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Value-based pricing of a COVID-19 vaccine

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A B S T R A C T  
Aim: The purpose of this study is to determine the value-based price of a COVID-19 vaccine from a societal perspective in Germany.  
Methods: A decision model was constructed using, e.g., information on age-specific fatality rates, intensive care unit (ICU) costs and outcomes, and the full vaccination rate. Three strategies were analysed: vaccination (with 95 % and 50 % efficacy against death), a mitigation strategy, and no intervention. The base-case time horizon was 5 years. The value of a vaccine includes savings from avoiding COVID-19 mitigation measures and productivity loss, as well as health benefits from preventing COVID-19 related mortality. The value of an additional life year was borrowed from new, innovative oncological drugs, as cancer reflects a condition with a similar morbidity and mortality burden in the general population in the short term as COVID-19.  
Results: A vaccine with a 95 % efficacy dominates the mitigation strategy strictly. The value-based price (€6,431) is thus determined by the comparison between vaccination and no intervention. The price is particularly sensitive to the full vaccination rate and the duration of vaccine protection. In contrast, the value of a vaccine with 50 % efficacy is more ambiguous.  
Conclusion: This study yields a value-based price for a COVID-19 vaccine with 95 % efficacy, which is considerably greater than the purchasing price.  
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1. Introduction  
During the first three waves of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) pandemic, the German federal government and federal states pursued a COVID-19 mitigation strategy (Bundesregierung, 2020a). This included measures such as partial shutdown of businesses, social distancing, contact tracking, testing, public mask wearing, and quarantine orders (Bundesregierung, 2020b). An important goal of this strategy was to control COVID-19 outbreaks or postpone them (‘flatten the curve’) and thus avoid over-stretching the intensive care unit (ICU) capacity at peak demand (cf. Bundesregierung, 2020b). At the time of writing of this manuscript, the forth SARS-CoV-2 wave has begun in Germany and is dominated by the Delta variant.  
In November 2020, the pharmaceutical companies Pfizer-Biontech and Moderna independently announced that their vaccine candidates against SARS-CoV-2 have demonstrated evidence of efficacy against COVID-19 in participants without prior evidence of SARS-CoV-2 infection. The case splits between vaccinated individuals and those who received the placebo indicate a vaccine efficacy rate above 90 %. The European Commission approved the Biontech-Pfizer and Moderna vaccines for use across the 27 Member States on December 21, 2020 and January 6, 2021, respectively. The Commission has so far given the conditional marketing authorization for 4 vaccines. As of September 5, 2021, 72 % of administered doses in Germany were from Pfizer-Biontech (Bundesministerium für Gesundheit, 2021b).  
The estimated cost of immunizing one person is €50 based on €8.9 billion total acquisition expenditures borne by the German government (Tagesschau, 2021) to vaccinate 176 million people (Bundesministerium für Gesundheit, 2021b). Given the pressing public health needs, manufacturers do not seek maximum returns (COVID-19 Vaccine Global Access, 2020) and therefore, the prices are cost-based rather than value-based (Towse & Firth, 2020). Cost-plus pricing includes a profit mark-up and may also be used in advanced market commitments, which entail purchasing a vaccine at a pre-agreed volume (Neumann, Cohen, Kim, & Ollendorf, 2021). In contrast, value-based pricing (VBP) sets the prices of medical technologies based on their health benefits and other factors. According to a narrow definition of VBP, an explicit willingness-to-pay threshold is used to determine the price (Bouvy & Vogler, 2013). VBP can also be used to define the size of large monetary prizes (rewards) that are used for incentivizing the development of vaccines (Gandjour & Chernyak, 2011).
2. Methods

