti</td>
<td>Low</td>
<td>21</td>
<td>45,173</td>
<td>7,576</td>
</tr>
<tr>
<td>Madagascar</td>
<td>Low</td>
<td>15</td>
<td>105,294</td>
<td>0</td>
</tr>
<tr>
<td>Malawi</td>
<td>Low</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mali</td>
<td>Low</td>
<td>19</td>
<td>108,948</td>
<td>6,179</td>
</tr>
<tr>
<td>Mozambique</td>
<td>Low</td>
<td>2</td>
<td>20,123</td>
<td>0</td>
</tr>
<tr>
<td>Nepal</td>
<td>Low</td>
<td>13</td>
<td>62,126</td>
<td>0</td>
</tr>
<tr>
<td>Niger</td>
<td>Low</td>
<td>24</td>
<td>183,674</td>
<td>134,466</td>
</tr>
<tr>
<td>Rwanda</td>
<td>Low</td>
<td>8</td>
<td>25,035</td>
<td>0</td>
</tr>
<tr>
<td>Country</td>
<td>Status</td>
<td>Population</td>
<td>Forested</td>
<td>Non-forested</td>
</tr>
<tr>
<td>------------------</td>
<td>-------------</td>
<td>------------</td>
<td>----------</td>
<td>--------------</td>
</tr>
<tr>
<td>Sierra Leone</td>
<td>Low</td>
<td>24</td>
<td>16</td>
<td>46,162</td>
</tr>
<tr>
<td>Togo</td>
<td>Low</td>
<td>21</td>
<td>4</td>
<td>42,623</td>
</tr>
<tr>
<td>Uganda</td>
<td>Low</td>
<td>8</td>
<td>0</td>
<td>108,355</td>
</tr>
<tr>
<td>Yemen</td>
<td>Low</td>
<td>26</td>
<td>23</td>
<td>180,923</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>Lower middle</td>
<td>23</td>
<td>13</td>
<td>592,799</td>
</tr>
<tr>
<td>Cambodia</td>
<td>Lower middle</td>
<td>20</td>
<td>0</td>
<td>61,602</td>
</tr>
<tr>
<td>Cameroon</td>
<td>Lower middle</td>
<td>17</td>
<td>0</td>
<td>119,244</td>
</tr>
<tr>
<td>Comoros</td>
<td>Lower middle</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Côte d'Ivoire</td>
<td>Lower middle</td>
<td>16</td>
<td>0</td>
<td>110,006</td>
</tr>
<tr>
<td>Ghana</td>
<td>Lower middle</td>
<td>3</td>
<td>0</td>
<td>23,785</td>
</tr>
<tr>
<td>India</td>
<td>Lower middle</td>
<td>18</td>
<td>0</td>
<td>3,511,214</td>
</tr>
<tr>
<td>Kenya</td>
<td>Lower middle</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Kyrgyzstan</td>
<td>Lower middle</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Lesotho</td>
<td>Lower middle</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mauritania</td>
<td>Lower middle</td>
<td>7</td>
<td>0</td>
<td>7,837</td>
</tr>
<tr>
<td>Nicaragua</td>
<td>Lower middle</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nigeria</td>
<td>Lower middle</td>
<td>17</td>
<td>0</td>
<td>922,743</td>
</tr>
<tr>
<td>Pakistan</td>
<td>Lower middle</td>
<td>25</td>
<td>19</td>
<td>1,164,963</td>
</tr>
<tr>
<td>Republic of Congo</td>
<td>Lower middle</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Republic of Sudan</td>
<td>Lower middle</td>
<td>23</td>
<td>6</td>
<td>244,785</td>
</tr>
<tr>
<td>Senegal</td>
<td>Lower middle</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>South Sudan</td>
<td>Lower middle</td>
<td>9</td>
<td>0</td>
<td>24,665</td>
</tr>
<tr>
<td>Tajikistan</td>
<td>Lower middle</td>
<td>23</td>
<td>9</td>
<td>51,199</td>
</tr>
<tr>
<td>Tanzania</td>
<td>Lower middle</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Uzbekistan</td>
<td>Lower middle</td>
<td>5</td>
<td>0</td>
<td>29,386</td>
</tr>
<tr>
<td>Vietnam</td>
<td>Lower middle</td>
<td>8</td>
<td>0</td>
<td>99,216</td>
</tr>
<tr>
<td>Zambia</td>
<td>Lower middle</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>Lower middle</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower middle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Supplementary Appendix Table 3. Sensitivity analysis around estimate of health opportunity cost: Net health impact (NHI) and net monetary impact (NMI)

<table>
<thead>
<tr>
<th></th>
<th>$25 per dose (option 1)</th>
