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ORIGINAL RESEARCH

The Association between Health Workforce and Health Outcomes: A Cross-Country Econometric Study

Jinlin Liu[1] · **Karen Eggleston**[2]

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Abstract
This study investigates the strength and significance of the associations of health workforce with multiple health outcomes and COVID-19 excess deaths across countries, using the latest WHO dataset. Multiple log-linear regression analyses, counterfactual scenarios analyses, and Pearson correlation analyses were performed. The average density of health workforce and the average levels of health outcomes were strongly associated with country income level. A higher density of the health workforce, especially the aggregate density of skilled health workers and density of nursing and midwifery personnel, was significantly associated with better levels of several health outcomes, including maternal mortality ratio, under-five mortality rate, infant mortality rate, and neonatal mortality rate, and was significantly correlated with a lower level of COVID-19 excess deaths per 100 K people, though not robust to weighting by population. The low density of the health workforce, especially in relatively low-income countries, can be a major barrier to improving these health outcomes and achieving health-related SDGs; however, improving the density of the health workforce alone is far from enough to achieve these goals. Our study suggests that investment in health workforce should be an integral part of strategies to achieve health-related SDGs, and achieving non-health SDGs related to poverty alleviation and expansion of female education are complementary to achieving both sets of goals, especially for those low- and middle-income countries. In light of the strains on the health workforce during the current COVID-19 pandemic, more attention should be paid to health workforce to strengthen health system resilience and long-term improvement in health outcomes.

Keywords Health workforce · Health outcome · COVID-19 excess death · Cross-country

1 Introduction

Health workforce is the core of a health system. No health without a health workforce has been a universal truth (Global Health Workforce Alliance, 2014). The World Health Organization (WHO) defines the health workforce as all people who are engaged in actions

✉ Jinlin Liu
liujl@nwpu.edu.cn

[1] School of Public Policy and Administration, Northwestern Polytechnical University, Xi'an, China

[2] FSI Walter H Shorenstein Asia Pacific Research Center, Stanford University, Stanford, CA, USA

with the primary intent of enhancing health (World Health Organization, 2006). Health systems can only function with a health workforce, and the availability, accessibility, acceptability, and quality of a health workforce arguably represent key prerequisites for improving health service coverage and realizing the right to the enjoyment of the highest attainable standard of health (World Health Organization, 2016a). In September 2015, the United Nations adopted a new development agenda with 17 Sustainable Development Goals (SDGs) which took place of the Millennium Development Goals (MDGs) (United Nations, 2015; World Health Organization, 2015). Of the 17 SDGs, SDG 3 focuses on a broad health goal to ensure healthy lives and promote well-being for all at all ages (United Nations, 2015). In the context of transition from the MDGs to the SDGs, a sufficient and qualified health workforce is essential to achieve the health-related SDGs (World Health Organization, 2016b), and it accounts for over one-third of health investments required for the health-related SDGs in low- and middle-income countries (Stenberg et al., 2017; World Health Organization, 2017). Currently, estimates indicate that 18 million additional health workers are needed to achieve the health-related SDGs in 2030, and the current pandemic further complicates achieving those goals (World Health Organization, 2017).

Given the above evidence of the importance of the health workforce, relatively very few cross-country studies have analyzed the relationship between health workforce and health outcomes. Using a database on 155 countries, Robinson and Wharrad reported that a high density of doctors was significantly associated with decreasing maternal, under-five, and infant mortality rates (Robinson & Wharrad, 2001; Robinson & Wharrad, 2000). In 2004, using a WHO dataset on 117 countries, Anand and Bärnighausen found that a high aggregate density of human resources for health and a high doctor density were significantly associated with a low level of maternal mortality, infant mortality, and under-five mortality (Anand & Bärnighausen, 2004). Both Farahani et al. (2009) and Or et al. (2005) identified a significant impact of increasing doctor numbers on lowering infant mortality. However, Hertz et al. (1994), Muldoon et al. (2011), Pinzón-Flórez et al. (2015), and Kim et al. (1992), recorded no significant associations between the density of doctors and life expectancy at birth, maternal, child, or infant mortality rates. Amiri et al. found that a 1% increase in the density of nurses would increase life expectancy at birth and at 65 years by 0.02 and 0.08 percent, respectively (Amiri & Solankallio-Vahteri, 2019). Five cross-country studies which investigated the links between density of nurses and maternal, under-five, and infant mortality rates did not note significant associations between them (Anand & Bärnighausen, 2004; Kim & Moody, 1992; Muldoon et al., 2011; Robinson & Wharrad, 2001; Robinson & Wharrad, 2000). In addition, a study conducted in 1978 using data of 18 developed countries even found a significant adverse relationship between density of doctors and infant and perinatal mortality (Cochrane et al., 1978).

