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Research article

Creating the vaccination improvement potential index

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A B S T R A C T

Background: Numerous social and behavioral factors have been implicated in vaccination coverage. There is no single measure that describes a country's ability to improve or maintain its immunization coverage.
Methods: We estimated the "Vaccination Improvement Potential" (VIP) by taking the geometric mean of 13 different indicators on health financing, vaccine confidence, and socio-demographics for more than 200 countries across 30 years. Potential VIP Index values range from 0 to 1, with a higher score indicating greater potential to improve or maintain high vaccination rates.
Findings: In 1990, the mean VIP score was 0.49 (range = 0.13 to 0.86). In 2019, the mean score was 0.59 (range = 0.25 to 0.84). Consistent high performers included countries in Western Europe and high-income North America and East Asia. Important differences in subcomponents of the index drove major trends including vaccine hesitancy in Western Europe and Asia as well as lower levels of per capita health spending and development assistance in sub-Saharan Africa.
Interpretation: The VIP Index is a first-of-its-kind tool for understanding the capacity that exists in a country to realize improved immunization rates. It is a new resource that can guide researchers, policymakers, and health officials to more effectively deploy resources to realize improvements in vaccination coverage, assess the impact of those improvements, and identify countries that might require additional support to improve vaccine coverage.
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1. Introduction

Increasing routine childhood vaccination rates remains a high priority for the World Health Organization (WHO) since nearly 20 million children are inadequately vaccinated worldwide [1]. In some countries, improvements in immunization coverage have plateaued or even declined for important childhood vaccines including Diphtheria-Tetanus-Pertussis (DTaP) and measles (MCV) [1,2]. Prior research has identified that important determinants of vaccination coverage among children include demographic [3–5], socio-economic factors [6], healthcare system characteristics [7], and psychological or attitudinal barriers [8,9]. These disparate factors complicate efforts to improve coverage at a global scale.

Composite indices are one potential tool in making use of all the existing data related to childhood vaccination coverage. They have been used in prior instances to track progress and understand a variety of important and complex global health phenomena [10]. For instance, the United Nations developed the Human Development Index (HDI) to track achievement in human development over time for every country in the world [11]. Composite indices, such as the HDI, have been leveraged to stimulate debate about policy

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priorities, to investigate how countries with similar economies can end up with different human development outcomes. More recently, the Global Health Security (GHS) Index was developed to measure global variation in countries' capacity to prepare for epidemics and pandemics [12]. The multidimensional nature of the GHS Index illuminates how, even in countries with a foundation for preparedness, unique barriers or risk factors may limit their ability to mitigate the spread of disease.

There are many reasons why indices relating to vaccination coverage could be similarly leveraged to advance public health as has been done with human development and pandemic preparedness. Firstly, the importance of routine childhood vaccines for childhood mortality and international infectious disease control cannot be overstated. Secondly, routine childhood vaccinations have been studied extensively to understand determinants and risk factors contributing to vaccination uptake. Finally, although there are some exceptions, there are international standards that countries can follow for establishing and evaluating childhood immunization programs. Understanding vaccine coverage through an index is a crucial first step in identifying where there are gaps and how to make improvements. Recent studies have made progress in this respect. For instance, using measles as a case study, the Vaccine Risk Index (VRI) examines which factors are important determinants of risk of outbreak and specifically looks at geographic variation in the risk [13]. This index is constructed using key variables which measure the physical and social determinants of measles vaccination. Other composite indices have been developed to measure vaccine confidence [14] and vaccine equity [15] to promote the strengthening of vaccine interventions. However, these indices have all been focused on specific vaccines, disease burden, or hesitancy alone.

Our Vaccine Improvement Potential (VIP) Index builds upon prior work to understand the determinants of childhood vaccination as well as these other efforts which leverage indices to make sense of the different factors. By compiling data sources from almost 200 countries for the 30 years before the COVID-19 pandemic, we created an index that considers a wide range of indicators. We explore how demographic, socioeconomic, government/healthcare, and attitudinal factors have a direct impact on a country's ability to realize or sustain high immunization rates in the face of potential disruptors. Additionally, with a focus on health spending and healthcare quality, the VIP Index is well suited to understanding a country's ability to realize improvements in vaccine coverage through policy decisions and resource allocation. Making data-informed comparisons between all countries is essential to ensure that no country falls behind and that emerging threats to sustained immunization coverage can be addressed.