<th>Gavi procurement support (per dose price differs by country, all &lt;=$4.50, option 4a)</th>
<th>$4.50 per dose (option 4b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
<td>Central estimate of health opportunity cost</td>
<td>Maximum</td>
</tr>
<tr>
<td><strong>Low-income</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net health benefits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of countries</td>
<td>1</td>
<td>2</td>
<td>21</td>
</tr>
<tr>
<td>Total +ive NHI (1,000s)</td>
<td>94</td>
<td>201</td>
<td>375</td>
</tr>
<tr>
<td>Total +ive NMI (1,000s 2019 US$)</td>
<td>12,603</td>
<td>33,281</td>
<td>76,156</td>
</tr>
<tr>
<td>Net health losses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of countries</td>
<td>21</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Total -ive NHI (1,000s)</td>
<td>-20,107</td>
<td>-17,134</td>
<td>-13,679</td>
</tr>
<tr>
<td>Total -ive NMI (1,000s 2019 US$)</td>
<td>-2,471,097</td>
<td>-2,331,849</td>
<td>-2,161,792</td>
</tr>
<tr>
<td>Net health impact</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of countries</td>
<td>22</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Total NHI (1,000s)</td>
<td>-20,013</td>
<td>-16,932</td>
<td>-13,304</td>
</tr>
<tr>
<td>Total NMI (1,000s 2019 US$)</td>
<td>-2,458,495</td>
<td>-2,298,568</td>
<td>-2,085,635</td>
</tr>
<tr>
<td><strong>Lower middle-income</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net health benefits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of countries</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>Total +ive NHI (1,000s)</td>
<td>1,427</td>
<td>1,715</td>
<td>1,988</td>
</tr>
<tr>
<td>Total +ive NMI (1,000s 2019 US$)</td>
<td>564,543</td>
<td>797,406</td>
<td>1,093,574</td>
</tr>
<tr>
<td>Net health losses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of countries</td>
<td>14</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>Total -ive NHI (1,000s)</td>
<td>-28,007</td>
<td>-22,755</td>
<td>-18,118</td>
</tr>
<tr>
<td>Net health impact</td>
<td># of countries</td>
<td>Net health impact</td>
<td># of countries</td>
</tr>
<tr>
<td>---------------------------</td>
<td>----------------</td>
<td>---------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Total -ive NMI (1,000s 2019 US$)</td>
<td>-6,055,675</td>
<td>-5,603,628</td>
<td>-5,124,730</td>
</tr>
<tr>
<td>Total NHI (1,000s)</td>
<td>-26,580</td>
<td>-21,041</td>
<td>-16,130</td>
</tr>
<tr>
<td>Total NMI (1,000s 2019 US$)</td>
<td>-5,491,133</td>
<td>-4,806,222</td>
<td>-4,031,156</td>
</tr>
<tr>
<td># of countries</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Net health benefits</th>
<th># of countries</th>
<th>Net health benefits</th>
<th># of countries</th>
<th>Net health benefits</th>
<th># of countries</th>
<th>Net health benefits</th>
<th># of countries</th>
<th>Net health benefits</th>
<th># of countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total +ive NHI (1,000s)</td>
<td>1,521</td>
<td>1,916</td>
<td>2,363</td>
<td>18,140</td>
<td>18,479</td>
<td>18,752</td>
<td>12,623</td>
<td>13,388</td>
<td>14,111</td>
</tr>
<tr>
<td>Total +ive NMI (1,000s 2019 US$)</td>
<td>577,145</td>
<td>830,687</td>
<td>1,169,730</td>
<td>4,123,966</td>
<td>4,938,709</td>
<td>5,890,201</td>
<td>3,268,65</td>
<td>4,055,431</td>
<td>4,972,751</td>
</tr>
<tr>
<td># of countries</td>
<td>11</td>
<td>13</td>
<td>14</td>
<td>43</td>
<td>43</td>
<td>43</td>
<td>34</td>
<td>35</td>
<td>38</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Net health losses</th>
<th># of countries</th>
<th>Net health losses</th>