In addition, several within-country studies have analyzed the link between density of health workers and different health outcomes (Aakvik & Holmås, 2006; Basu et al., 2019; Doyle, 2020; Gulliford, 2002; Liang et al., 2019; Russo et al., 2019; Sakai et al., 2016; Subramaniam et al., 2018). However, these studies also present inconsistent findings. Basu et al. identified a significant effect of greater primary care physician supply on the longer life expectancy at birth in the United States (Basu et al., 2019). Liang et al. (2019) and Sakai et al. (2016) found that an increase in pediatrician density or health professional density was associated with a reduction in the under-five mortality in Japan and rural China, respectively. Russo et al. found that primary care physician supply could significantly contribute to the decline of infant mortality rate in Brazil (Russo et al., 2019). Subramaniam et al. showed density of doctors had a significant beneficial effect on infant mortality in Indonesia and Philippines, but had an adverse effect in Thailand and no effect in Malaysia

(Subramaniam et al., 2018). Moreover, Doyle identified a significant positive association between patient availability and patient survival in the U.S. (Doyle, 2020). However, the study of Gulliford (2002) and Aakvik et al. (2006) rejected a significant relationship between population mortality and the number of general practitioners per capita in England and Norway, respectively.

The inconsistent results reported in these cross-country or within-country studies may not be surprising in light of their heterogeneity in data, methods, and institutional contexts. Since increased density of health workforce can be both a cause and effect of the broader socioeconomic and health system development, generalizing findings from associational studies or attributing causal relationships can be fraught with difficulty, and contrasting findings would be expected in studies have adopting different methods, levels of analyses, and explanatory variables. Therefore, the strength and significance of health workforce for health outcomes are still worth exploring, and using multiple health outcomes and the latest WHO dataset on health workforce, our study will provide an update and extension of previous cross-country studies. Meanwhile, in the context of striving to meet the health-related SDGs while controlling the COVID-19 pandemic, useful evidence for policy may stem from investigating the association between a country's health workforce and multiple health outcomes of its citizens, accounting for other confounding variables.

Considering the data availability of the health workforce, the WHO member countries were included in our study. And based on the above, our study aimed to investigate the strength and significance of the cross-country associations of health workforce with multiple health outcomes, and besides a global depiction, the study would also identify the role of the health workforce in addressing the disparities of health outcomes across countries in different income categories (i.e., low-, lower-middle-, upper-middle-, and high-income countries).

2 Material and Methods

2.1 Choice of Variables

2.1.1 Dependent Variables

The dependent variables used in our study included multiple measures of health outcomes. Besides the maternal mortality ratio, under-five mortality rate, and neonatal mortality rate that were health-related SDG indicators, we further introduced the indicators of healthy life expectancy at birth, the mortality rate of adults aged $15-60$ (hereafter $15-60$ adult mortality rate), and infant mortality rate. The COVID-19 excess deaths per 100 K people was also included as an additional health outcome measure proxying for the health impact of the coronavirus pandemic.

2.1.2 Independent Variables

The independent variables used in this study included three measures of the health workforce. The first was the aggregate measure of skilled health workers, including medical doctors and nursing and midwifery personnel. As defined in the WHO dataset (World Health Organization, 2018), medical doctors included generalist medical practitioners, specialist medical practitioners, and other medical doctors that were not further defined, and nursing and midwifery personnel included all related nurses and midwives. In addition to medical doctors and nursing and midwifery personnel, there are some other categories of health workers such as the dentistry personnel, pharmaceutical personnel, community health workers, and traditional and complementary medicine personnel (World Health Organization, 2018). The choice of the aggregate measure of skilled health workers in our study stemmed from the fact that the numbers of medical doctors and nursing and midwifery personnel were available on a relatively comprehensive basis across countries, and accounted for the largest proportion of total health workers in almost all countries. Other than the study of Anand and Bärnighausen (2004) which had taken the aggregate density of the health workforce as an independent variable, all previous cross-country studies just analyzed the associations between density of medical doctors and/or density of nurses and health outcomes (Amiri & Solankallio-Vahteri, 2019; Cochrane et al., 1978; Farahani et al., 2009; Hertz et al., 1994; Kim & Moody, 1992; Muldoon et al., 2011; Or et al., 2005; Pinzón-Flórez et al., 2015; Robinson & Wharrad, 2001; Robinson & Wharrad, 2000).