2. Methods

2.1. *Identifying index components*

We conducted a review of the literature to identify the factors previously established as important determinants of childhood vaccination rates. In our initial list we found approximately two dozen factors which we grouped into four categories: demographic, socioeconomic, government/healthcare, and attitudinal determinants (see Table 1 for factors identified initially).

The final version of our VIP Index was constructed using thirteen indicators for which we were able to find publicly accessible data which were uniformly available for multiple countries, regions, and years (Table 2). For the demographic determinants category, we included the proportion of population that are immigrants or residing in urban areas [5,16]. We also included the Socio-Demographic Index (SDI) since it is itself a composite of several key determinants such as education [4,5], and family size [16–18]. For socioeconomic factors, we included total health spending per person, government health spending per person, and development assistance for health since these have been identified as important determinants of vaccination coverage [7] and also the best proxies we could find for per capita spending on immunization programs. For government and healthcare factors, we included health care access and quality index and births attended by skilled healthcare staff [6]. We also included public perception of government corruption since this impacts a government's capacity to support the health of their constituents. For attitudinal factors, we included public perceptions of vaccine safety, importance, and effectiveness [3,8]. Public trust in government was also included as an attitudinal factor, because it has been found to be associated with vaccine uptake in recent studies [19].

2.2. *Data sources*

We used six data sources to construct our index (Table 2). Three indicators came from the 2017 Institute for Health Metrics and Evaluation (IHME) Financing Global Health (FGH) Report [20,21]: total health spending, government health spending, and development assistance for health for countries eligible to receive aid according to World Bank income levels [22]. Public trust in government was obtained from the World Values Survey (WVS) [23]. Perceptions of government corruption came from Transparency International (TI) [24]. Three indicators came from the United Nations (UN): births attended by skilled health workers [25], immigrant population [26], and urban population [27]. Three variables related to the public's belief that vaccines are safe, important, and effective came from the Vaccine Confidence Project (VCP) [19]. Two indicators came from the Global Burden of Disease (GBD) estimates: the Socio-Demographic index (SDI) [28] in the 2019 version, and the Healthcare Access and Quality Index (HAQI) from the 2019 data or the 2016 data for years that were not included in the latest estimate [28,29].

2.3. *Calculating the index*

To calculate the index, we estimated the geometric mean by multiplying together as many of the thirteen indicators available for each location for a given year between 1990 and 2019 and then taking the *n*th root of the product. For instance, if a location had all thirteen indicators available we would take the 13th root. If the same country only had 12 indicators available in a different year, we would take the 12th root. Through this method all of the indicators were weighted equally in creating the index. We chose this

Table 1
Indicators identified and considered in construction of the VIP Index.

Demographic Factors	Religious and minority group affiliation
	Immigration status
	Family size/Number of children
	Urban/Rural area of residence
	Maternal age
Socioeconomic Factors	Education level of parents
	Family income/financial barriers
	Parental occupation
	Vaccination status of mother and/orr caregivers
Government and Healthcare Setting Factors	Government health spending
	Civil unrest
	Gender inequity
	Government spending per birth
	Bribery
	Characteristics of the immunization system
	Proportion of births attended by healthcare staff
	Access to healthcare
	Quality of antenatal care
	Transportation and accessibility of health clinics
	Vaccine infrastructure and supply chains
Attitudinal Factors	Misleading knowledge about vaccines
	Perceived vaccine safety
	Confidence in vaccine importance

Table 2
Characteristics of the data sources used to construct the VIP Index.

	Source[1]	Indicator	Original unit of measurement	Direction of association with vaccination coverage	Years	Frequency	Countries Represented	Theoretical Category
1	IHME FGH	Total health spending per person	2020 USD per person	Positive	1995–2018	Annual	204	Socioeconomic
2	IHME FGH	Government health spending per total spent	Percent	Positive	1995–2018	Annual	204	Socioeconomic
3	IHME FGH	Development assistance for health per person	2020 PPP per person	Positive	1995–2018	Annual	204	Socioeconomic
4	WVS	Trust in Government	Percent	Positive	1990–2020	Every 10 years	101	Attitudinal
5	TI	Corruptions Perception Index	Index (0–1)	Negative	2012–2020	Annual	178	Government and Healthcare
6	UN	Births attended by skilled healthcare staff	Percent	Positive	2000–2020	Annual	196	Government and Healthcare
7	UN	Immigrant population proportion	Percent	Negative	1990–2020	Every 5 years	203	Demographic
8	UN	Urban population proportion	Percent	Positive	1950–2020	Every 5 years	204	Demographic
9	VCP	Vaccines considered safe	Percent	Positive	2015–2020	Annual	145	Attitudinal
10	VCP	Vaccines considered important	Percent	Positive	2015–2020	Annual	145	Attitudinal
11	VCP	Vaccines considered effective	Percent	Positive	2015–2020	Annual	145	Attitudinal
12	GBD	Socio-Demographic Index	Index (0–1)	Positive	1990–2019	Annual	204	Demographic
13	GBD	Healthcare Access and Quality Index	Index (0–1)	Positive	1990–2016	Every 5 years	195	Government and Healthcare