2.1. Pricing framework

In a VBP framework that relies on an economic evaluation, the maximum acceptable price of a new vaccine is determined by equating the incremental cost-effectiveness ratio (ICER) of the new vaccine compared with a less effective treatment to the cost-effectiveness threshold $\lambda$:

$$\frac{c}{h} = \frac{p - s + b}{h} = \lambda,$$  \hspace{1cm} (1)

where $c$ is incremental costs; $h$ denotes incremental net health benefit including harm from side effects; $p$ is the maximum acceptable additional price of the new vaccine net of the costs of the comparator as well as costs of vaccination, subsidies, establishing vaccination centres, transportation, and managing side effects; $s$ denotes savings from avoiding morbidity, productivity loss, and mitigation measures related to COVID-19; and $b$ is the cost resulting from avoidance of premature death. Given the consideration of subsidies, the value-based price is adjusted downwards for public push for research and development (R&D) and manufacturing funding (cf. Towsé & Firth, 2020). Of note, the real-world costs of purchasing the vaccines and the costs of scientific research failures are not included in the calculation of the value-based price because they matter only for cost-plus pricing but not for VBP.

Rearranging Eq. (1) yields the maximum acceptable price of a new vaccine (Gandjour & Chernyak, 2011):

$$p = \lambda h + s - b.$$  \hspace{1cm} (2)

In the following, I will call a VBP rule that applies an absolute cost-effectiveness threshold ‘absolute’ rule. In contrast, a proportional rule for VBP sets that costs induced by a vaccine should (only) increase in proportion to its incremental health benefits (Gandjour, 2011). This rule was recently validated (Gandjour, 2020). It implies a constant trade-off between costs and health benefits as shown in the following:

$$\frac{p_1 - s_1 + b_1}{h_1} = \frac{p_2 - s_2 + b_2}{h_2}.$$  \hspace{1cm} (3)

If the comparator of a COVID-19 vaccine are mitigation and ‘no intervention’, then subscript 1 denotes the comparison between the mitigation strategy and ‘no intervention’ and subscript 2 refers to the comparison between COVID-19 vaccine and the mitigation strategy. Importantly, comparators need to be non-dominated.

Solving for $p_2$ yields the value-based price of a COVID-19 vaccine:

$$h_2 \frac{p_1 - s_1 + b_1}{h_1} + s_2 - b_2 = p_2.$$  \hspace{1cm} (4)

In this study, both rules are applied to derive the value-based price of a COVID-19 vaccine.

2.2. Comparators

The study uses two comparators of a COVID-19 vaccine, ‘no intervention’ and a mitigation strategy including a partial lockdown/shutdown.

In the short term, a vaccination strategy must be regarded as an add-on to a mitigation strategy because vaccination of a large part of the population cannot be achieved immediately. However, in the mid- to long-term, vaccination avoids the costs of mitigation strategy, which is the contribution of the lockdown/shutdown to the total economic burden of the SARS-CoV-2 pandemic. In addition, vaccination avoids the deaths associated with mitigation strategy, which is not able to suppress the pandemic. Nevertheless, a vaccine with only 50 % efficacy may still require imposing lockdown measures even in the long-term (Reuters, 2020). In a sensitivity analysis, the costs and benefits of the latter were included.

As a mitigation strategy is not economically sustainable in the long run, ‘no intervention’ is chosen as a more realistic long-term comparator. ‘No intervention’ lifts the lockdown/shutdown and results in herd immunity through natural infection. Considering that an uncontrolled pandemic in Germany would require a peak capacity of several hundred thousand ICU beds (Khailaie et al., 2020), overburdening of ICUs was assumed, leading to voluntary restrictions on economic activities. Many German commentators have hypothesized such a response following the pictures from the main hospital in the Italian city of Bergamo in March 2020.

2.3. Decision model

A decision model was constructed based on a previously developed and validated model (Gandjour, 2020). The latter model determines the gain in life years of a strategy that is successful in ‘squashing the curve’ compared to the situation before the pandemic. It is based a life-table model that summarizes the age-specific mortality impact of the SARS-CoV-2 pandemic. The base-case calculation relies on an independence assumption, implying that individuals not dying from COVID 19 have the same probability of death as all individuals before the rise of the pandemic. Given that patients who die from COVID 19 tend to have more comorbidities (Wu & McGoogan, 2020), I assumed a harvesting effect in a sensitivity analysis. This approach presumes that those who die from COVID-19 are sicker and would have died anyway. In this scenario, I assumed for age groups with excess mortality associated with COVID-19 (the difference between observed and pre-pandemic mortality rates) that except for COVID-19, there are no other causes of death over 12 months in the event of a natural spread of SARS-CoV-2 in the immunologically naïve population. To account for the age distribution of the population, the model weighs age-specific life-expectancy changes by age-specific population sizes.