In addition, in accordance with all previous cross-country studies (Amiri & Solankallio-Vahteri, 2019; Anand & Bärnighausen, 2004; Cochrane et al., 1978; Farahani et al., 2009; Hertz et al., 1994; Kim & Moody, 1992; Muldoon et al., 2011; Or et al., 2005; Pinzón-Flórez et al., 2015; Robinson & Wharrad, 2001; Robinson & Wharrad, 2000), the study would investigate independent associations of densities of medical doctors and nursing and midwifery personnel with multiple health outcomes. In line with the statistics of WHO (Anand & Bärnighausen, 2004; World Health Organization, 2018), here the nursing and midwifery personnel were counted as one category because nurses and midwives receive similar training and undertake overlapping tasks in many countries.

Therefore, the three independent variables were density of skilled health workers, density of medical doctors, and density of nursing and midwifery personnel, all of which were reported as the numbers per 100,000 population. The density of skilled health workers was equal to the sum of the density of medical doctors and density of nursing and midwifery personnel for each country.

2.1.3 Confounding Variables

To account for other country-level factors important in determining health outcomes (i.e., what may be considered as confounding variables), we also collected and analyzed data on several measures.

First, health spending per capita, an important indicator which was included in previous studies (Muldoon et al., 2011; Pinzón-Flórez et al., 2015), was included in this study as a key confounding variable and was measured in international dollars at purchasing power parity (PPP) rates.

Second, following previous studies (Anand & Bärnighausen, 2004; Kim & Moody, 1992; Robinson & Wharrad, 2001; Robinson & Wharrad, 2000), we introduced the gross national income (GNI) per capita in international dollars at PPP rates. The average income per capita is an important variable included in most of the prior studies (Anand & Bärnighausen, 2004; Cochrane et al., 1978; Farahani et al., 2009; Kim & Moody, 1992; Or et al., 2005; Robinson & Wharrad, 2001; Robinson & Wharrad, 2000) and is closely related to several distal factors that affect population mortality rates such as housing, safe water, sanitation, nutrition, and so on (Anand & Bärnighausen, 2004). Compared with the gross domestic product or GNI per capita in US dollars at market exchange rates used in some studies (Cochrane et al., 1978; Hertz et al., 1994; Kim & Moody, 1992; Robinson &

Wharrad, 2001; Robinson & Wharrad, 2000), the method based on PPP rates better reflects real income and purchasing power gaps between different countries.

Third, consistent with previous studies (Anand & Bärnighausen, 2004; Schell et al., 2007; Tavares, 2017), our study included a measure of absolute poverty as an explanatory variable. Eradicating poverty is the first target among the SDGs, and there are very few studies that included income poverty as a confounder when examining associations between health workforce and health outcomes. Although the effect of income on an individual's health may decrease gradually when income reaches a high level, there may be relatively high returns to investments in health for individuals living below the poverty line; moreover, for countries with the same income per capita, a higher poverty headcount ratio might result in higher population mortality rates, so accounting for poverty can be important when investigating the role of other factors like health workforce for improving health outcomes (Anand & Bärnighausen, 2004).

Fourth, female education is another crucial variable. Some related indicators such as female literacy rate, average years of schooling for female adult or all population, and percentage of primary education in women were used in prior studies (Anand & Bärnighausen, 2004; Farahani et al., 2009; Or et al., 2005; Pinzón-Flórez et al., 2015; Robinson & Wharrad, 2001; Robinson & Wharrad, 2000). Because the data of female literacy rate in recent years are missing in many countries, we used the mean years of female schooling as a proxy to measure female educational attainment.

Although there were many other confounders that had been included in previous studies, since our study focused on the strength and significance of the association between health workforce for health outcomes (rather than identifying health outcomes' influencing factors), we limited the confounding variables to the above four.

2.2 Data Sources

The data for health workforce, i.e., density of skilled health workers, density of medical doctors, and density of nursing and midwifery personnel, were extracted from the *Global Health Workforce Statistics* published by the WHO (2018, 2019c). The data used in this study were from the most recent year available between 2007 and 2017 in each country, resulting in a dataset covering the health workforce for 191 countries.

For the measures of multiple health outcomes, the latest data of healthy life expectancy at birth in 2016 were extracted from the report of *World Health Statistics 2020: Monitoring Health for the SDGs* and covered 183 countries (World Health Organization, 2020). The latest data about 15 – 60 adult mortality rate in 2016 was extracted from the *Global Health Observatory Data Repository* in the WHO and covered a total of 183 countries (World Health Organization, n.d.). The data of maternal mortality ratio were extracted from the report of *Trends in Maternal Mortality: 2000–2017, estimated by WHO, UNICEF, UNFPA, World Bank Group, and the United Nations Population Division* (World Health Organization, 2019b). The latest data in 2017, including 183 countries, were used in our study. The data related to under-five mortality rate, infant mortality rate, and neonatal mortality rate in 2017 were extracted from the *Levels & Trends in Child Mortality Report 2018: estimated developed by the UN Inter-agency Group for Child Mortality Estimation* and consisted of 194 countries (UNICEF, WHO, World Bank Group, & United Nations, 2018). The data of COVID-19 excess deaths per 100 K people were available for 81 countries and the latest data on September 10th, 2021 were collected from the statistical database of *The Economist* (2020).

