The international trade in human vaccines before COVID-19

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Abstract:

The current Covid-19 pandemic has highlighted the importance of global access to human vaccines. There is, however, no empirical work on the determinants of their international trade. Applying a gravity model to the UN Comtrade database between 2000 and 2019, we analyse the determinants of bilateral trade across 116 countries. Using the Poisson Pseudo-Maximum Likelihood (PPML) methodology, our results show that inequalities in international vaccine trade have steadily increased. Broadly speaking, rich countries invest more in R&D to create expensive vaccines, manufacture a wide variety of human vaccines, consume their most expensive products, and export to the rest of the world. Middle-income countries are newcomers to manufacturing and increasingly export to developing countries. Finally, driven by immunization campaigns by international organizations, low-income countries act as net vaccine importers. The increasing imbalance endangers the global fight against the current Covid-19 pandemic.

Keywords: human vaccines, bilateral trade, global inequalities, Covid-19.

JEL Codes: F14, F63, I15, H51

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1. Introduction

The dramatic consequences of the Covid-19 pandemic on worldwide health and economic activity forced pharmaceutical companies and governments to develop vaccines to stop the virus spreading. In parallel, the WHO, non-profit organizations, and private foundations started inviting state administrations to join the Vaccine Global Access Facility (COVAX Facility) to ensure that vaccine doses were distributed to the most vulnerable global populations. However, there is a very unequal access to vaccines depending on the level of income of the population and the strength of their health systems (Agarwal and Gopinath, 2021).[1] Since contemporary societies facilitate the spread of those diseases that are transmitted through human contact, especially those that involve airborne germs or that persist on commonly used surfaces (Tisdell, 2020), all countries need vaccines to fight global pandemics. However, only a scarce number of countries have the capacity to produce them. Hence, it is essential to explore the trends in global trade in human vaccines in recent decades to completely eradicate the current pandemic.

This paper analyses the drivers of international trade in human vaccines during the period 2000–2019, paying particular attention to the differences in the determinants among three clusters of countries: OECD members or high-income countries, middle-income countries, and low-income countries.[2] Despite the relevance of the topic and the proliferation of studies on the Covid-19 pandemic, to date the literature on bilateral trade in human vaccines between countries is sparse (Narayan, 2021). Equitable global distribution of vaccines is an ethical and humanitarian responsibility for developed countries, one which also results in significant economic benefits for the world economy. Thus, if we want to minimize the economic costs of the pandemic, a coordinated worldwide push is required to produce and distribute Covid-19 vaccines (Cakmakli et al., 2021). Although, in an unprecedented effort, the big pharmaceutical companies have produced a large number of effective vaccines in a short time, the dose distribution in lower income countries has been low. Therefore, understanding the drivers of worldwide trade in human vaccines is necessary for successfully distributing the Covid-19 vaccines globally.

To undertake this study, we use an exhaustive information contained in the Trade Statistics Database (UN Comtrade) for nearly 200 countries over the period 2000–2019. After data cleansing,

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[1] At the end of 2021, only 58.3% of the world population has received at least one dose of a Covid-19 vaccine. However, this share hides an unequal vaccine distribution; while in high-income countries 78.3% of the population received at least one dose, in low-income countries this figure was a mere 8.5% (Our World in Data).

[2] We do not distinguish between the terms "high-income" and "developed" countries for OECD member countries, while we divide developing countries into two groups: the "middle-income" and the "low-income" countries. We also refer the latter as "poor" countries.

our final sample contains bilateral human vaccine flows for 116 countries representing more than 95% of the world's population. Of these, 34 countries belong to the OECD (high-income countries) group, 38 to middle-income countries, and the remaining 44 to the low-income country group.[3] At methodological level, we apply a Poisson Pseudo-Maximum Likelihood (PPML) estimation method proposed by authors such as Larch et al. (2019) and Santos Silva and Tenreyro (2006).

Our empirical results identify the influence of the drivers on the demand and supply of human vaccines. These highlight that the drivers of such international trade clearly differ across the three groups we consider. For high-income countries, pull drivers related to health and GDP per capita, together with some push drivers (such as the public funding of R&D and tax advantages) are the main export determinants. Most low-income countries act only as importers and factors related to population size are the main determinants of bilateral trade.

As far as we are aware, there are no similar empirical works in this field. This should not be surprising when we consider that studies on bilateral trade drivers in pharmaceutical products have received little attention. Among previous studies, we note the value of Blanc (2015), Boring (2010), Joshi (2015), Lee and Yun (2018) and Smith (2002). For instance, Smith (2002) shows the importance of patents on the trade flows of biological products. Blanc (2015) analyses the determinants of EU exports of pharmaceuticals. Her findings show the main drivers are the protection of intellectual property in the final countries, the economic size of final markets, the importance of their health sector, and the quality of their infrastructures. Finally, Lee and Yun (2018) analyse the global pharmaceutical value chain in South Korea. They show that the pharmaceutical value chain is heavily regional, where European countries are positioned as a first-tier supplier and the Asian region as the second-tier supplier. Therefore, we contribute to analyse the determinants of the international trade of a specific pharmaceutical product.

From a policy point of view, our results show that low and rich countries have different drivers of the international trade that lead to an unequal distribution of vaccines in the world. Consequently, the market-driven paradigm seems insufficient to address the unequal effects of Covid-19 across social groups, income levels, and countries. This suggests that the development of more ambitious

[3] Over the period considered, the three subgroups show clear differences in their international trade patterns. OECD member countries accounted for 98% of worldwide exports (Belgium, Ireland, France, United States, United Kingdom, among others); middle-income countries such as India, China, and Singapore exported mainly to less developed countries which, in turn, acted as net importers thanks to the support from international health agencies. Most developing countries are net importers. Developed countries absorb 85% of world vaccine imports, while developing countries receive only the remaining 15%.

vaccination strategies may help to control the current pandemic. For instance, it will be necessary to re-allocate resources from mature vaccines to developing countries and there will be an undoubted overall growth in the human vaccine market over the next few years. This is an important issue if we cannot ignore the fact that vaccination programs will only achieve herd immunity when a high proportion of the population is vaccinated (Neumann-Böhme et al., 2020), especially in cases like Covid-19 where the rate of infection and the severe symptoms create a risk of collapse for health systems in some countries.

The paper is organised as follows. Section 2 reviews the theoretical and empirical literature on the pharmaceutical industry and bilateral trade. Section 3 presents our hypotheses and Section 4 describes the database and our econometric methodology. Section 5 contains the results obtained and, finally, Section 6 provides our main concluding remarks.