The time horizon was set to 5 years reflecting the expected maximum acceptable period of lockdowns under a mitigation strategy in the absence of a vaccine. The transmission dynamics of SARS-CoV-2 are comparable to those of influenza (Van Damme et al., 2020), which typically causes epidemics in temperate climates every year during winter. In the absence of a vaccine, future SARS-CoV-2 pandemic waves were therefore assumed to peak in winter and return yearly.

2.4. Vaccine efficacy

Vaccine efficacy can be defined based on the attack rate (the proportion of individuals infected in the specific risk group over a nominated period) or the frequency of only severe cases (Préziosi & Halloran, 2003). The herd immunity threshold is calculated based on an inversely proportional relationship with vaccine efficacy measured in terms of attack rate (Chowell et al., 2009):

$$\varphi = \frac{1}{\varepsilon} \left( 1 - \frac{1}{R_0} \right),$$  \hspace{1cm} (5)

where $\varphi$ refers to the herd immunity threshold, $\varepsilon$ is vaccine efficacy, and $R_0$ is the basic reproduction number of a disease.
Vaccination-induced herd immunity is not assumed in the base case, however, as it has been apparent that efficacy of vaccines against transmission of the Delta variant is insufficient (The Guardian, 2021). Given the estimated $R_0$ of the Delta variant (6.4 according to Mallapaty (2021)), efficacy against transmission needs to be above 80% to achieve herd immunity. This is unlikely to be the case even based on data on the less contagious Alpha variant (COVID-END 2021). Hence, it is assumed that herd immunity will be achieved only by vaccination together with natural infection. Therefore, all unvaccinated individuals are assumed to become infected at some point in the future. The time until herd immunity through vaccination and natural infection is not relevant for modelling the value of a vaccine, however. The reason is that infection of unvaccinated individuals also occurs in the comparator arms, i.e., the mitigation strategy and no intervention. Hence, the costs of associated possible restrictive measures due to local outbreaks are also included in the comparator arms and thus cancel out in an incremental analysis.

2.5. Cost calculation

The study took a societal viewpoint, by including both direct medical costs and indirect/productivity costs. The savings in health care expenditures by avoiding the spread of SARS-CoV-2 in the population under no intervention were not added to the GDP estimate because the savings were assumed to be offset by higher health expenditures for elective procedures and emergency and physician visits for unrelated medical conditions. That is, in case of a natural spread, providers and patients were assumed to reduce utilization of elective procedures as well as emergency and physician visits for unrelated medical conditions.

Conversely, productivity gains from avoiding sickness by mitigation and vaccination were added to the GDP estimates. They were calculated by multiplying the proportion of symptomatic patients with the duration of sickness and the daily productivity loss. For the latter calculation a few simplifying assumptions were made. First, all undiagnosed but symptomatic infections were assumed to be mild. This assumption is indirectly supported by official data on excess mortality in Germany (Statistisches Bundesamt, 2021a) showing that the peak in excess mortality in the first half of April 2020 and in December 2020 both coincided with surges in COVID-19 deaths (thus essentially ruling out deaths due to undiagnosed COVID-19 cases). Second, the maximum number of quarantined contact persons per diagnosed reached the maximum in August 2020 and cannot increase further due to labor and technological constraints in local public health departments. Third, infected and quarantined individuals are representative of the general population.