[1] IHME FGH=Institute for Health Metrics and Evaluation Financing Global Health Report; WVS=World Values Survey; TI = Transparency International; UN=United Nations; VCP=Vaccine Confidence Project; GBD = Global Burden of Disease.

approach because of its simplicity and because it has been used to construct other health-related indices [30]. This form of calculating the average required two steps (1) performing the necessary data transformations, and (2) dealing with missing data in indicator values.

2.4. Data transformations

We conducted the necessary transformations in order to create consistency across index components and calculate the geometric mean. We ensured that the data satisfied the following requirements: (1) there were no values of zero, (2) all numbers were positively associated with the outcome of interest, (3) all variables were normally distributed or transformed to approximate a normal distribution, and (4) all component variables ranged from 0 to 1.

The first step in transforming the data was to remove all values of zero. The only variable with zero as a potential value was development assistance for health (DAH) since some high-income countries may not be eligible to receive funds. DAH was only included as a component in the index for locations that were eligible to receive such funds each year. DAH eligibility was determined yearly for each location using eligibility criteria that is based on country income level as determined by the World Bank. High-income countries and upper middle-income countries were deemed not eligible for development assistance and low-income countries were considered eligible. Middle income and lower middle-income countries were determined eligible only for all years in which they received funds. Determining development assistance for middle income countries is more complex and is classified by disease burden in addition to income. All locations had a constant of 1 added to avoid zero values.

The next step was to ensure that all variables were positively associated with vaccination coverage. Two variables were negatively associated with vaccination coverage initially and required transformation: the Corruption Perception Index and immigrant population proportion. For these variables, a lower number is associated with better vaccination improvements. In order to reverse their association with the outcome, improved vaccination coverage, we calculated the complement of the two variables. Since each of these variables originally ranged from 0 to 100, we subtracted all values from 100 to create a new variable that represents the complement of the original value. The exact formula is shown below:

$$\textit{Final index value with positive association} = 100 - \text{actual value}$$

We also ensured all variables followed a normal distribution. Four variables did not approximate a normal distribution and required transformation: total health spending, development assistance for health, proportion of births attended by skilled healthcare staff, and immigrant population proportion. Total health spending and development assistance for health were transformed by taking the natural log of the value (log transformed). Proportion of births attended by skilled healthcare staff and immigrant population proportion were raised to the third power (cubed).

Finally, total health spending and development assistance for health did not range from 0 to 1 either before or after transforming them so we re-scaled them using the following normalization formula:

$$\textit{Final index value} = \frac{\textit{actual value} - \textit{minimum value}}{\textit{maximum value} - \textit{minimum value}}$$

2.5. Missing data

We used regression models to account for missing data where estimation was appropriate. Some indicators had a higher rate of missing values because they were not available for all years or all locations. For instance, immigrant population size is estimated every five years. To address this issue, we fit a regression with year as a predictor in each country to ensure the following variables with missing values had a complete time series: SDI, total health spending, DAH, government health spending, HAQI, births attended by skilled, immigrant population size, urban population, and the public's trust in their government. The regression model depended on the variable type: we used linear regression for monetary variables (such as total health spending, and development assistance for health) and logistic regression for variables that range between 0 and 1 (all other variables).

Although variables such as corruption perception and those related to vaccine confidence had some missing data as well, we did not use regression to complete these values to avoid extrapolating beyond the observable data. We included these variables in our analyses for years and locations in which they are available for a particular country. Table 2 provides full details on years and countries included in each dataset.

All analyses were conducted using R version 4.1.3 [31].