2. Patterns of international trade in human vaccines

The international trade in human vaccines has specific features which are summarised in the following points. First, it is a high growth market. Global exports of human vaccines amounted 31.7 billion US $ in 2019. During the period 2015–2019, the human vaccine trade increased by 19.8%, and the Covid-19 pandemic will undoubtedly cause considerable further growth. Second, the market is highly concentrated. In 2019, European suppliers accounted for 87.5% of global human vaccines exports, North American exporters 7.8%; Asian exporters 4.3% and Oceania 0.3%, while other areas exported negligible amounts. Third, low-income countries participate less in the international trade of human vaccines. During the first decade of the 21st century, bilateral flows of vaccines to countries with the lowest per capita income increased, but the flows decreased after the 2008 crisis. Fourth, the vaccine trade has become a regional trade, where pharmaceutical firms locate in some developed countries and invest substantial amounts in R&D to develop human vaccines for these markets. Consequently, the trade of human vaccines among OECD countries has grown, while remaining stable or decreasing between developed and developing countries.[4]

Overall, the global trade of human vaccines between countries shows persistent imbalances which are related to per capita income. First, although the populations with the highest exposure risks live in countries with low per-capita income, the global market for vaccines continues to be

[4] According to the Global Forum for Health Research, only about 10% of global spending on US health R&D went to research on 90% of the world's health problems. The 10/90 ratio reflects a broader problem best described as the growing number of "underserved populations". This problem has increased in recent years as large pharmaceutical corporations invest increasing R&D resources in the development of vaccines for developed countries, to the detriment of diseases that predominantly affect developing countries, the "neglected diseases" (Viergever, 2013).

concentrated in a few developed countries (Jadhav et al., 2014).[5] Second, developed countries purchase the most expensive and modern human vaccines, while low-income countries suffer a high impact from diseases preventable by vaccination. Third, there is an imbalance in production and international dependence. Despite WHO programs to promote the global vaccine production capacity, OECD countries are net exporters of human vaccines, while many developing countries import doses of human vaccines designed to immunise their local population. Fourth, a group of strong suppliers in emerging economies such as China, Brazil and India has appeared. Their success is mainly attributable to the development of an intellectual property system that significantly reduces production costs and achieves the strict quality controls mandated by international organisations (Antoñanzas et al., 2011; Milstien et al., 2007).

Finally, there is a clear imbalance between demand needs and private incentives. Human vaccine producers have few incentives to develop products with low commercial margins (Offit, 2005; Rovira, 2002).[6] There are several reasons for this. First, human vaccines are usually a single dose (or at most a few). Second, the demand for these low-margin vaccines is uncertain and depends on the results achieved during the vaccination campaigns. Finally, the vaccine demand in developing countries also depends on the decisions taken by the WHO, UNICEF, or non-profit organisations in their immunisation programs (Milstien and Kaddar, 2006). Consequently, since rich markets can pay higher prices, the R&D costs for the development of new human vaccines have increased. These higher prices in developed countries work to the detriment of social responsibility for the population most affected by diseases in developing countries (Plotkin et al., 2017).

To shed some light to these features, Table 1 presents the absolute values of trade for our three country clusters. We distinguish between relative values according to the final markets (percentage of supply) and the share of the origin of the imports for each group (percentage of demand). Our results show that high-income countries act as final markets. This confirms that rich countries mainly produce products characterised by high value-added and high prices intended for countries that are also rich. Conversely, emerging countries mainly trade with poor countries. Interestingly, we observe diverse markets where buyers and sellers exchange differentiated goods.

Table 1. Bilateral trade of human vaccines (2000–2019)

	Importing countries	
	Absolute values (millions $)	**Relative values of supply**

[5] According to the UN Comtrade dataset, during the period 2000–2004, OECD member countries accounted for 96.33% of global exports (73.66% of imports) in current dollars. For the period 2014–2018, the corresponding figures were 96.08% of exports (80.14% of imports).

[6] Stern and Markel (2005) stated that "many pharmaceutical companies avoid the vaccine business because it is economically prohibitive and encumbered by regulatory barriers".

Level of income in the country according to the World Bank			High	Medium	Low	High	Medium	Low
Exporting countries	Absolute values	High	235000	31900	16900	83%	11%	6%
		Medium	114	953	1940	28%	24%	48%
		Low	513	1230	3340	10%	24%	66%
	Relative values of demand	High	99.3%	93.6%	76.2%			
		Medium	0.5%	2.8%	8.57%			
		Low	0.2%	3.6%	15.1%			

Source: own elaboration from UN Comtrade. N.B. The data on the three income groups covers 98% of the human vaccine world exports, and 99% of world.
Note: Table A-2 in Appendix 1 contains a complete list of countries per cluster.

Concerning the relative values of demand, the results reveal a high dependence of all countries for production originating in rich countries. The most extreme data belongs to the rich countries with a 99.3% share, while low-income countries have a relatively high share of trade in low-income countries. Therefore, despite a high share of the vaccines produced in low-income countries having as final market other low-income countries, this production is not enough to satisfy their needs.[7]

3. Hypotheses

From a supply-demand side, the drivers of low-profit markets such as vaccines can be grouped into "push" and "pull" forces (Milstien and Kaddar, 2006). In essence, a human vaccine is developed either because of a clear demand (a "pull demand force"), or because it becomes technically and operationally feasible (a "push supply force"). The following subsections develop our hypotheses.

3.1. Demand drivers: health system and market size

Demand forces are crucial in explaining the bilateral trade in human vaccines. The level of global health in each country constitutes one of the most relevant "pull demand forces" in the global vaccine market.

On the one hand, there is evidence that the vaccine market is stratified by income segment (Cernuschi et al., 2020). In 2017, high-income countries accounted for 56% of the total market value, followed by middle-income country market at 26%. Furthermore, the middle-income countries received little financial support from donors for vaccine purchases and limited vaccine price and market information, hampering their ability to negotiate equitable prices. Conversely,

[7] Appendix 2 highlights the heterogeneity of the international trade of human vaccines across countries (Table A-6). The results for the skewness and kurtosis (Table A-7) are highly concentrated regardless of we consider the intensive margin and the number of markets. However, the skewness analysis is not significant for the period 2009–2019.

low-income countries received financial support for low-priced purchase of vaccines. Most middle-income countries have two challenges: they are slow to introduce new vaccines and, in some cases, lag behind in the coverage of traditional vaccines.

On the other hand, health system expenditure affects vaccine demand. Countries with a strong health system will ensure domestic demand for medical goods and facilities, whereas poor countries lack the resources to become active participants in this international trade niche. An extremely low (or non-existent) level of investment in public health is a key characteristic of these countries, who often rely on WHO and UNICEF campaigns. This factor becomes relevant in the human vaccine context, as does the location patterns of vaccine manufacturers and the specific industrial and technological production skills needed.

Furthermore, the development of new vaccines depends on market size. For instance, using US and OECD data, Acemoglu and Joshua (2004) investigate the effect of market size on drug entry and pharmaceutical innovation. Their results show that the development and launch of new drugs are susceptible to standard economic explanations such as market size. Furthermore, they show the reaction to the entry of non-generic drugs, "which correspond more closely to new products and innovation." Consequently, we expect that market size and the investment in health system will positively affect the demand for vaccines.

> **H1: The national health system and country market size foster international trade in human vaccines.**

3.2. Supply drivers: R&D investments and pharma specialisation

The relationship between R&D investment and pharma specialisation is clear in the literature. R&D processes act as a "push supply force" for low-profit vaccine markets since a stronger innovation structure at country level will facilitate production of more added-value pharmaceutical products. Consequently, a stronger R&D and innovation system is particularly important due to the incentives that apply to private companies. The connection between public basic research and the development of new medicines is clear. Cohen et al. (2002) reported that public research influenced new project ideas in the pharmaceutical industry more than in any other manufacturing industry. Similarly, Toole (2012) shows that public basic research fosters the entry of new drugs. As pointed out in Plotkin (2005), the consequence is that, if manufacturers do not see an evident feasibility for the scaling up and production of a particular vaccine from academia or a biotech firm, its production will quickly be abandoned. Therefore, public research usually plays a crucial role in the earliest stage of pharmaceutical drug discovery. Conversely, having a robust R&D system is a necessary, but not sufficient, condition for exporting pharmaceutical industry products. Since countries with strong innovation system may foster the added value of vaccine production, then we expect that the trade in human vaccines will be higher in countries with more R&D investment.