From the perspective of static efficiency, the drop in the gross domestic product (GDP) associated with the lockdownshutdown till today can be considered sunk, while from the perspective of dynamic efficiency, which sets incentives for innovations (e.g., for vaccines in future pandemics), it is still relevant. As in future pandemics vaccine development and distribution is likely to occur only in conjunction with a mitigation strategy, considering the full mitigation cost avoids introducing excessive incentives for innovation. Therefore, a dynamic efficiency perspective was considered in the base case.

3. Data

3.1. Economic data

Regarding the economic contraction due to another pandemic wave mitigated by a lockdown, I took the GDP contraction in the first quarter of 2021 (1.7% (Statistisches Bundesamt, 2021a)), which was essentially driven by the second wave (and the concomitant lockdown policy). In terms of the GDP loss independent of the second wave, I took the GDP loss in 2020 (4.9%), accounted for the projected GDP increase in 2021 (3.5%) (Bundesministerium für Wirtschaft und Energie), and subtracted the GDP contraction of the second wave.

However, this calculation assumes the absence of a pandemic in the counterfactual scenario, without considering the voluntary restrictions such as social distancing in view of the rapid spread of the virus in the population (cf. Aum, Lee, & Shin, 2020). That is, individuals may take precautions even without the lockdown orders. Accounting for the latter would decrease the incremental cost of the lockdown/shutdown over no pandemic. In a sensitivity analysis I assumed the contribution of the lockdown/shutdown to the total loss of economic activities to be 10%, to account for the voluntary restrictions that may take place in the absence of a lockdown/shutdown. This estimate agrees with the one regarding the contribution of a shutdown to the loss of economic activities in Denmark, which was estimated to be 14% (= 4%/29%) (Sheridan, Andersen, Hansen, & Johannesen, 2020).

To determine the productivity gains resulting from a vaccination or mitigation strategy, as compared to no intervention, I used the data and methods reported in Table A1 of the Appendix. The productivity gain was assumed to be proportional to the level of vaccine efficacy.

The German federal government has been funding three vaccine developers with a total of 750 million euros. Biontech from Mainz received 375 million euros and Curevac from Tübingen received 230 million euros through a special vaccine development program (Zeit, 2020). In addition, the federal government planned 1.4 billion euros for the construction and operation of the planned vaccination centers (Bundesministerium für Gesundheit, 2021a). Both types of costs were included in the analysis and related to one vaccinated individual.

The number of acquired doses of approved vaccines until the end of 2021 is predicted to be 316 million (Bundesministerium für Gesundheit, 2021b), which would allow vaccination of 176 million people assuming up to 2 doses per individual. Based on the full vaccination rate assumed in the base case, 62% of doses will not be used. Nevertheless, due to the existing purchase agreements the value-based price also needs to include the unused doses. Effectively, the value-based price thus needs to be reduced by the proportion of unused vaccines.

All costs are presented in euros, year 2020 values.

3.2. Clinical and epidemiological data

To calculate the per capita gain in life years through a relockdown in conjunction with revaccination, I applied data on age-specific mortality, ICU fatality, and the ICU admission rate from the end of December 2020 (i.e., at the time of vaccine launch in Germany) to the previously developed model (Gandjour, 2020). These data were updated based on findings for the Delta variant. To determine the COVID-19 infection fatality rate (IFR) of the Delta variant, I used an estimate on the wild-type strain as a baseline (0.83% in Germany (Dimpfl, Sönksen, Bechmann, & Grammig, 2021)) and multiplied it with the mortality hazard ratio of the B.1.1.7 (Alpha) variant (Challen et al., 2021) (the relative mortality of the Delta variant was unclear at the time of writing the manuscript). In a sensitivity analysis, I presumed dominance of the wild-type strain and therefore assumed that herd immunity would be achieved by vaccination only.