The following sources provided data of four confounding variables: *Global Health Expenditure Database* for the health spending (current health expenditure) per capita (PPP$) (World Health Organization, 2019a); *Human Development Indices and Indicators: 2018 Statistical Update* for the GNI per capita (constant 2011 PPP$) and mean years of female schooling (United Nations Development Programme (UNDP), 2018); and *SDG Index and Dashboards Report* for the poverty headcount ratio (at PPP$1.90 – a – day) (Sachs et al. 2018). Data for the current health expenditure per capita, GNI per capita, mean years of female schooling, and poverty headcount ratio in 2017 covered 186, 188, 170, and 181 countries, respectively.

To compare the differences in mean values of above variables and the association of health workforce with health outcomes between countries with different income economies, we used the standard of World Bank income classification (The World Bank, 2019) and classified countries into four income categories: low-, lower-middle-, upper-middle-, and high-income countries (eTable 1 in the Supplement). Meanwhile, the number of population of each country in 2017 was extracted from the *World Health Statistics 2019* (World Health Organization, 2019c), which was used to weight the regression models.

2.3 Statistical Analysis

Each of the variables used in our study was continuous and displayed by mean value, standard deviation (SD), minimum, and maximum. One-way ANOVA was conducted to assess the difference in the mean value of each variable between low-income, lower-middle-income, upper-middle-income, and high-income countries. One-way MANOVA was also conducted to assess the differences in the mean values of six health outcomes between low-income, lower-middle-income, upper-middle-income, and high-income countries. A series of scatter plots with fitting curves by log–log (least squares fit) were drawn to show the relationships between density of health workforce and health outcomes in all countries. Correlation coefficients between density of the health workforce (i.e., density of skilled health workers, density of medical doctors, and density of nursing and midwifery personnel) and COVID-19 excess deaths per 100 K people were calculated using Pearson correlation measures, unweighted and weighted by population.

Multivariable linear regression equations were set. In the first set of regression equations, six dependent variables, i.e., healthy life expectancy at birth, 15 – 60 adult mortality rate, maternal mortality ratio, under-five mortality rate, infant mortality rate, and neonatal mortality rate, were regressed separately with density of skilled health workers as an independent variable and current health expenditure per capita, GNI per capita, mean years of female schooling, and poverty headcount ratio as confounding variables. In the second set of regression equations, they mimicked the first set but with density of medical doctors and density of nursing and midwifery personnel as independent variables. We carried out these two sets of regression equations twice, unweighted and weighted by population of each country. Besides, all regression analyses were carried out using heteroskedasticity-robust standard errors. 156 countries were finally included in the multivariable linear regression analyses (eTable 2 in the Supplement).

In addition to above regression analyses, we further interacted the density of health workforce (i.e., density of skilled health workers, density of medical doctors, and density of nursing and midwifery personnel) with different income categories (i.e., low-, lower-middle-, upper-middle-, and high-income), with low-income as the reference group omitted. Then the estimated coefficients would represent the association of density of health workforce with six health outcomes on average in that given income group of countries. After that, based on these coefficients, we could build a series of computational models of six health outcomes with density of health workforce and four confounding variables for low-, lower-middle-, upper-middle-, and high-income countries, separately. Then we would make counterfactual scenario analyses by estimating the health outcomes for low-, lower-middle-, and upper-middle-income countries by plugging the average level of density of health workforce of high-income countries, ceteris paribus, or simultaneously plugging the average levels of density of health workforce, current health expenditure per capita, GNI per capita, mean years of female schooling, and poverty headcount ratio of high-income countries into these computational models. More details about the interaction analyses and counterfactual scenario analyses were introduced in the Supplement.

All variables were transformed into natural logarithms before they were introduced into the regression models. Particularly, for the variable of poverty headcount ratio, as it was zero in some countries, which meant that there was no population living below the PPP$1.90-a-day in these countries, we calculated its natural logarithm based on its value plus two, and for the variable of mean years of female schooling, as the value in some countries was one, its natural logarithm was calculated based on its value plus one. In terms of the results, the estimated coefficients, i.e., b, in regression equations on the log-linear functional form were elasticities, which could be interpreted as a 1% increase in the independent variable, ceteris paribus, resulting in a b% change in the dependent variable (Anand & Bärnighausen, 2004). A p-value of less than 0.05 was set as the significance level.