3. Results

VIP Index results were produced for 204 countries for each year between 1990 and 2019. Potential VIP Index values range from 0 to 1, with a higher score indicating greater potential to improve or maintain high vaccination rates. In 2019, the mean vaccine index value was 0.60, and ranged from 0.26 (in Somalia) to 0.87 (in San Marino). In 1990, the mean vaccine index potential value among all countries was 0.52, and ranged from 0.17 (in Somalia) to 0.86 (in Iceland). The difference between the highest and lowest scoring countries was smaller in 2019 (0.34) compared to 1990 (0.69). The lowest scores were found in several regions in sub-Saharan Africa and South Asia in both 1990 and 2019 (Fig. 1). In 1990, Myanmar, Somalia, Afghanistan, Ethiopia, and the Democratic Republic of the Congo had the lowest scores. By 2019 most of the lowest ranked countries in 1990 saw an improvement in VIP except Somalia, which had a similar low ranking over the 20-year period. Regions with a high score in 1990 included Western Europe, North America, and Australasia (Fig. 1). These regions generally continued to have higher scores on average in 2019, although there were some decreases in the countries within some of these regions as well (Fig. 2).

The highest scoring countries in 2019 tended to have high proportion of births overseen by skilled attendants and, high government

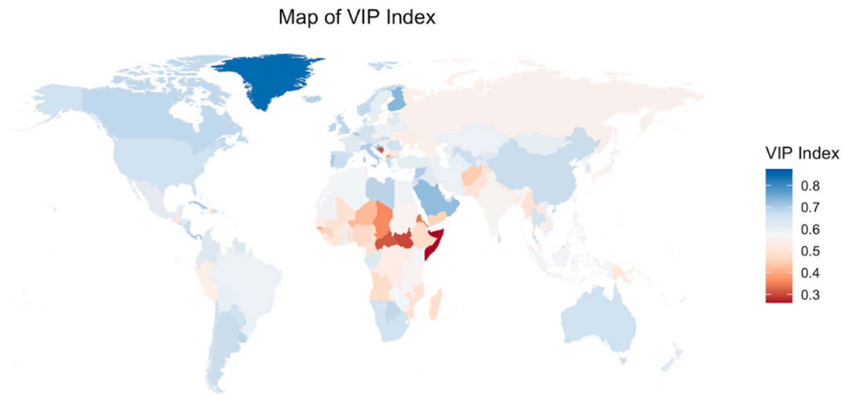

Fig. 1. Map of VIP Index results in 2019.

spending on health, and high percentage of population residing in urban areas (Fig. 3). The lowest scoring countries in 2019 on the other hand had a low proportion of births overseen by skilled attendants and low levels of government health spending (Fig. 4). Additional exploration of VIP Index results can be done by accessing our study's visualizations on our project website at https://rsc.csde.washington.edu/vaccinationimprovementpotential/.

The factors contributing to decreased index scores tended to be similar within regions. For many countries in Western Europe, such as France, Switzerland, Sweden, Italy, and the United Kingdom, survey data on vaccine confidence lowered the overall VIP Index results in these locations. Data has shown that these and many other countries in the region have relatively lower rates of public trust in the safety and effectiveness of vaccines. Similar trends in vaccine confidence occurred in several East and Southeast Asian countries such as Japan, the Republic of Korea, Singapore, Vietnam, and the Philippines. Countries in sub-Saharan Africa, in contrast, reported relatively high levels of trust in vaccination safety and effectiveness. Countries in this region, however, reported generally low levels of overall health-related expenditures and government spending on health, as well as low-levels of births attended by skilled health workers, which affected their index results. Countries in South Asia also had relatively low values on the Socio-Demographic Index as well as low levels of health-related expenditures, government-spending on health, and development assistance for health which resulted in lower VIP Index results.

4. Discussion

This project successfully created a first-of-its-kind global Vaccination Improvement Potential (VIP) Index that summarizes the potential that exists within countries to improve and sustain high-vaccination coverage. This index was built using existing data on some of the most important variables that have been previously found to be determinants of vaccination rates: including socio-demographic characteristics, government spending, health care system characteristics, and personal attitudes and beliefs. Our index results for more than 200 countries over the past three decades revealed distinct geographic patterns in the index results. In 2019, countries in sub-Saharan Africa (such as Somalia and South Sudan) had the lowest VIP Index values (between 0.25 and 0.27). While high-income countries in Western Europe (such as Finland and San Marino) and North America (such as Greenland) had the highest scores (between 0.72 and 0.84). Although the average index scores improved for all countries between 1990 and 2019, the general regional differences between Sub-Saharan Africa and Western Europe remained, further highlighting another health-related disparity that has persisted between these regions. This is consistent with reporting data which has shown that the Africa region continues to have a large portion of children that have not been vaccinated [1].