The IFR was adjusted upwards to account for the long-term mortality of ICU survivors. Furthermore, given that the IFR is lower than the case fatality rate (CFR) in Germany, I adjusted the percentage of patients admitted to the ICU accordingly because a lower CFR also implies a lower percentage of cases admitted to the ICU (Gandjour,
### Table 1
Input values and distributions used in the base case and sensitivity analysis.

| Input                                                                 | Mean (range) | Reference                                      |
|----------------------------------------------------------------------|--------------|------------------------------------------------|
| Epidemiological and clinical data                                    |              |                                                |
| Probability of death by age and gender in Germany                    |              | Statistisches Bundesamt, 2019                  |
| Population size by age                                               | see reference| Statistisches Bundesamt, 2021b                 |
| IFR in Germany (without vaccine)                                     | 0.014 (0.011 – 0.017) | Challen et al., 2021; Dimpf et al., 2021      |
| CFR in Germany (without vaccine)                                     |              | Robert Koch Institut, 2020a                    |
| Total population                                                     | 0.017        |                                                |
| 0–9 years                                                            | 0.00013      |                                                |
| 10–19 years                                                          | 0.00002      |                                                |
| 20–29 years                                                          | 0.00010      |                                                |
| 30–39 years                                                          | 0.00026      |                                                |
| 40–49 years                                                          | 0.00087      |                                                |
| 50–59 years                                                          | 0.00302      |                                                |
| 60–69 years                                                          | 0.01554      |                                                |
| 70–79 years                                                          | 0.06305      |                                                |
| 80–89 years                                                          | 0.12154      |                                                |
| 90+ years                                                            | 0.15168      |                                                |
| Probability of ICU indication                                        | 0.03 (0.03 – 0.08) | Robert Koch Institut, 2020a, Twohig et al., 2022 |
| False-positive ICU admissions                                         | 0.1 (0.1 – 0.2) | Abens and Musher, 2014                        |
| CFR in the ICU                                                        | 0.26 (0.25 – 0.27) | Robert Koch Institut, 2020a                    |
| CFR one year post ICU discharge                                      | 0.59 (0.47 – 0.73) | Damuth, Mitchell, Bartock, Roberts, & Trzeeciak, 2015 |
| Full vaccination rate                                                 | 0.85 (0.80 – 0.90) | COVID-19 Snapshot Monitoring (COSMO), 2021     |
| Immunity following full vaccination, years                           | 1 (1–5)      | MedPage Today, 2021                           |
| Cost data                                                            |              |                                                |
| GDP reduction per pandemic wave, %                                   | 1.7          | Statistisches Bundesamt, 2021a                 |
| GDP reduction in 2020/21 without a second wave, %                    | 4.8          | Bundesministerium für Wirtschaft und Energie   |
| GDP drop attributable to shutdown versus voluntary restrictions, %   | 100 (10–100) | Estimate                                      |
| Construction and operation of vaccination centers, €                  | 1,400,000,000 | Bundesministerium für Gesundheit, 2021a       |
| Vaccinations by primary care physicians, €                           | 1,500,000,000 | n-tv, 2021                                   |
| Transport, storage, syringes, and needles, €                         | 231,000,000  | WDR, 2020                                    |

Note: CFR = case fatality rate, ICU = intensive care unit, IFR = infection fatality rate.

2021a). The sensitivity analysis on ICU admission rate accounted for a higher hospitalization risk for the Delta variant compared with the Alpha variant (Twohig, Nyberg, & Zaidi, 2022).

In agreement with other authors who foresaw a high probability of a second and third SARS-CoV-2 pandemic wave under no intervention strategy (e.g., Fakhruddin, Blanchard, & Ragupathy, 2020; Pollock, Roderick, Cheng, & Pankhania, 2020), I assumed two remaining pandemic waves under no intervention in the base case. I arrived at the annual death toll of the pandemic (i.e., the number of deaths per pandemic wave) by halving the expected death toll of the second and third pandemic wave in Germany (between October 2020 and July 2021 [DW, 2021]). The death toll was multiplied with the average loss of life years.