3 Results

3.1 Global Profiles of Health Outcomes, Health Workforce, and Other Variables

Table 1 reports the mean value, standard deviation, minimum, and maximum of each variable in the natural unit, i.e., non-log form. Significant differences were observed in the mean values of all variables between high-, upper-middle-, lower-middle-, and low-income countries, which presented a clear gradient across countries in different income groups (all p-values < 0.001). Specifically, the mean values of healthy life expectancy at birth, density of skilled health workers, density of medical doctors, density of nursing and midwifery personnel, current health expenditure per capita, GNI per capita, and mean years of female schooling presented a significant gradual decline from high-income countries to low-income countries, and the mean values of 15 – 60 adult mortality rate, maternal mortality ratio, under-five mortality rate, infant mortality rate, neonatal mortality rate, and poverty headcount ratio increased gradually and significantly from high-income countries to low-income countries. Besides, we also identified the significant differences of six health outcomes between high-, upper-middle-, lower-middle-, and low-income countries using the MANOVA (eTable 2 and eTable 3 in the supplement).

3.2 Relationship between Health Workforce and Health Outcomes by Scatter Plots

These fitted curves in Fig. 1 indicate that, compared with countries that had a lower density of skilled health workers, those with a higher density of skilled health workers could expect to have a longer healthy expectancy at birth, a lower 15 – 60 adult mortality rate, a

Table 1 Profiles of variables

	Global	Income categories				ANOVA
		HIC	UMIC	LMIC	LIC	
Healthy life expectancy at birth *(years, 2016)*	63.23 (6.94) 44.90–76.20 *n* = 183	70.26 (2.98) 63.30–76.20 *n* = 52	64.83 (3.68) 53.80–70.90 *n* = 54	59.41 (5.07) 46.60–67.50 *n* = 46	54.30 (4.39) 44.90–64.60 *n* = 31	120.07 < 0.001
15 – 60 adult mortality rate *(death per 1000 alive at age 15, 2016)*	163.34 (87.16) 49.00–483.00 *n* = 183	83.50 (33.06) 49.00–172.00 *n* = 52	147.33 (55.77) 53.00–305.00 *n* = 54	206.59 (83.17) 69.00–483.00 *n* = 46	260.97 (64.27) 123.00–412.00 *n* = 31	66.13 < 0.001
Maternal mortality ratio *(deaths per 100,000 livebirths, 2017)*	160.82 (233.45) 2.00–1150.00 *n* = 183	13.23 (15.92) 2.00–70.00 *n* = 52	62.72 (61.24) 2.00–301.00 *n* = 54	216.85 (201.40) 19.00–917.00 *n* = 46	496.13 (294.38) 17.00–1150.00 *n* = 31	67.97 < 0.001
Under-five mortality rate *(deaths per 10,000 livebirths, 2017)*	291.70 (292.01) 20.00–1270.00 *n* = 194	59.47 (43.61) 20.00–260.00 *n* = 57	193.79 (145.97) 40.00–900.00 *n* = 58	428.26 (239.82) 90.00–1000.00 *n* = 46	708.39 (295.96) 170.00–1270.00 *n* = 31	94.62 < 0.001
Infant mortality rate *(deaths per 10,000 livebirths, 2017)*	221.08 (199.20) 20.00–880.00 *n* = 194	51.23 (39.01) 20.00–230.00 *n* = 57	161.90 (110.67) 30.00–650.00 *n* = 58	328.91 (162.31) 80.00–670.00 *n* = 46	490.32 (185.77) 140.00–880.00 *n* = 31	96.58 < 0.001
Neonatal mortality rate *(deaths per 10,000 livebirths, 2017)*	130.67 (107.51) 10.00–440.00 *n* = 194	34.21 (27.45) 10.00–170.00 *n* = 57	104.83 (66.66) 20.00–310.00 *n* = 58	195.00 (93.09) 50.00–440.00 *n* = 46	264.52 (86.02) 90.00–420.00 *n* = 31	90.80 < 0.001
Density of skilled health workers *(per 100,000 population, 2007–2017)*	592.09 (522.73) 8.40–2682.42 *n* = 191	1116.13 (501.71) 194.00–2682.42 *n* = 57	546.72 (340.63) 63.98–1598.00 *n* = 57	274.37 (273.38) 38.21–1444.24 *n* = 46	130.19 (187.68) 8.40–811.27 *n* = 29	65.76 < 0.001
Density of medical doctors *(per 100,000 population, 2007–2017)*	172.84 (156.76) 1.57–819.00 *n* = 191	318.05 (120.47) 92.57–656.17 *n* = 57	181.06 (143.63) 10.53–819.00 *n* = 57	70.87 (81.45) 5.29–320.02 *n* = 46	33.54 (74.22) 1.57–367.45 *n* = 29	57.24 < 0.001
Density of nursing and midwifery personnel *(per 100,000 population, 2007–2017)*	419.25 (394.30) 6.11–2026.25 *n* = 191	798.08 (426.30) 86.00–2026.25 *n* = 57	365.65 (233.65) 30.99–1143.83 *n* = 57	203.51 (212.26) 30.67–1207.39 *n* = 46	96.65 (121.39) 6.11–523.30 *n* = 29	53.11 < 0.001
Current health expenditure per capita *(PPP$, 2017)*	1470.71 (1771.63) 37.33–10,246.14 *n* = 184	3570.32 (1859.87) 1070.77–10,246.14 *n* = 56	965.41 (439.72) 141.02–2485.81 *n* = 54	304.44 (175.29) 94.30–863.29 *n* = 46	105.28 (48.15) 37.33–231.42 *n* = 26	109.21 < 0.001