This has caused a division in the production of high-added value vaccines in countries with intense R&D investment, and the production of low added-value vaccines in countries with weak innovation systems. The result is the production fragmentation, which has facilitated that some developing countries (India, Singapore, and Indonesia) have become large-scale vaccine manufacturers, while international vaccine trade remains concentrated in a few logistic hubs. These countries are both major exporters and importers of human vaccines. Thus, the relationship between demand (import) and supply (export) of human vaccines will differ between developed and developing countries. As described by Melitz (2003) and Helpman and Melitz (2004), international trade between firms located in different markets may explain the expansion of the pharmaceutical industry among countries and the intra-industry trade growth among countries.[8]

H2: R&D investments promote exports of human vaccines.

In the pharmaceutical industry, accumulated experience and learning are huge advantages for production and internationalisation activities.[9] Hence, technological spillovers from robust scientific, technological, and innovative systems and universities are the fundamental determinants for the location of large companies' research centres (US, Germany, and France, among others). Finally, the extension of intellectual property rights abroad has also facilitated the growth of international trade in human vaccines (Pore et al., 2008), together with a higher interest in searching for market opportunities abroad and the lower productivity in developed countries. Therefore, we expect that countries specialised in pharmaceutical activities will generate virtuous cycles that facilitate the production of human vaccines and their export.[10] Our hypothesis is the following:

[8] Despite not being the aim of the article, we must point out that the Covid-19 pandemic has modified the strategies of multinationals have modified (Antràs, 2020) and will alter global value chains (Strange, 2020). Covid-19 may have affected also to the production fragmentation developed by multinationals producing vaccines.

[9] Malerba and Orsenigo (2015) present the traits of the pharmaceutical industry from an evolutionary approach. This is characterised by the historical evolution of different agents due to the adaptation to knowledge and the technological context, firms' strategies, demand, and institutional frameworks.

[10] Since the vaccine industry belongs to the pharma industry, we could think that there is a certain endogeneity among both industries. Consequently, the general trade in the pharma industry may condition to the vaccine industry. However, the vaccine industry represents a relatively small share in the pharmaceutical industry. As pointed out by Douglas and Samant (2018), in the past 20 years, the vaccine sector, previously a mature sector in the pharmaceutical business, has shown remarkable growth fueled by innovative new vaccines coupled with superior pricing strategies. Therefore, the evolution of trade in a particular sector may not condition the evolution of the pharma industry given its small share.

H3: Countries specialised in pharmaceutical activities present a higher exporting propensity for human vaccines.

Finally, we include an explanatory variable that captures differences in the relative factor endowments between trading countries. Specifically, this index measures the difference in GDP per capita for each pair. Although this index is correlated with more insightful indexes such as the Economic Complexity Index, it is simpler in both formulation and interpretation.

According to New Trade Theories, the scenarios are usually two. On the one hand, if the associated coefficient is positive, it implies that flows between countries with different GDP per capita are predominant. On the other hand, a negative relationship hints at an intra-industrial type of trade. Major differences in GDP per capita signal country pairs whose factorial endowments are quite different, and which would negatively affect the transaction. In this scenario, similar countries trade among themselves.

Given the above, and the preliminary hints that the data offer in terms of overall flows, we hypothesise that:

H4: International trade is characterised by flows going from more advanced and developed countries to poorer countries, which lack the economic structure to produce the needed human vaccines.

4. Data sources and econometric methods

Our analysis is based on the bilateral trade flow data compiled by the United Nations Statistical Division in the Comtrade database.[11] The data spans the period 2000–2019, covers nearly 200 countries, and reports bilateral trades for over six thousand goods, classified according to the Standard International Trade Classification and the Harmonized System (HS), which can be broken down to the 6-digit level. For the purposes of this work, we use the HS classification.

We focus on a specific 6-digit product: 300220, human vaccines. In addition, to reduce biases due to lack of data, we restrict the sample to those countries with populations greater than 1.5 million inhabitants. We categorize countries on three clusters: OECD or high-income countries (34

[11] Specifically, we rely on The Growth Lab at Harvard University: International Trade Data (2019) version of the data, which applies a cleaning process, known as Bustos-Yildirim method, with the aim of increasing the consistency and reliability of trade flows by combining export and import information.

countries), middle-income countries (38 countries), and low-income countries (44 countries). Table A-2 in Appendix 1 contains a complete list of countries per cluster. Additionally, we match the international trade values with different geographical and socio-economic data from a small number of validated sources. First, we include distances, common languages, and borders from the GeoDist database, compiled by CEPII. Then, we add records on immunisation ratios and expenditure on the national health systems from the WHO.

After these refinements, we end with more than 59,000 observations of global bilateral trade of human vaccines relative to 2000–2019 and the associated, previously mentioned, country-level information, varying both by country and by year. Our data set includes 116 countries which together account for 99% of exports and 98% of world imports of human vaccines.

Concerning the empirical methodology applied, our point of departure is recent developments in the field of gravity models. The gravity model takes Newton's Law of Gravity (stating that the gravity between two objects is positively related to their masses and inversely related to the distance between them), as a point of departure. Gravity equations can be restated in the following log-linear form,

$$\ln X_{ijt} = \alpha + \beta_1 \, lnGDP_{it} + \beta_2 \, lnGDP_{jt} + \beta_3 \, lnD_{ij} \qquad [1]$$

where X_{ijt} are the exports from country i to country j, GDP corresponds to the Gross Domestic Product (GDP) of countries i and j, and D is the geographical distance between the two countries. In the empirical estimations, usually the β_1 and β_2 parameters are positive and β_3 has a negative sign.

Recently, the econometrics of the gravity equation has advanced in correcting biases that occur in estimates of trade flows between countries. Specifically, the issues concerning zero trade values and heteroskedastic residual have attracted debate (Martínez-Zarzoso, 2011). To address these issues, Santos Silva and Tenreyro (2006) show that PPML is more appropriate than the traditional OLS technique. PPML assures maximum likelihood estimation convergence. Finally, PPML facilitates the inclusion of fixed effects for large data sets and allows for correlated errors across countries and time.[12]

Our final equation takes the following form:

[12] For a more complete explanation of gravity models see Yotov (2016).

$$X_{ijt} = exp\big(\alpha_0 + \alpha_1 POP_{it} + \alpha_2 POP_{jt} + \alpha_3 GDPpc_{it} + \alpha_4 GDPpc_{jt} + \alpha_5 DIST_{ij} + \alpha_6 COMMON_{ij} + \alpha_7 BORDER_{ij} + \alpha_8 GLindex_{it} + \alpha_9 DTP3_{it} + \alpha_{10} DTP3_{jt} + \alpha_{11} PRIV_{it} + \alpha_{12} PRIV_{jt} + \alpha_{13} HEALTH_{it} + \alpha_{14} HEALTH_{jt} + \alpha_{15} RD_{it} + \alpha_{16} RD_{jt} + \alpha_{17} PHARMA_{it} + \alpha_{18} SIMILAR_{ijt} + \lambda_t\big) + \varepsilon_{ijt} \quad [2]$$

where X_{ijt} are the vaccine exports from country *i* to country *j* in year *t* expressed in current US$. *POP* denotes the population of each country, *GDPpc* is the income per capita (current purchasing power parity, US$ per thousand inhabitants) of countries *i* and *j* respectively, and *DIST* is the distance in kilometres between the capitals of a pair of countries. There are also some standard control variables in these estimates such as *COMMON* and *BORDER* which take a value equal to one if the countries share the same official language or a common border. These explanatory variables correspond to our baseline model.