According to the United States Food and Drug Administration (2020), the efficacy of the primary endpoint in a placebo-controlled efficacy trial should be at least 50 %, to classify a widely deployed COVID-19 vaccine as effective, while ensuring safety. Hence, I took this estimate as the lower limit of the vaccine efficacy. As the FDA allows both SARS-CoV-2 infection and deaths associated with COVID-19 to be defined as primary endpoints, applying the 50 % threshold to the life years gained as a measure of vaccine efficacy is still valid. While efficacy of the vaccine against death from the Delta variant needs to be confirmed, I took a 95 % efficacy in preventing hospitalizations (COVID-END, 2021) as the upper limit of vaccine efficacy.

In the base case, I assumed a full vaccination rate of 75 % and, in a sensitivity analysis, a range between 65 % and 90 %. The upper limit of the range was based on a survey conducted in July 2021 in the German population (COVID-19 Snapshot Monitoring (COSMO), 2021) reporting a 10 % rate of individuals who refuse vaccination.

Immunity was assumed to last between one and five years. The range is based on diverging opinions around the need for annual booster shots (MedPage Today, 2021). In the base case, the duration of immunity was presumed to be the same for both natural infection and immunization and hence cancels out. In a sensitivity analysis, it was assumed that vaccine protection wanes twice as fast as protection from natural infection based on evidence of a faster exponential decay of antibody titers following vaccination (Israel et al., 2021).

### 3.3. Discounting

For comparison between vaccination and mitigation, the GDP drops associated with annual pandemic waves under mitigation were discounted at an annual rate of 3%, based on the social rate of time preference derived from the Ramsey equation (Ramsey, 1928). For health benefits of mitigation, I applied a 2% discount rate, reflecting a 1% expected growth rate of the consumption value of health in Germany (cf. John, Koerber, & Schad, 2019).

### 3.4. Willingness to pay (WTP)

The WTP for an additional life year (€101,493 per life year gained) based on the absolute rule was calculated by dividing the incremental costs of new, innovative cancer drugs (€39,751) by the incremental survival benefit (0.39 life years) (Gandjour, 2021b). As the WTP estimate does not account for life extension costs, the latter were not considered in the pricing model either (variable b in Eq. 2).

WTP based on the proportional rule was derived from the ICER of a mitigation strategy. Spending on the mitigation strategy may be seen as an appropriate reflection of its value given that the benefits and opportunity costs of the mitigation strategy have been intensely discussed in the public and the media.

### 4. Results

Table 1 shows the input values and distributions used in the base case and sensitivity analysis. As shown in Table 2, a vaccine with 95 % efficacy (with a price of zero) dominates the mitigation strategy strictly because it yields more life years at lower costs. A vaccine with 95 % efficacy yields more life years because it prevents...
annual waves of infection leading to deaths. The reason for lower costs is related and lies in the prevention of annual lockdowns that are associated with the waves of infection.

The value-based price based on an absolute rule (€6,431) is thus determined by the comparison between vaccination and no intervention because the latter is the next most effective intervention. The value-based price refers to the complete vaccination course, i.e., it includes all doses. Furthermore, the proportional rule yields a price that is lower.

In contrast, a vaccine with 50% efficacy is less effective than the mitigation strategy. As the savings are not sufficiently large to pass the ICER threshold, vaccination is not cost-effective (the value-based price is zero). Nevertheless, if a vaccine with 50% efficacy is accompanied by partial lockdown measures in the long-term, based on the ICER of mitigation versus no intervention, the costs to achieve efficacy on par with long-term mitigation will be 3.2% of GDP. The corresponding value-based price is €1,661. A value-based price can also be determined based on the proportional rule because the loss of life years carries a lower weight due to the lower ICER threshold.

As shown in the sensitivity analysis (Fig. 1), the range for the value-based price of a vaccine with a 95% efficacy, based on the absolute rule, lies between €3,215 and €8,926. The major drivers of the price are the full vaccination rate and the duration of vaccine protection.

### 5. Discussion

This study yields a value-based price for a COVID-19 vaccine with 95% efficacy that is more than 100 times greater than the purchasing price even after incorporating the results of the sensitivity analysis (€6,431 vs. €50 in the base case). In contrast, a vaccine with 50% efficacy has a negative value compared to a mitigation strategy. However, if the latter is not sustainable for economic, psychological, or other reasons, a vaccine with 50% efficacy is able to obtain a positive value compared to no intervention.