Table 1 (continued)

	Global	Income categories				ANOVA
		HIC	UMIC	LMIC	LIC	
Gross national income per capita *(PPP$, 2017)*	17,420.01 (18,555.55) 663.00–116,818.00 *n* = 188	39,556.11 (19,212.27) 5554.00–116,818.00 *n* = 56	13,417.74 (5104.92) 5125.00–26,107.00 *n* = 58	5237.58 (2460.35) 1399.00–10,846.00 *n* = 45	1582.76 (628.38) 663.00–3317.00 *n* = 29	117.65 < 0.001
Poverty headcount ratio *(percentage of population living below PPP$1.90-a-day, 2017)*	13.25 (20.08) 0.00–83.54 *n* = 181	0.46 (0.49) 0.003–1.91 *n* = 52	4.21 (6.97) 0.00–28.65 *n* = 53	16.55 (15.46) 0.06–53.89 *n* = 46	46.35 (21.26) 3.02–83.54 *n* = 30	103.32 < 0.001
Mean years of female schooling *(years, 2017)*	8.29 (3.49) 1.00–13.60 *n* = 170	11.58 (1.40) 8.00–13.60 *n* = 51	9.32 (1.83) 4.00–12.80 *n* = 51	6.12 (2.50) 1.70–11.60 *n* = 41	3.42 (1.97) 1.00–10.10 *n* = 27	129.33 < 0.001

HIC, high-income country; UMIC, upper-middle-income country; LMIC, lower-middle-income country; LIC, low-income-country

The numbers in the cells from second to sixth columns are mean, SD, minimum, maximum, and number of countries

The numbers in the cells of seventh column are *F*-value and *p*-value for one-way ANOVA