<th># of countries</th>
<th>Net health losses</th>
<th># of countries</th>
<th>Net health losses</th>
<th># of countries</th>
<th>Net health losses</th>
<th># of countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total -ive NHI (1,000s)</td>
<td>-48,114</td>
<td>-39,889</td>
<td>-31,797</td>
<td>-392</td>
<td>-306</td>
<td>-2,351</td>
<td>-1,638</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total -ive NMI (1,000s 2019 US$)</td>
<td>-8,057,611</td>
<td>-7,478,196</td>
<td>-6,843,323</td>
<td>-71,412</td>
<td>-53,198</td>
<td>-30,775</td>
<td>-378,979</td>
<td>-332,803</td>
<td>-276,208</td>
</tr>
<tr>
<td># of countries</td>
<td>35</td>
<td>33</td>
<td>32</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>12</td>
<td>11</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Net health impact</th>
<th># of countries</th>
<th>Net health impact</th>
<th># of countries</th>
<th>Net health impact</th>
<th># of countries</th>
<th>Net health impact</th>
<th># of countries</th>
<th>Net health impact</th>
<th># of countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total NHII (1,000s)</td>
<td>-46,593</td>
<td>-37,973</td>
<td>-29,434</td>
<td>17,748</td>
<td>18,226</td>
<td>18,629</td>
<td>9,563</td>
<td>11,036</td>
<td>12,473</td>
</tr>
<tr>
<td>Total NMI (1,000s 2019 US$)</td>
<td>-7,480,465</td>
<td>-6,647,509</td>
<td>-5,673,593</td>
<td>4,052,554</td>
<td>4,885,511</td>
<td>5,859,426</td>
<td>2,899,67</td>
<td>3,722,627</td>
<td>4,696,543</td>
</tr>
</tbody>
</table>
### Supplementary Appendix Table 4. Sensitivity analysis around estimate of health opportunity cost: Pricing arrangements

<table>
<thead>
<tr>
<th>Country</th>
<th>Income group</th>
<th>Per dose price reduction required (2019 US$)</th>
<th>Total reduction using country specific price (1,000s 2019 US$, option 3)</th>
<th>Total reduction using country income group price (1,000s 2019 US, option 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Estimate of health opportunity cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benin</td>
<td>Low</td>
<td>19</td>
<td>60,544</td>
<td>81,035</td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>Low</td>
<td>11</td>
<td>63,934</td>
<td>80,661</td>
</tr>
<tr>
<td>Burundi</td>
<td>Low</td>
<td>11</td>
<td>36,106</td>
<td>22,783</td>
</tr>
<tr>
<td>Chad</td>
<td>Low</td>
<td>22</td>
<td>103,060</td>
<td>122,671</td>
</tr>
<tr>
<td>Democratic Republic of the Congo</td>
<td>Low</td>
<td>23</td>
<td>589,252</td>
<td>666,116</td>
</tr>
<tr>
<td>Eritrea</td>
<td>Low</td>
<td>22</td>
<td>18,858</td>
<td>21,978</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>Low</td>
<td>18</td>
<td>519,696</td>
<td>729,365</td>
</tr>
<tr>
<td>Gambia</td>
<td>Low</td>
<td>11</td>
<td>7,359</td>
<td>17,170</td>
</tr>
<tr>
<td>Guinea</td>
<td>Low</td>
<td>15</td>
<td>51,670</td>
<td>89,790</td>
</tr>
<tr>
<td>Guinea Bissau</td>
<td>Low</td>
<td>22</td>
<td>11,246</td>
<td>13,220</td>
</tr>
<tr>
<td>Haiti</td>
<td>Low</td>
<td>22</td>
<td>47,084</td>
<td>56,250</td>
</tr>
<tr>
<td>Madagascar</td>
<td>Low</td>
<td>16</td>
<td>111,744</td>
<td>177,601</td>
</tr>
<tr>
<td>Malawi</td>
<td>Low</td>
<td>1</td>
<td>4,039</td>
<td>129,186</td>
</tr>
<tr>
<td>Mali</td>
<td>Low</td>
<td>19</td>
<td>111,987</td>
<td>149,946</td>
</tr>
<tr>
<td>Mozambique</td>
<td>Low</td>
<td>5</td>
<td>44,948</td>
<td>222,358</td>
</tr>
<tr>
<td>Nepal</td>
<td>Low</td>
<td>15</td>
<td>73,030</td>
<td>125,032</td>
</tr>
</tbody>
</table>

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance placed on this supplemental material which has been supplied by the author(s).