Departing from this baseline model, we include different sets of variables to analyse our hypotheses. First, *GLindex* is the Grubel and Lloyd index of human vaccines in the exporting country. This variable measures the existence of intra-industry trade in the market.[13] As can be seen in Table A-6, inter-industry trade predominates in global human vaccine trade since only 15.8% of the 59,986 observations included in our database register bilateral trade between two countries. Furthermore, the Gruebel and Lloyd index of these intra-industry flows averages 0.256 and derives mostly from developed countries. Indeed, Table A-6 shows that reciprocal trade in vaccines is concentrated in European countries, where Germany (0.370), Austria (0.347), Hungary (0.321) Italy (0.319) and Denmark (0.316) stand out. Developed countries such as Singapore (0.314), Switzerland (0.314), Canada (0.282), and the United States (0.268) are also represented, as are China (26.2) and India (0.243). Most undeveloped countries are net importers of vaccines.

Second, since supply and demand factors affect the vaccines trade, we include a vector of determinants which indicate the demand and supply of human vaccines. In particular, these relate to a well-developed health system and where there is governmental influence on whether to vaccinate the population. The Diphtheria-tetanus-pertussis (DTP3) variable represents immunisation coverage for 1-year-old children. *PRIV* represents the share of private health expenses over total expenditures. *HEALTH* is the public health expenditure ratio to GDP. Finally, we include a set of variables that analyse the technological development and knowledge

[13] The index takes values in the range 0 to 1 and is estimated by the following equation:

$$GL_{it} = \frac{(x_{it}+m_{it})-|x_{it}-m_{it}|}{(x_{it}+m_{it})} = 1\text{-}\frac{|x_{it}-m_{it}|}{(x_{it}+m_{it})} = \frac{2Min(x_{it};m_{it})}{(x_{it}+m_{it})}$$

specialisation in the pharmaceutical industry. *RD* is the share of R&D investment to GDP and *PHARMA* is the share of pharmaceutical exports of total trade.[14] Finally, *SIMILAR* is the absolute value of the difference between the log GDP per capita between partner countries. This simple measurement captures the differences in the relative factor endowments between the two partners such as technology, skills, or education levels, but also captures consumer preferences.

a are the parameters to estimate, λ_t is time trend and ε corresponds to the error term. All the explanatory variables, except the dummy variables, are in logs. See Tables A-3 to A-5 in Appendix 1 for a description of the variables, their database sources, a statistical description, and a correlation matrix.

Finally, we must remark that since we aim to capture to time-invariant country dummies such as *DIST*, *COMMON* and *BORDER*, we have avoided to include exporter-time and importer-time fixed effects. This may cause that there can be an omitted variable problem because the impact of other time-variant country characteristics would not be captured. However, our dummies can capture unobservable multilateral resistances and time-invariant country characteristics.

5. Results

5.1. Main estimates

This section contains the empirical results obtained from the gravity model presented above. Table 2 presents the estimates for all the country samples. Column 1 gives the baseline results for the main control variables, and we now describe the key estimation results. First, according to the literature, the bilateral trade of human vaccines is related to the market size of the exporting country, but it is not significantly related to the importer's size. As expected, the distance between importer and exporter countries exerts a negative impact on trade. Conversely, countries with a common official language, or contiguous frontiers, have more bilateral trade. Finally, the GDP per capita is significant, not only for the exporting country, but also for the importing country. Hence, vaccines exporting countries are rich countries, but the main importing countries also have a larger GDP per capita. In general, the results are robust across all our estimates except for the population of the importing country in Columns (5) and (7) when we include the R&D expenditure of the country and the similarity index.

[14] Milstien and Kaddar (2006) worry that strong IPR protection could also be a barrier for access to future vaccines and Smith (2002) confirms the influence of patents on the trade flows of drugs for the USA.

Column (2) incorporates our proxy for intra-industrial trade. The estimate shows a non-significant positive impact so, in our initial analysis, we confirm the lack of intra-industry trade of human vaccines. This is related to the fact that some countries play the role of trade hubs in the human vaccine market. Concerning health system variables (Columns (3) and (4)), we do not observe any effect of the Diphtheria-tetanus-pertussis coverage on international trade. Additionally, the ratio of public health expenditures (*HEALTH*) from the exporting countries presents a negative and significant influence on the international trade of vaccines. Hence, exporters which invest more in their health system export fewer human vaccines. As a consequence, we do not confirm Hypothesis 1 which aims to test the link between the health system and the flows of human vaccines with their commercial partners.

Table 2. Results of the PPML. Entire world.

Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
POP_EXP	5.352***	5.355***	4.375***	6.191***	5.369***	5.750***	5.464***
	(1.340)	(1.336)	(1.480)	(1.262)	(1.385)	(1.289)	(1.359)
POP_IMP	-0.510	-0.511	-0.501	-0.362	-0.799**	-0.438	-0.608*
	(0.320)	(0.319)	(0.320)	(0.316)	(0.367)	(0.326)	(0.319)
DIST	-0.239***	-0.239***	-0.239***	-0.240***	-0.221***	-0.240***	-0.217***
	(0.054)	(0.056)	(0.054)	(0.053)	(0.054)	(0.053)	(0.055)
COMMON	0.406***	0.404***	0.406***	0.406***	0.432***	0.410***	0.364***
	(0.135)	(0.132)	(0.134)	(0.132)	(0.138)	(0.129)	(0.136)
BORDER	0.337***	0.337***	0.337***	0.335***	0.327***	0.333***	0.363***
	(0.113)	(0.113)	(0.114)	(0.107)	(0.115)	(0.107)	(0.113)
GDPpc_EXP	1.014**	1.015**	1.003*	0.0210	1.114**	0.682	1.148**
	(0.493)	(0.494)	(0.513)	(0.380)	(0.518)	(0.466)	(0.494)
GDPpc_IMP	0.342**	0.341**	0.338**	0.331**	0.408**	0.434***	0.364**
	(0.146)	(0.146)	(0.144)	(0.144)	(0.160)	(0.141)	(0.150)
GL_index		0.009					
		(0.130)					
DTP3_EXP			2.010				
			(1.354)				
DTP3_IMP			4.914				
			(7.067)				
HEALTH_EXP				-2.297***			
				(0.800)			
HEALTH_IMP				1.097			
				(2.887)			
RD_EXP					0.013		
					(0.040)		
RD_IMP					0.029		
					(0.022)		
PHARMA_EXP						0.925***	
						(0.110)	
PHARMA_IMP						0.046	
						(0.033)	
SIMILAR							-0.086***
							(0.032)
Constant	-77.28***	-77.32***	-91.73***	-80.57***	-74.00***	-78.72***	-78.47***
	(22.73)	(22.70)	(33.74)	(22.84)	(23.54)	(21.88)	(23.03)
Pseudo-R^2	0.8079	0.8096	0.8077	0.8100	0.8074	0.8145	0.8088
Wald χ^2	1337.07	1382.92	1356.06	1378.49	1266.42	1412.66	1451.93

Prob > χ^2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Observations	59,986	59,986	59,277	59,288	48,469	56,873	59,986

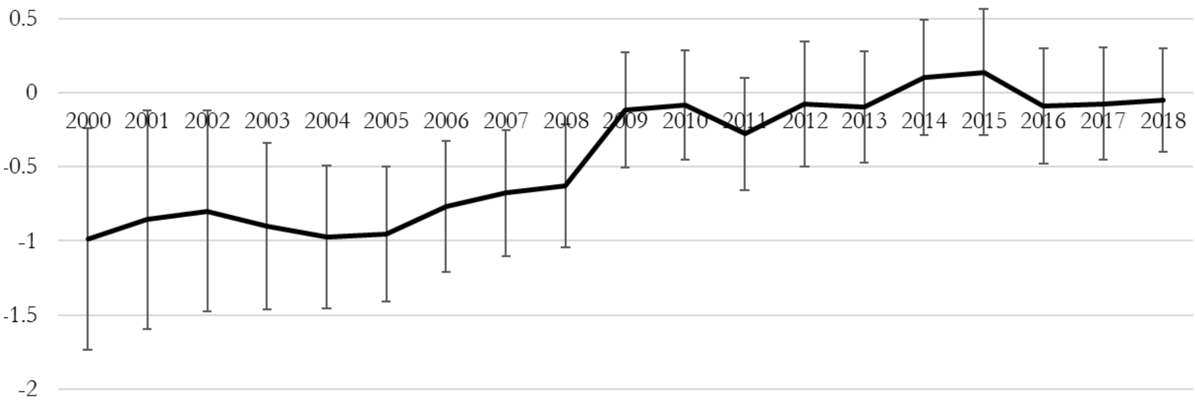
*** p<0.01, ** p<0.05, * p<0.1
Note: time, export country and import country dummies are included. Robust standard errors in parentheses.