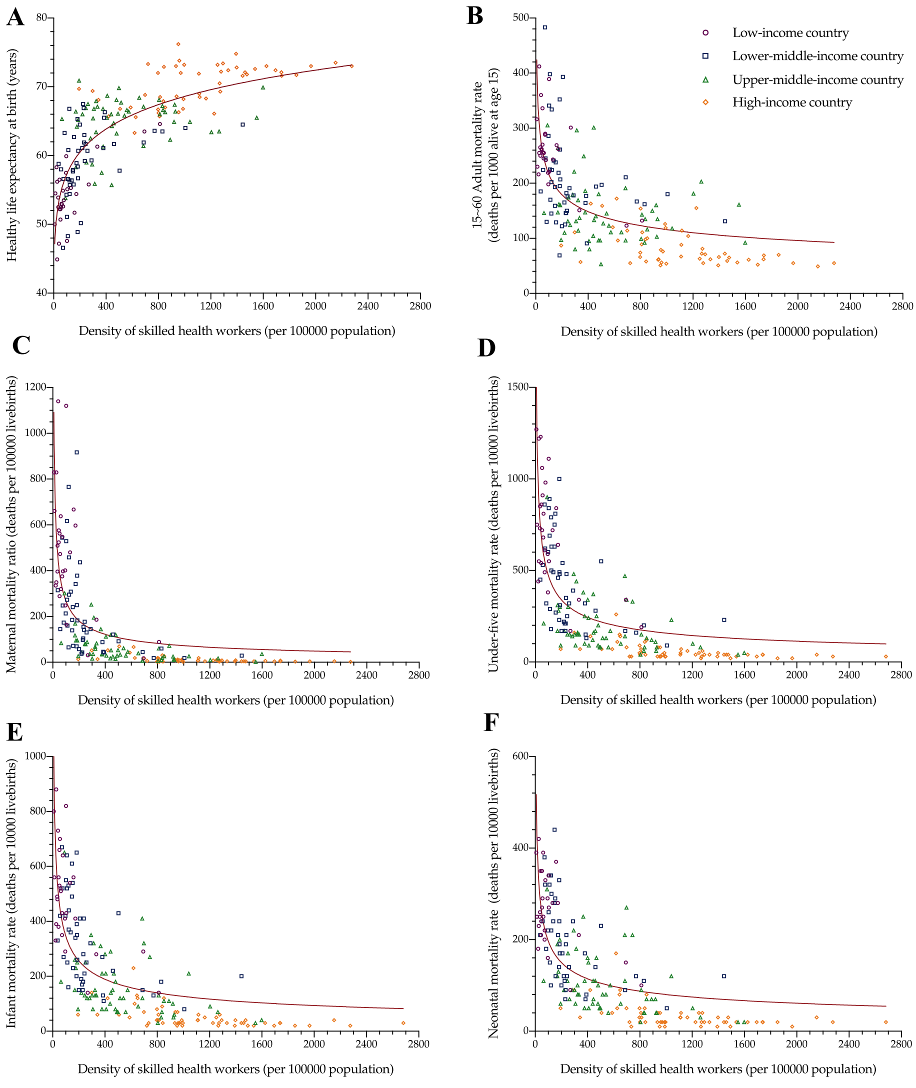

Fig. 1 Global scatter plots of six health outcomes and density of skilled health workers

lower maternal mortality ratio, a lower under-five mortality rate, a lower infant mortality rate, and a lower neonatal mortality rate. However, these links between density of skilled health workers and health outcomes flattened out, which meant that at a low-level density of skilled health workers, a further increase in density of skilled health workers was associated with a large increase in healthy life expectancy at birth and a large decrease in 15 – 60 adult, maternal, under-five, infant, and neonatal mortality rate, but at high levels of density of skilled health workers, increased density of skilled health workers was associated with small changes in health outcomes. Unsurprisingly, consistent with results in Table 1, the figure shows that high-income countries generally enjoy both a high density of skilled health workers and world-leading health outcomes, whereas low-income countries suffer from both few health workers and poor health outcomes. Similar patterns emerge for the relationship between health outcomes and the density of medical doctors or the density of nursing and midwifery personnel (eFig. 1 and eFig. 2 in the Supplement).

3.3 Multiple Log-Linear Regression Analyses

Table 2 presents the regression results for the associations between the density of skilled health workers and health outcomes. In the *Block I* (i.e., regressions unweighted by population), the explained variations, i.e., coefficients of determination R^2, were more than 74% in all regression equations and the F tests decisively rejected the hypothesis of joint non-significance of the independent and confounding variables. The density of skilled health workers varied in both elasticities and levels of significance in different equations for six health outcomes. Specifically, density of skilled health workers was significantly associated with maternal mortality ratio, under-five mortality rate, infant mortality rate, and neonatal mortality rate, except for healthy life expectancy at birth and 15 – 60 adult mortality rate. The elasticities of maternal, under-five, infant, and neonatal mortality rates with respect to density of skilled health workers were – 0.45, – 0.17, – 0.18, and – 0.19 (all p-values ≤ 0.016), respectively. However, after weighted by population in the *Block II*, the associations between the density of skilled health workers and these health outcomes were not significant.

Table 3 shows the results of the associations of density of medical doctors and density of nursing and midwifery personnel with six health outcomes. In the *Block I* (i.e., regressions unweighted by population), the coefficients of determination R^2, were more than 74% in all regression equations and the F tests decisively rejected the hypothesis of joint non-significance of the independent and confounding variables. The density of medical doctors and density of nursing and midwifery personnel varied in both elasticities and levels of significance in difference equations for difference health outcomes. Specifically, density of medical doctors was significantly associated with healthy life expectancy at birth (b: 0.02) and maternal mortality ratio (b: – 0.22). Meanwhile, density of nursing and midwifery personnel was significantly associated with maternal mortality ratio (b: – 0.28), under-five mortality rate (b: – 0.14), infant mortality rate (b: – 0.16), and neonatal mortality rate (b: – 0.20). However, after weighted by population, the associations of density of medical doctors and density of nursing and midwifery personnel with these health outcomes were no longer significant.

The four confounding variables, i.e., current health expenditure per capita, GNI per capita, mean years of female education, and poverty headcount ratio, varied in both elasticities and levels of significance in different regressions in accounting for multiple health outcomes, unweighted and weighted by population.