<p>| Country          | Income Status     | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 | Year 7 | Year 8 | Year 9 | Year 10 | Year 11 | Year 12 | Year 13 | Year 14 | Year 15 | Year 16 | Year 17 | Year 18 | Year 19 | Year 20 | Year 21 | Year 22 | Year 23 |
|------------------|-------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Niger            | Low               | 24     | 24     | 24     | 185,145| 183,674| 180,348| 197,070| 196,160| 195,208|
| Rwanda           | Low               | 10     | 8      | 6      | 32,167 | 25,035 | 17,935 | 82,045 | 81,666 | 81,269 |
| Sierra Leone     | Low               | 24     | 24     | 23     | 46,581 | 46,162 | 45,308 | 50,554 | 50,321 | 50,076 |
| Togo             | Low               | 21     | 21     | 20     | 43,783 | 42,623 | 41,179 | 53,479 | 53,232 | 52,974 |
| Uganda           | Low               | 10     | 8      | 6      | 130,674| 108,355| 78,439 | 336,756| 335,200| 333,574|
| Yemen            | Low               | 26     | 26     | 26     | 181,762| 180,923| 180,045| 180,923| 180,045| 180,045|
| Bangladesh       | Lower middle      | 24     | 23     | 23     | 607,475| 592,799| 575,924| 652,287| 645,928| 637,843|
| Cambodia         | Lower middle      | 21     | 20     | 19     | 65,569 | 61,602 | 58,604 | 79,452 | 78,677 | 77,693 |
| Cameroon         | Lower middle      | 18     | 17     | 16     | 123,380| 119,244| 112,024| 176,774| 175,050| 172,859|
| Comoros          | Lower middle      | 0      | 0      | 0      | 0      | 0      | 0      | 5,286  | 5,236  | 5,170  |
| Côte d'Ivoire    | Lower middle      | 17     | 16     | 15     | 115,698| 110,006| 100,313| 175,261| 173,553| 171,380|
| Ghana            | Lower middle      | 6      | 3      | 1      | 42,040 | 23,785 | 3,723  | 180,076| 178,321| 176,089|
| India            | Lower middle      | 19     | 18     | 16     | 3,761,298| 3,511,214| 3,239,681| 5,132,563| 5,082,526| 5,018,906|
| Kenya            | Lower middle      | 0      | 0      | 0      | 0      | 0      | 0      | 319,250| 316,137| 312,180|
| Kyrgyzstan       | Lower middle      | 0      | 0      | 0      | 0      | 0      | 0      | 34,285 | 33,951 | 33,526 |
| Lesotho          | Lower middle      | 0      | 0      | 0      | 0      | 0      | 0      | 10,511 | 10,408 | 10,278 |
| Mauritania       | Lower middle      | 9      | 7      | 4      | 10,097 | 7,837  | 5,041  | 29,391 | 29,105 | 28,741 |
| Nicaragua        | Lower middle      | 0      | 0      | 0      | 0      | 0      | 0      | 29,243 | 28,958 | 28,595 |
| Nigeria          | Lower middle      | 18     | 17     | 15     | 970,840| 922,743| 838,130| 1,401,421| 1,387,758| 1,370,387|
| Pakistan         | Lower middle      | 26     | 25     | 25     | 1,176,432| 1,164,963| 1,150,381| 1,176,432| 1,164,963| 1,150,381|
| Republic of Congo| Lower middle      | 0      | 0      | 0      | 0      | 0      | 0      | 36,140 | 35,787 | 35,339 |
| Republic of Sudan| Lower middle      | 24     | 23     | 22     | 250,691| 244,785| 237,822| 272,927| 270,266| 266,883|
| Senegal          | Lower middle      | 1      | 0      | 0      | 3,988  | 0      | 0      | 113,804| 112,695| 111,284|
| South Sudan      | Lower middle      | 11     | 9      | 7      | 30,157 | 24,665 | 18,190 | 71,723 | 71,023 | 70,134 |
| Tajikistan       | Lower middle      | 24     | 23     | 22     | 52,923 | 51,199 | 49,400 | 57,670 | 57,107 | 56,392 |
| Tanzania         | Lower middle      | 0      | 0      | 0      | 0      | 0      | 0      | 414,704| 410,661| 405,521|</p>
<table>
<thead>
<tr>
<th>Country</th>
<th>Status</th>
<th>Prevalence</th>
<th>Prevalence 95% CI</th>
<th>Incidence</th>
<th>Incidence 95% CI</th>
<th>Deaths</th>
<th>Deaths 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uzbekistan</td>
<td>Lower middle</td>
<td>9</td>
<td>5</td>
<td>1</td>
<td>53,265</td>
<td>7,204</td>
<td>150,218</td>
</tr>
<tr>
<td>Vietnam</td>
<td>Lower middle</td>
<td>12</td>
<td>8</td>
<td>4</td>
<td>156,971</td>
<td>54,461</td>
<td>334,872</td>
</tr>
<tr>
<td>Zambia</td>
<td>Lower middle</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>128,541</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>Lower middle</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>97,990</td>
</tr>
<tr>
<td>Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2,474,668</td>
<td>2,158,140</td>
<td>3,725,020</td>
</tr>
<tr>
<td>Lower-middle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7,420,824</td>
<td>6,450,897</td>
<td>10,972,795</td>
</tr>
<tr>
<td>All</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9,895,492</td>
<td>8,609,037</td>
<td>14,542,394</td>
</tr>
</tbody>
</table>