In Column (5), R&D investments present a non-significant impact on human vaccine trade for both, exporting and importing countries. Hence, our global results are not able to confirm to disentangle the relationship between trade of human vaccines and the strength of the innovation system. Consequently, we cannot confirm Hypothesis 2 which argues that investment in R&D promotes human vaccine exports. Column (6) measures whether specialization in the pharmaceutical industry exerts a significant role in the international trade of human vaccines. The results demonstrate that such specialization has a positive influence for the exporter countries. Hence, we confirm our Hypothesis 3.

Finally, Column (7) incorporates our proxy for similarity in the endowments of the two countries (*SIMILAR*). The coefficient has a significant negative sign, showing that similar countries have a greater bilateral trade in human vaccines, while dissimilar countries have less intensive trade.

In regard to the estimates of time trend in our baseline model (Column (1) of Table 2), we observe that during the period 2000–2008 the trade flow of human vaccines was significantly lower than in the reference year 2019 (Graph 1). Furthermore, once we control for all the variables, the coefficients show the trade of human vaccines increasing yearly. However, this trend changed in 2009, and our estimates for the second half of the period show that the time trend does not exert any significant impact. In line with Rodrigues and Plotkin (2020), this graph highlights the stagnation in human vaccine trade following the 2008 crisis.

Graph 1. Estimated impact of the year coefficient in comparison with year 2019.



Note: vertical lines correspond to standard deviations. Discontinuous lines are non-statistically significant values.

5.2. The influence of the income level of countries in the international trade of human vaccines

As pointed out in Section 2.2, both the demand and supply of human vaccines are complex. On the one hand, the demand for human vaccines differs according to the socioeconomic and technological characteristics of the countries involved. On the other hand, supply is concentrated in relatively few exporting countries. This section examines the extent to which the income-level of countries affect the determinants of supply and demand of vaccines. Table 3 shows the same estimates as Table 2 but classifies importing countries according to whether they are high-, medium-, or low-income countries.

Regarding high-income countries, similar coefficients and signs appear as in our previous estimations. We should, however, point out some relevant differences. First, for the exporting countries, the DTP3 exerts a positive and significant influence on the trade flow, while the share of health expenditure exerts a negative impact. Second, the estimated coefficient of the R&D share for importing rich countries is significant and positive. The results show that more technologically advanced countries may have a different level of intensiveness of trade of human vaccines, while countries with a less robust innovation systems participate less in the international trade of human vaccines. This result reinforces the role of the strong innovation systems in defining international flows. Interestingly, also the specialization in the pharmaceutical industry of exporting countries is significant and positive. Hence, importing rich countries trade with countries that are already specialized in the pharma industry..

Table 3. Results of the PPML according to the income country classification.

	High-income countries							Medium-income countries							Low-income countries						
Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	**(12)**	**(13)**	**(14)**	**(15)**	**(16)**	**(17)**	**(18)**	**(19)**	**(20)**	**(21)**
POP_EXP	6.487***	6.459***	4.336**	7.742***	7.102***	6.523***	6.375***	0.486	0.474	0.827	-0.114	0.537	1.458	0.481	4.367***	4.326***	2.566**	2.670**	3.218**	4.438***	4.368***
	(1.610)	(1.607)	(1.828)	(1.547)	(1.648)	(1.551)	(1.593)	(1.416)	(1.397)	(1.579)	(1.286)	(1.387)	(1.389)	(1.413)	(1.163)	(1.179)	(1.269)	(1.195)	(1.345)	(1.235)	(1.159)
POP_IMP	-1.317	-1.316	-1.204	-1.287	-0.359	-1.133	-1.354	1.128***	1.122***	1.130***	1.133***	0.984**	1.033***	1.116***	1.581***	1.595***	1.504***	1.582***	1.347***	1.458***	1.581***
	(0.974)	(0.974)	(0.979)	(0.948)	(1.027)	(0.983)	(0.964)	(0.315)	(0.314)	(0.313)	(0.316)	(0.404)	(0.308)	(0.318)	(0.394)	(0.395)	(0.395)	(0.391)	(0.454)	(0.417)	(0.394)
DIST	-0.179***	-0.185***	-0.180***	-0.178***	-0.180***	-0.184***	-0.188***	-0.371***	-0.395***	-0.372***	-0.373***	-0.412***	-0.358***	-0.380***	-0.279***	-0.285***	-0.282***	-0.280***	-0.393***	-0.289***	-0.280***
	(0.056)	(0.0579)	(0.056)	(0.057)	(0.056)	(0.055)	(0.056)	(0.066)	(0.0667)	(0.066)	(0.065)	(0.071)	(0.068)	(0.067)	(0.061)	(0.061)	(0.061)	(0.061)	(0.058)	(0.062)	(0.061)
COMMON	0.515***	0.529***	0.514***	0.514***	0.520***	0.510***	0.550***	0.301***	0.311***	0.303***	0.302***	0.413***	0.312***	0.307***	-0.283***	-0.276***	-0.288***	-0.280***	-0.446***	-0.289***	-0.283***
	(0.146)	(0.143)	(0.144)	(0.143)	(0.144)	(0.139)	(0.142)	(0.114)	(0.113)	(0.114)	(0.114)	(0.144)	(0.113)	(0.114)	(0.083)	(0.083)	(0.083)	(0.083)	(0.096)	(0.087)	(0.084)
BORDER	0.309**	0.308**	0.308**	0.312**	0.308**	0.310**	0.286**	-0.137	-0.070	-0.151	-0.153	-0.148	-0.126	-0.215	-0.161	-0.164	-0.174	-0.162	-0.297	-0.152	-0.160
	(0.129)	(0.129)	(0.129)	(0.126)	(0.130)	(0.123)	(0.129)	(0.162)	(0.168)	(0.165)	(0.163)	(0.175)	(0.164)	(0.164)	(0.170)	(0.172)	(0.172)	(0.172)	(0.189)	(0.172)	(0.170)
GDPpc_EXP	1.446**	1.439**	1.546**	-0.101	1.675***	0.946	1.339**	0.183	0.168	0.016	0.141	0.188	0.165	0.317	0.290*	0.286*	-0.0596	0.249	0.470**	0.308*	0.289*
	(0.649)	(0.650)	(0.644)	(0.603)	(0.623)	(0.624)	(0.642)	(0.267)	(0.265)	(0.336)	(0.257)	(0.299)	(0.256)	(0.272)	(0.157)	(0.158)	(0.195)	(0.155)	(0.192)	(0.160)	(0.169)
GDPpc_IMP	1.186***	1.191***	1.159***	1.047***	1.626***	1.193***	1.116***	0.666***	0.668***	0.669***	0.671***	0.712***	0.691***	0.646***	-0.029	-0.026	-0.016	-0.018	0.018	0.017	-0.029
	(0.385)	(0.384)	(0.369)	(0.401)	(0.389)	(0.354)	(0.383)	(0.188)	(0.188)	(0.187)	(0.188)	(0.188)	(0.189)	(0.186)	(0.114)	(0.113)	(0.114)	(0.113)	(0.138)	(0.128)	(0.114)
GL index		-0.077							-0.875**							-0.662					
		(0.126)							(0.423)							(0.476)					
DTP3_EXP			4.933**							0.684							2.315***				
			(2.066)							(1.049)							(0.693)				
DTP3_IMP			6.193							-12.24**							2.301				
			(8.483)							(5.331)							(4.980)				
HEALTH_EXP				-2.759***							-0.447							-0.303			
				(0.974)							(0.616)							(0.359)			
HEALTH_IMP				2.497							-3.727*							-9.419***			
				(3.374)							(2.081)							(1.598)			
RD_EXP					0.266							-0.073**							-0.007		
					(0.280)							(0.032)							(0.024)		
RD_IMP					0.569*							0.042**							-0.004		
					(0.343)							(0.020)							(0.011)		
PHARMA_EXP						1.129***							0.381***							-0.025	
						(0.132)							(0.114)							(0.089)	
PHARMA_IMP						0.094							-0.005							0.027	
						(0.093)							(0.029)							(0.021)	
SIMILAR							0.054							-0.135**							0.001
							(0.039)							(0.035)							(0.052)
Constant	-95.88***	-95.34***	-112.1**	-98.37***	-127.6***	-89.40***	-91.82***	-16.82	-16.13	31.00	2.435	-15.30	-30.66	-16.28	-90.99***	-90.43***	-74.88***	-41.35*	-67.35***	-90.27***	-90.99***
	(32.48)	(32.33)	(46.82)	(33.28)	(36.01)	(31.14)	(31.96)	(26.04)	(25.73)	(30.46)	(22.47)	(24.85)	(25.75)	(25.98)	(21.75)	(21.85)	(26.06)	(24.06)	(24.64)	(23.33)	(21.68)
Pseudo-R^2	0.829	0.830	0.829	0.831	0.825	0.838	0.829	0.772	0.773	0.772	0.772	0.774	0.775	0.773	0.6858	0.6859	0.6871	0.6895	0.6943	0.6802	0.6858
Wald χ^2	971.7	996.9	981.9	1027.9	951.6	1026.3	1039.6	1440.2	1461.1	1536.5	1435.6	1330.2	1508.1	1442.2	1625.6	1640.6	1592.1	1676.5	1183.1	1365.2	1665.8
Prob > χ^2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Observations	28,188	28,188	27,727	27,725	25,792	27,848	28,188	15,454	15,454	15,301	15,309	12,599	15,113	15,454	13,536	13,536	13,441	13,446	8,670	11,878	13,536