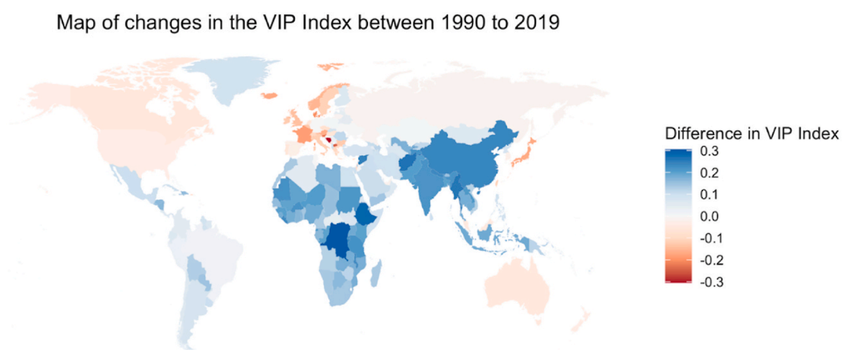

Fig. 2. Map showing the difference in VIP Index results in each country between 2019 and 1990.

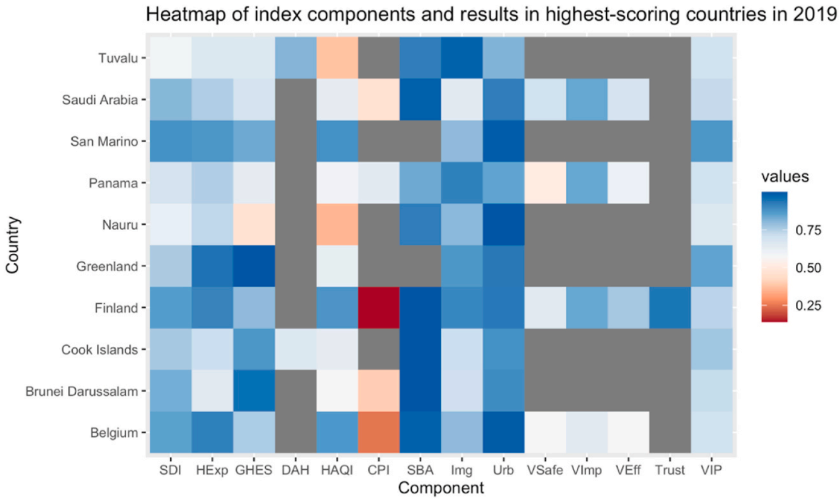

Fig. 3. Component[2] scores and final VIP value for the highest-scoring countries in 2019.

[2] SDI=Socio-Demographic Index; HExp = Overall health expenditure; GHES = Government spending on health; DAH = development assistance for health; HAQI=Healthcare Access and Quality Index; CPI=Corruptions Perception Index; SBA=Skilled Birth Attendants; Img = Immigrant Population; Urb = Urbanicity; VSafe = Vaccines considered safe; VImp = Vaccines considered important; VEff = Vaccines considered effective; Trust = Government Trust; VIP=Final VIP Result.

Our study also found that nearly all regions had at least one persistent or emerging issue of concern with regards to the index subcomponents. For instance, in recent years vaccine confidence contributed to lower index results in Western Europe, East Asia, and Southeast Asia. Similarly, public trust in government has seen steep declines in Latin America, North Africa, Middle East, and Central Europe. In addition, lower levels of health spending per capita and development assistance could jeopardize ongoing improvements in coverage in several areas of sub-Saharan Africa and South Asia. The trends of worsening vaccine confidence are of concern given that rise of vaccine misinformation spread through social media [17] and the potential for misinformation through spread between countries and regions with a shared language, histories, or extensive communication. Similarly, declining levels of government trust are important given how trust in government was one of the drivers of COVID-19 preparedness during the earliest days of public health emergency [16]. Ongoing conflict and wars in several regions could similarly contribute to reducing coverage through instability and lack of trust in institutions [1].

Although no index can perfectly capture the real-world forces which determine vaccination coverage, having a single summary measure for each country and year can simplify efforts to track change for a given country, evaluate national interventions, compare within and between regions, and identify positive outliers worthy of further investigation.