Of note, the value of a COVID-19 vaccine as determined in the present study deviates from the value of a shutdown presented in an earlier study using the same underlying decision model (Gandjour, 2021a). Apart from differences in input data due to different time points in the course of the pandemic, the major reason is that the drop in GDP until the time of introducing the vaccine (i.e., until the end of 2020) is considered in the present study (for the reasons mentioned below “Cost calculation”) while not so in the previous study (Gandjour, 2021a).

Towe and Firth (2020) argue that prices of COVID-19 vaccines need to be a value-based rather than cost-based to incentivise “a number of vaccines” and in particular “better vaccines” and “to avoid incentivising high cost low quality vaccines at the expense of lower cost, but better quality, ones.” In agreement, Neumann et al. (2021) make the case that not including the full value of a COVID-19 vaccine in its price encounters the risk of “having few effective products for the next pandemic”. Towe and Firth (2020) suggest that the commitment to supply the vaccine on a not-for-profit basis must be time-limited because private investors expect a return. Hence, they propose supplying the vaccine on a not-for-profit basis only initially, but on “a normal commercial basis” in subsequent years. Based on this reasoning, the results of this study allow defining the potential for a price increase in the long-term. Otherwise, when VBP is not seen as realistic or desirable, the present results allow defining the portion of the price that reflects the contribution of the vaccine developers and the manufacturers to society, thus displaying their commitment in taking corporate social responsibility.

A few studies on the monetary value of COVID-19 vaccines have been published so far (e.g., Hagens et al., 2021; Kohli, Maschio, Becker, & Weinstein, 2021; Marco-Franco, Pita-Barros, González-de-Julián, Sabat, & Vivas-Consuelo, 2021; Padula et al., 2021; Sandmann et al., 2021). Studies seem to concur that the clinical and economic value of COVID-19 vaccines is positive. Nevertheless, the variety of assumptions used in the studies makes comparisons inherently difficult. In addition, differences exist in terms of healthcare systems, perspectives, methods, comparators, and prevailing coronavirus variants. Both a Turkish (Hagens et al., 2021) and a U.K. study (Sandmann et al., 2021) used a dynamic transmission model and – similar to this study – a societal perspective. While the Turkish study used no intervention as a comparator, the U.K. study considered a lockdown strategy. Of note, the U.K. study explored a wide range of estimates (between 2% and 15%) for the GDP loss per day when COVID-19 incidence exceeded 1000 new reported cases and physical distancing was imposed.

As a word of caution, given the time constraints and the rapid inflow of new information on the SARS-CoV-2 pandemic while conducting the study and writing this manuscript, which made it necessary to update the projections continuously, this decision-analytic study has several caveats. There are reasons why the study may underestimate or overestimate the health benefits and cost-effectiveness of a vaccine compared to the alternative strategies, and its value-based price. Some of these reasons were already captured in the sensitivity analysis and include the full vaccination rate and the duration of vaccine protection. In contrast, exclusion of potential deaths secondary to the pandemic but unrelated to COVID-19 such as suicides are not likely to have a major impact. As mentioned in the Methods section, official data on excess mortality in Germany (Statistisches Bundesamt, 2021a) show that the peak in excess mortality in the first half of April 2020 and in December 2020 both coincided with the surges in COVID-19 deaths, thus indicating that excess mortality was driven by COVID-19 and not by other causes. In terms of health-related quality of life, it appears...
that its inclusion would rather support the value of a vaccine with 95% efficacy. The reason is that a vaccine avoids not only the psychological burden of lockdowns and social distancing but also the long COVID syndrome, which affects approximately 14% of infected individuals (Office for National Statistics, 2021). Quality-adjusted life years (QALYs) are able to capture an additional health benefit resulting from improved quality of life. However, as the QALY metric discriminates against the elderly and the disabled, it has been considered ethically controversial (Ubel, Richardson, & Prades, 1999).