Note: time, export country and import country dummies included. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Robust standard errors in parentheses.

For the group of medium-income countries, the market size of the exporter does not have an influence, while the population coefficient is a significant variable in determining the trade flow of human vaccines. This is a significant result in comparison with the group of rich countries where the population coefficient was only significant for the exporting countries. In this sense, some further explanation is due. Among high-income countries, given that there are very few strong exporters and many importers, it derives from the fact that the changes in population size among exporters are in a much smaller variation range than importers. For middle income countries, the situation reverses, as the countries are more numerous, relatively wealthy and they all have growing populations, two factors which also triggers the possibility and necessity of importing more vaccines. Finally, among low-income countries both population coefficients turn out positive and significative, as growing importing populations need vaccines (also helped financially by humanitarian campaigns) and the exporting population of pharmaceutical-producing countries such as India, is steadily growing.

Continuing the discussion of the results, few note that for medium-income countries, sharing a common border and the GDP per capita of exporters are non-significant variables. Therefore, medium-income countries import from non-neighbourhood countries that are not necessarily richer. In comparison with our main results (Table 2), in column (9) our proxy of intra-industrial trade is significant and negative between medium-income countries; the greater the intra-industry trade, the lower the flow of human vaccines. Hence, for medium-income countries, we observe the international trade of human vaccines is characterised by an intra-industry trade. Regarding the health system (columns (10) and (11)), our proxies are significant for the importing countries. so medium-income countries import more human vaccines if they have both lower DTP3 ratios and low health expenditure. The results show the influence of weak health systems as a driver of vaccine flows for medium-income countries. Additionally, the fact that the coefficient of the R&D expenditure over GDP of exporting countries is negative, shows that medium-income countries import more human vaccines from countries with less robust innovation systems. Furthermore, medium-income countries import from countries with a high share of trade in the pharmaceutical industry. Finally, the degree of similarity (column (14)) between the importing and exporting country has a negative and significant coefficient. Recall our interpretation is that similar countries have a greater bilateral trade in human vaccines, while dissimilar countries have fewer intensive exchanges. In this interpretation, middle-income countries tend to intensify their trade among countries which are more similar in terms of their endowments.

Concerning the estimates for low-income countries, we observe some interesting results. First, contrary to the expectations of the trade literature, a common language and border contiguity have significant negative impacts. Additionally, the market size of exporters and importers exert a positive and significant impact on the flow. Second, the intra-industrial proxy shows a non-significant impact which highlights the role of low-income countries as mere buyers in the global market. All these evidences suggest that most poor countries around the world are highly dependent of the supply of vaccines from exporter countries. In other words, intra-industrial trade in human vaccines takes place between relatively few rich and middle-income countries, while the poorest ones have a trade deficit.

Another notable outcome is that exports to low-income income countries increase with the share of DTP3 among exporting countries (Column (17)). Our proxies of public health expenditure of the poor importing countries exert a significant and negative impact on the trade volume. The results show that, among low-income countries, the weaker the health system of the poorest country, the lower the trade of vaccines (column (18)). This points out a permanent penalty in terms of access to vaccines for low-income countries that already have a weaker health system.

The above results allow us to reach a series of interesting conclusions. First, the standard explanatory factors for trade may not be adequate for explaining the human vaccine trade. For instance, sharing a common official language and contiguous borders are no longer significant for medium- and low-income countries. The main reason for this is that producers of human vaccines locate in developed countries (and some developing) countries. Second, high-income countries tend to export to high-income countries and the developing countries (middle and low-income countries); middle-income countries produce for developing countries, and low-income countries merely act as net importers.

Finally, complementing the above result with detailed price data from the World Integrated Trade Solution (WITS), we gain an additional insight put forward in Section 4.1.

Table 4. Average trade price (in thousands of dollars per kilo) of human vaccines for the clusters

2019			
Export		Import	
Income cluster	Average price	Income cluster	Average price
High	0.713	High	0.724
Medium	0.419	Medium	0.619
Low	0.311	Low	0.49
2000			
Export		Import	
Income cluster	Average price	Income cluster	Average price
High	0.301	High	0.703
Medium	0.169	Medium	0.190
Low	0.080	Low	0.095

Source: own elaboration from WITS data.

Table 4 confirms an intuition derived from this framework. Considering the values per unit, we notice at least two additional features that give robustness to our interpretation. On the one hand, the average price for exported and imported vaccines varies considerably across income clusters, diminishing in the low-income countries cluster. This confirms the fact that newly developed vaccines tend to stay in rich countries, while the more standard ones are produced and traded among medium and low-income economies. On the other hand, from 2000 to 2019, these prices have increased, but not by the same magnitude in all clusters. Looking at the OECD countries, their average export price increased far more than the import counterpart, hinting that development centres stay localised in these rich countries.

6. Conclusions

Trends in international human vaccine trade during the first two decades of the 21st century show a worrying reduction in the participation of low-income countries, while developed countries have increased their share. Since 2008, to the detriment of humanitarian goals, market forces have increasingly dominated the production of human vaccines. Accordingly, large pharmaceutical companies have reoriented their R&D activities toward discovering new vaccines for high-income countries, while the development of mature vaccines has languished.