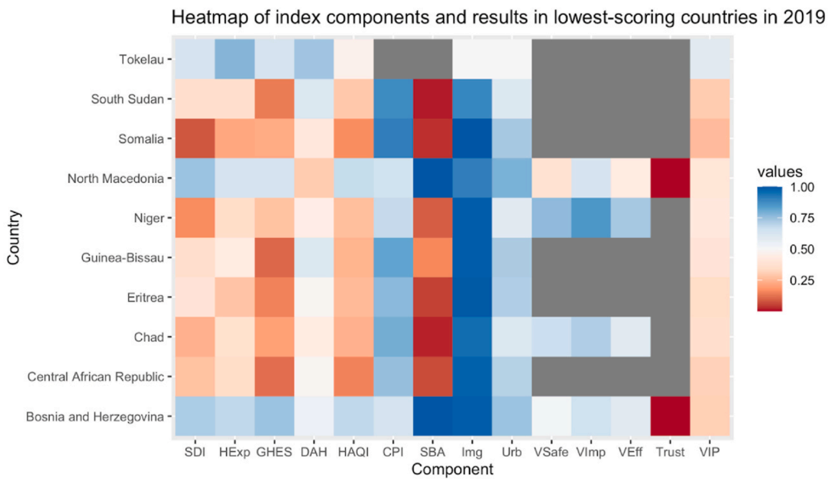

Fig. 4. Component scores and final VIP value for the lowest-scoring countries in 2019.

4.1. Limitations and future expansion

Our study had a few limitations. First, we relied upon the published literature to understand the determinants of childhood vaccination coverage and it is possible that we could be missing important factors that are not reflected in previous published studies. Secondly, we did not collect data ourselves and relied only on publicly available data sources to conduct our analyses. Although we were able to identify data for several important determinants of vaccination coverage, we were unable to find standardized and high-quality information on factors which influence adequate vaccination supply such as transportation systems, breaks in the vaccine cold chain, or vaccine stock management. For the secondary data included, potential quality issues diminish the precision of our VIP Index. Additionally, not all datasets have the same number of countries and years represented which may limit comparisons. Increased data availability in the future could result in an even greater predictive power of the index. Furthermore, incorporating uncertainty from the data sources could improve confidence in the index and assessment of data quality. There exist multiple potential methods to construct an index such as ours with each having different strengths and limitations.

Our study specifically focused on factors that are important drivers of routine childhood immunizations and there is room for additional research on the VIP Index's utility. Future research could also evaluate whether the VIP Index can be applied to understand other vaccines such as those against Human Papilloma Virus or whether more additions are necessary to refine the use of this index for other adolescent and adult vaccines.

Future versions of the VIP Index could include subnational analyses to identify specific areas within countries that are showing unique patterns of vaccination improvement potential, or locations that are falling behind and struggling to improve. Similarly, creating subdomains of the index could also be helpful in identifying trends in different dimensions of importance and making the data easier for policy purposes.

Finally, the VIP Index is pre-COVID. Future versions of the VIP Index should incorporate the most recent data. Considerations of additional indicators specific to the ways in which the COVID-19 pandemic changed determinants to vaccination and global perspectives on vaccines should be addressed.

5. Conclusion

Our VIP Index has a unique capacity to summarize important patterns and trends on the capacity to improve and sustain high childhood vaccination coverage around the world. We found there were distinct regional patterns in VIP Index results. Consistent high performers included countries in Western Europe and high-income North American and Asian countries. There were also important differences in subcomponents of the VIP Index between regions. For example, increased vaccine hesitancy in recent years was found to pose a risk to high vaccine coverage in Western Europe and several regions of Asia. Our findings suggest that targeting key components of the VIP Index could help realize improved vaccination rates, especially for countries with low Socio-Demographic development. The VIP Index could be an additional and important tool, similar to other public health indices, which can be used with a variety of data to guide researchers, policymakers, and health officials in more effectively deploying resources to realize improvements in vaccination coverage and reduce disease burden.

Role of the funding source

The funders of the study had no role in study design, data analysis, data interpretation, or writing of the report.

Data availability

All statistical code to conduct the analysis is available at https://github.com/Frank31/uw-phi-vax/tree/main/global_vac_index. The original raw files can all be accessed from publicly available sources referenced in the methods section. However, we also include data that was processed and cleaned in a standardized format for all analyses on our project repository to assist in reproducibility and transparency.

CRediT authorship contribution statement

Francisco Rios Casas: Writing – review & editing, Writing – original draft, Formal analysis. **Jacob Armitage:** Writing – original draft, Visualization, Formal analysis. **Joanna Yuan:** Writing – original draft, Visualization. **Shan Liu:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Ali H. Mokdad:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ali Mokdad reports a relationship with Merck Sharp & Dohme Corp that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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