According to a recent report published by the German National Academy of Sciences (2021), the crisis can have significant long-term effects on the level and distribution of income in Germany. According to this report, this is mainly due to the unequal impact of the pandemic on education. Thus, the recurring distance learning hinders students’ access and success in higher education and reduces the income potential of the young generation as a whole, but especially of low-performing students and those from educationally disadvantaged families. Therefore, there may be costs in the long term in the form of a reduction of accumulated human capital and greater educational inequality. The extent of this cost probably depends non-linearly on the duration of the lockdown measures (Swiss National COVID-19 Science Task Force, 2021). For shorter lockdown periods, it is conceivable that certain learning deficits can be made up later (Swiss National COVID-19 Science Task Force, 2021). An explicit quantification of this cost is difficult, however. In Germany, the costs of school closures over the remaining lifetime of school-aged children have been estimated to be approximately ¬€3 trillion (discounted to present value at an annual rate of 3%) (Hanushek & Wößmann, 2020). Thus, the value is approximately 10 times larger than the ongoing costs of the pandemic included in this study (¬€300 billion). Hanushek and Wößmann (Hanushek & Wößmann, 2020) caution, however, that “current reactions to the pandemic do, however, open the possibility of moving in directions that improve school quality and thus offer hope of eliminating the learning gap faced by today’s students”. Given the large impact of this estimate and its uncertainty, particularly due to policy changes induced by the grim outlook, costs of school closures were not included in the model. In any case, an inclusion would further increase the value of a vaccine and support the conclusions of this study.

Independent of questions around capturing additional value components, it may be reasonable to subtract from the value-based price the portion of the vaccine’s value that is based on government-funded R&D costs (Neumann et al., 2021). While the total subsidy by the German federal government for the three companies is known (€750 million), the total R&D spending incurred by the companies is not known, however.

It may be argued that vaccines against conditions more closely related to COVID-19 (e.g., SARS-CoV-1 and Ebola) would provide a more accurate estimate for the WTP for a COVID-19 vaccine. However, a vaccine against SARS-CoV-1 has never been brought to the market, and vaccines against Ebola exist but have not been launched in Germany. In addition, WTP values for other vaccines may not be comparable due to differences in route of transmission, CFR, and basic reproduction number (which may reflect a sense of urgency).

In terms of the transferability and relevance of the results and conclusions of this study to other countries, the usual caveats apply. The reasons for caution include between-country differences in clinical and epidemiological data, costs, and the WTP for health benefits.

To summarize, this study demonstrates the applicability of VBP to a novel COVID-19 vaccine. In spite of the non-negligible uncertainties around the mean, the value-based price shows a considerable deviation from the cost-based price.

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**Appendix A**

**Table A1**

Input data used for calculating the productivity loss due to an uncontrolled infection in the absence of a vaccine.

| Input                                      | Mean (range) | Reference                                                                 |
|--------------------------------------------|--------------|---------------------------------------------------------------------------|
| **Epidemiological**                        |              |                                                                           |
| IFR in Germany                             | 0.014        | Challen et al., 2021, Dimpfl et al., 2021, CDC, 2020                      |
| Percent of infections that are asymptomatic | 0.4          |                                                                           |
| Percent of diagnosed infections that are asymptomatic | 0.38          | Robert Koch Institut, 2020b                                               |
| Percent of diagnosed infections that are hospitalized | 0.07          | Robert Koch Institut, 2020b                                               |
| Quarantined contact persons per diagnosed case | 5           | Tagesschau, 2020                                                          |
| Number of newly diagnosed cases in August 2020 | 33,683       | Robert Koch Institut, 2020b                                               |
| **Cost data**                               |              |                                                                           |
| Hours worked per head and year in the population | 753.3        | Organisation for Economic Co-operation and Development, 2021              |
| Labor productivity per hour, €              | 55.1         | Organisation for Economic Co-operation and Development, 2021              |
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