The development over time of human vaccine trade underlines the above polarisation. High-income countries acquire the most sophisticated and expensive vaccines, while work on vaccines for the classic diseases of developing countries stagnates. This empirical evidence shows the increasing fragmentation of the international human vaccine trade.

In the light of the growing inequality in the international human vaccine trade, the current paper aims to analyse the determinants of the trade pattern and the differences between country groups. Several aspects of our findings shed light on specific determinants of these flows.

First, plotting the time coefficients of the model gives a simple and clear picture of the general trend of the global trade in human vaccines. We observe that trade had been continuously increasing up to the global economic crisis of 2008 when it started to stagnate.

Applying a gravity model, our results confirm the results expected from the literature. The market size of exporters affects positively the trade of human vaccines; the bilateral trade of vaccines diminishes with the distances and increases with neighbouring and common language countries. Furthermore, exporters of vaccines are characterised by a higher GDP per capita.

However, our results also highlight the heterogeneity according to the income of the countries. When we introduce variables related to the health system and the productive specialization into the estimation, our findings show that they tend to spend relatively less on health and show strong sectoral patterns of trade specialisation. The similarity index shows that a gap between countries' GDPs per capita lowers bilateral trade, implying that (particularly middle-income) countries preferentially trade among themselves. This evidence confirms that vaccine exporters locate in high- and middle-income countries with the above-listed characteristics.

The current Covid-19 pandemic requires a more ambitious strategy for vaccine development and successive vaccination campaigns. There is a risk that the enormous resources which advanced countries devoted to developing effective vaccines against Covid-19 will detract from those that were normally allocated to combating diseases still active in some parts of the world.

The challenges posed by Covid-19 are not solvable without correcting the growing disparities that have characterised this century's global human vaccine trade. Overcoming the pandemic and guaranteeing developing countries adequate tools to immunise their populations, requires a global strategy. In this approach, a stimulation of the manufacturing capacity in newcomer countries, and more favourable access to vaccines for poorer populations who are subject to a high burden of disease, need to accompany the development of a vaccine for Covid-19.

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Appendix 1.

Table A-1. Market shares of the main exporters of human vaccines (periods 2000-2004 and 2015-2019)

	2000	2001	2002	2003	2004	2015	2016	2017	2018	2019	2000-2004	2015-2019
European Union	50.05%	49.42%	51.34%	50.55%	52.50%	46.29%	50.81%	51.23%	49.53%	47.67%	50.77%	49.10%
USA	18.01%	20.63%	23.81%	22.69%	15.70%	27.68%	21.82%	24.06%	25.19%	28.06%	20.17%	25.36%
United Kingdom	10.05%	8.38%	5.24%	7.04%	10.58%	7.99%	9.20%	9.46%	7.95%	6.63%	8.26%	8.25%
India	2.51%	1.13%	1.40%	1.93%	2.58%	0.95%	1.10%	0.96%	1.01%	1.14%	1.91%	1.03%
China	1.37%	1.06%	1.88%	1.35%	1.08%	0.84%	1.12%	1.60%	1.78%	3.82%	1.35%	1.83%
Russia	0.92%	1.50%	1.15%	0.99%	0.79%	0.48%	0.57%	0.49%	0.59%	0.39%	1.07%	0.50%
Switzerland	0.76%	1.27%	0.83%	0.95%	2.38%	0.25%	0.37%	0.49%	0.30%	0.41%	1.24%	0.37%
Singapore	0.17%	0.45%	0.14%	0.64%	0.10%	0.14%	0.17%	0.13%	0.17%	0.18%	0.30%	0.16%
Japan	0.13%	0.12%	0.10%	0.12%	0.15%	0.98%	1.55%	1.10%	1.05%	0.76%	0.12%	1.09%
Korea	0.02%	0.09%	0.03%	0.02%	0.09%	0.01%	0.01%	0.02%	0.02%	0.04%	0.05%	0.02%
Rest of Countries	16.00%	15.96%	14.10%	13.73%	14.05%	14.41%	13.29%	10.47%	12.42%	10.90%	14.77%	12.30%

Source: UN Comtrade.

Table A-2. List of countries included in the analysis by cluster

OECD	Middle-income countries	Low-income countries
Australia	Albania	Afghanistan
Austria	Argentina	Algeria
Belgium	Armenia	Angola
Canada	Azerbaijan	Bangladesh
Chile	Brazil	Bolivia
Colombia	Bulgaria	Cambodia
Czech Republic	China	Cameroon
Denmark	Costa Rica	Central African Republic
Estonia	Croatia	Congo
Finland	Cuba	Cote d'Ivoire
France	Cyprus	Egypt
Germany	Dominican Republic	El Salvador
Greece	Ecuador	Ethiopia
Hungary	Georgia	Ghana
Iceland	Guatemala	Guinea
Ireland	Hong Kong	Haiti
Israel	Indonesia	Honduras
Italy	Iran	India
Japan	Iraq	Kenya
South Korea	Jamaica	North Korea
Latvia	Jordan	Laos
Lithuania	Kazakhstan	Madagascar
Luxembourg	Kuwait	Mali
Mexico	Lebanon	Mauritania
Netherlands	Libya	Morocco
New Zealand	Malaysia	Mozambique
Norway	Malta	Nepal
Poland	Namibia	Nicaragua
Portugal	Oman	Niger
Slovak Republic	Panama	Nigeria
Slovenia	Peru	Pakistan
Spain	Romania	Paraguay
Sweden	Russian Federation	Philippines
Switzerland	Saudi Arabia	Rwanda
Turkey	Serbia	Senegal
United Kingdom	Singapore	Sudan
United States	South Africa	Syria
	Taiwan	Tunisia
	Thailand	Uganda
	United Arab Emirates	Ukraine
	Uruguay	Uzbekistan
	Venezuela	Vietnam
		Yemen
		Zambia
		Zimbabwe

Source: own elaboration. Please note that for the classification of non-OECD countries according to the income groups, we referred to the World Bank classification

Table A-3. Description of variables		
Variable	**Definition**	**Source**
	Dependent variables	
V	*Export value of human vaccines*	*UN Comtrade*
	Independent variables	
POP	*Population (in logs)*	*World Bank*
GDPpc	*GDP per capita (in logs)*	*World Bank*
DIST	*Distance between capital of both countries (in logs)*	*CEPII*
COMMON	*Dummy variable identifying if both countries share the same official language*	*CEPII*
BORDER	*Dummy variable identifying if both countries share the border*	*CEPII*
GL_INDEX	*Grubel and Loyd (GL) intraindustrial index*	*UNCTAD*
DTP3	*DTP3 coverage among population 1 year (in logs)*	*WHO*
HEALTH	*Current health expenditure (% of GDP)*	*WHO*
RD	*Gross domestic expenditure on R&D (GERD) as a percentage of GDP*	*UNESCO*
PHARMA	*Share of pharmaceutical trade over total trade at country level (HS 3002) (in logs)*	*UNCTAD*
SIMILAR	*Absolute difference of the log GDP per capita between exporter and importer*	*World Bank*

Table A-4. Statistical descriptive					
	Observations	**Mean**	**Std. Dev**	**Min.**	**Max**
Export value	59986	4.8×10^{6}	6.3×10^{7}	0	4.2×10^{9}
Population (exporter)	59986	1.05×10^{8}	2.6×10^{8}	1794583	1.4×10^{9}
Population (importer)	59986	1.0×10^{8}	2.6×10^{8}	281205	1.4×10^{9}
Distance between countries (dummy)	59986	6171.4	4385.8	59.6	19772.3
Common official language (dummy)	59986	0.1653	0.3714	0	1
Contiguity in the borders (dummy)	59986	0.0625	0.24206	0	1
GDP per capita (exporter)	59986	22495.7	21159.1	111.9	102913.5
GDP per capita (importer)	59986	22082.9	21291.2	111.9	118823.6
GL index	59986	0.040	0.148	0	0.999
DTP3 coverage at 1 year-old population (exporter)	59277	90.3	11.5	8	100
DTP3 coverage at 1 year-old population (importer)	59277	91.0	2.4	71.7	96.6
Share health expenditure over GDP (exporter)	59288	7.4	3.1	1.7	40.4
Share health expenditure over GDP (importer)	59288	7.2	0.7	3.8	9.9
GERD/GDP (exporter)	56873	0.004	0.01	2.2×10^{-8}	0.1
GERD/GDP (importer)	48469	0.017	0.011	7×10^{-11}	8.6×10^{-2}
Share of the pharmaceutical trade over total trade (exporter)	48469	1.7×10^{-2}	1.1×10^{-2}	4.5×10^{-9}	8.6×10^{-2}
Share of the pharmaceutical trade over total trade (importer)	56873	0.004	0.008	1.3×10^{-8}	0.071
Index of similarity	59986	9.508	1.440	-0.004	11.64
Source: own elaboration.					

Table A-5. Table of Pearson correlations.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
(1) Export value	1																
(2) POP_EXP	-0.00	1															
(3) POP_IMP	0.01*	-0.04*	1														
(4) DIST	-0.04*	0.10*	0.10*	1													
(5) COMMON	0.04*	-0.00	-0.00	-0.09*	1												
(6) BORDER	0.06*	0.00	0.01	-0.30*	0.17*	1											
(7) GDPpc_EXP	0.09*	-0.19*	-0.10*	-0.03*	-0.07*	-0.06*	1										
(8) GDPpc_IMP	0.05*	-0.10*	-0.18*	-0.03*	-0.06*	-0.05*	-0.05*	1									
(9) DTP3_EXP	0.03*	-0.17*	-0.07*	-0.06*	-0.10*	0.00	0.39*	-0.00	1								
(10) DTP3_IMP	0.01*	-0.23*	0.02*	-0.09*	-0.05*	0.03*	0.15*	0.24*	0.20*	1							
(11) HEALTH_EXP	0.07*	-0.19*	-0.08*	-0.01	-0.02*	-0.03*	0.63*	-0.07*	0.32*	0.06*	1						
(12) HEALTH_IMP	0.01	-0.30*	0.02*	-0.07*	0.03*	0.02*	0.07*	0.25*	0.07*	0.62*	0.11*	1					
(13) SIMILAR	-0.02*	-0.19*	-0.18*	0.09*	-0.16*	-0.24*	0.33*	0.32*	0.17*	0.15*	0.24*	0.09*	1				
(14) GL index	0.12*	0.01	0.01*	-0.16*	0.07*	0.16*	0.14*	0.14*	0.07*	0.02*	0.09*	-0.01	-0.06*	1			
(15) GERD/GDP (exporter)	0.02*	-0.02*	-0.06*	-0.02*	-0.07*	-0.03*	0.28*	-0.04*	0.15*	0.15*	0.26*	0.02*	0.10*	0.06*	1		
(16) GERD/GDP (importer)	0.02*	-0.06*	0.03*	-0.02*	-0.08*	-0.03*	-0.04*	0.28*	-0.01	0.17*	-0.05*	0.17*	0.10*	0.07*	-0.03*	1	
(17) PHARMA_EXP	0.13*	-0.10*	-0.06*	-0.05*	-0.01*	-0.03*	0.63*	-0.06*	0.18*	0.08*	0.40*	0.08*	0.21*	0.06*	0.17*	-0.01*	1
(18) PHARMA_IMP	0.04*	-0.05*	-0.10*	-0.04*	-0.02*	-0.03*	-0.07*	0.61*	-0.01*	0.16*	-0.06*	0.21*	0.20*	0.07*	-0.02*	0.17*	-0.06*

(*) Significant at 1%. Source: own elaboration.

Table A-6 - Country leaders in intra-industrial trade. Gruebel and Lloyd index.			
Country name	**Mean**	**Standard deviation**	**Observations**
Germany	0.370	0.313	538
Austria	0.347	0.312	292
Hungary	0.321	0.316	130
Italy	0.319	0.308	318
Denmark	0.316	0.293	276
Singapore	0.314	0.291	187
Czechia	0.314	0.321	154
Switzerland	0.291	0.289	326
Spain	0.287	0.271	272
Canada	0.282	0.307	248
United States of America	0.268	0.293	466
China	0.262	0.296	135
India	0.243	0.280	373
Australia	0.198	0.251	265
Ireland	0.240	0.291	180
Poland	0.196	0.287	153
United Kingdom	0.234	0.275	534
Netherlands	0.190	0.250	486
Japan	0.226	0.256	207
Belgium	0.184	0.265	581
Indonesia	0.181	0.248	124
Republic of Korea	0.156	0.229	245
No intra-industrial trade	0.000	0.000	50.505
Intra-industrial trade	0.256	0.2899	9.481

N.B. The above table reports an extraction of the countries showing more intra-industrial trade for the whole period of observation, and with at least 50 intra-industrial transactions.
Source: own elaboration.

Appendix 2. Analysis of the heterogeneity of the trade of human vaccines.

A relevant element in our analysis is the heterogeneity of the flows of trade in human vaccines. Accordingly, we disaggregate the total exports from a country into two different margins:

$$X_{i,t} = \sum_{n-1}^{N} X_{i,j,t} = N_{i,t} \times \bar{X}_{i,t}$$

where X_{ijt} is the volume of exports from country i to country j, $N_{i,t}$ is the number of countries where country i exports, and $\bar{X}_{i,t}$ represents the average export value that country i has in each destination country. Taking logs, we have the following equation:

$$ln(X_{i,t}) = ln(N_{i,t}) + ln(\bar{X}_{i,t})$$

In a sense, we have split the total value of exports into an extensive margin (number of countries where the country is present) and an intensive margin (average value of exports).

Given the spatial distribution of the markets, we perform several analyses to check the skewness and kurtosis of our data. We expect that the UN Comtrade database will be highly skewed since a handful of countries accounts for most aggregate flows of human vaccines.

As expected, the correlation matrix in Table A-6 shows a high correlation (0.9596) between intensive and total flows. Furthermore, there is a high correlation with the extensive margin (0.8953 and 0.7271 respectively).

Table A-6. Correlation matrix

$ln(X_i)$	1		
$ln(\bar{X}_i)$	0.9657	1	
$ln(N_i)$	0.9077	0.7675	1

Note: all correlations are significant at 1% based on the Pearson correlation.

Table A-7 demonstrates that the skewness tests for the average export value show a non-significant p-value. The results for the kurtosis are, however, highly significant regardless of whether we consider the intensive margin or the number of markets. Hence, our results point to a small number of source countries acting as origins for a large number of final markets.

Table A-7. Skewness/Kurtosis tests for normality

			From 2000–2008		From 2009–2019	
	Pr(Skewness)	**Pr(Kurtosis)**	**Pr(Skewness)**	**Pr(Kurtosis)**	**Pr(Skewness)**	**Pr(Kurtosis)**
$ln(\bar{X}_i)$	p-value =0.34	p-value =0.00	p-value =0.98	p-value =0.00	p-value =0.71	p-value =0. 00
$ln(N_i)$	p-value =0.00	p-value =0.00	p-value =0.00	p-value =0.00	p-value =0.32	p-value =0.00

Source: own elaboration.