3.4 Interaction Analyses and Counterfactual Scenario Analyses

The results of interaction analyses between health workforce and income categories were shown in eTables 5 – 8 in the Supplement. First, the results show that part of interaction variables between health workforce (i.e., density of skilled health workers, density of medical doctors, and density of nursing and midwifery personnel) and income categories (i.e., low-, lower-middle-, upper-middle-, and high-income) were significantly associated with 15 – 60 adult, maternal, under-five, infant, and neonatal mortality rates, unweighted and weighted by population. Second, the elasticities of healthy life expectancy at birth, 15 – 60 adult, maternal, under-five, infant, and neonatal mortality rates with respect to densities of

Table 2 Multiple log-linear regression equations with density of skilled health workers as an independent variable

	Healthy life expectancy at birth	15 – 60 adult mortality	Maternal mortality	Under-five mortality	Infant mortality	Neonatal mortality
Block I (Regressions unweighted by population)						
Constant	3.97 (54.21) < 0.001	5.92 (15.17) < 0.001	9.57 (10.37) < 0.001	8.45 (15.88) < 0.001	8.31 (14.89) < 0.001	7.90 (13.74) < 0.001
Density of skilled health workers	< −0.001 (−0.01) 0.991	−0.01 (−0.30) 0.765	−0.45 (−4.14) < 0.001	−0.17 (−2.43) 0.016	−0.18 (−2.46) 0.015	−0.19 (−2.60) 0.010
Current health expenditure per capita	0.04 (3.65) < 0.001	−0.30 (−4.61) < 0.001	−0.47 (−3.00) 0.003	−0.54 (−6.34) < 0.001	−0.55 (−6.32) < 0.001	−0.51 (−6.11) < 0.001
GNI per capita	−0.01 (−0.83) 0.406	0.02 (0.41) 0.679	0.01 (0.06) 0.955	0.16 (1.83) 0.070	0.14 (1.59) 0.114	0.13 (1.41) 0.161
Mean years of female schooling	0.04 (1.81) 0.073	0.23 (2.07) 0.041	−0.33 (−1.57) 0.120	−0.28 (−2.13) 0.035	−0.16 (−1.17) 0.244	−0.16 (−1.22) 0.226
Poverty headcount ratio	−0.04 (−5.23) < 0.001	0.17 (3.87) < 0.001	0.31 (3.74) < 0.001	0.19 (3.32) 0.001	0.14 (2.42) 0.017	0.08 (1.47) 0.144
n	156	156	156	156	156	156
R^2	0.80	0.74	0.84	0.86	0.83	0.80
F	116.43	90.59	163.16	192.59	156.84	124.98
P	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Block II (Regressions weighted by population)						
Constant	4.25 (26.24) < 0.001	4.31 (6.38) < 0.001	5.19 (2.96) < 0.001	6.50 (6.10) < 0.001	6.41 (6.51) < 0.001	6.15 (5.65) < 0.001
Density of skilled health workers	−0.01 (−0.71) 0.481	0.12 (1.29) 0.198	−0.21 (−1.43) 0.154	−0.01 (−0.07) 0.942	−0.005 (−0.04) 0.970	0.06 (0.35) 0.727

Table 2 (continued)

	Healthy life expectancy at birth	15 – 60 adult mortality	Maternal mortality	Under-five mortality	Infant mortality	Neonatal mortality
Current health expenditure per capita	0.03	−0.15	−0.46	−0.37	−0.41	−0.42
	(1.80)	(−1.35)	(−1.95)	(−2.40)	(−2.55)	(−2.15)
	0.073	0.178	0.053	0.018	0.012	0.033
GNI per capita	−0.02	−0.002	0.31	0.16	0.17	0.20
	(−1.06)	(−0.02)	(1.10)	(1.16)	(1.29)	(1.25)
	0.289	0.986	0.274	0.248	0.199	0.215
Mean years of female schooling	0.05	0.09	−0.50	−0.56	−0.49	−0.76
	(1.93)	(0.62)	(−1.81)	(−2.45)	(−2.10)	(−2.58)
	0.055	0.533	0.072	0.015	0.038	0.011
Poverty headcount ratio	−0.07	0.37	0.72	0.45	0.37	0.31
	(−4.62)	(4.87)	(5.44)	(3.85)	(3.46)	(2.55)
	< 0.001	< 0.001	< 0.001	< 0.001	0.001	0.012
n	156	156	156	156	156	156
R^2	0.82	0.71	0.85	0.86	0.84	0.80
F	40.26	16.87	86.45	61.43	50.40	33.83
P	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

All dependent and independent variables were transformed into natural logarithms for the regressions

Robust standard errors were reported in all regression equations.

The numbers in the cells are b (regression coefficient), t_b (t value of b), and p-value.

Table 3 Multiple log-linear regression equations with density of medical doctors and density of nursing and midwifery personnel as independent variables

	Healthy life expectancy at birth	15 – 60 adult mortality	Maternal mortality	Under-five mortality	Infant mortality	Neonatal mortality
Block I (Regressions unweighted by population)						
Constant	3.94 (54.12) < 0.001	5.98 (15.27) < 0.001	9.36 (10.15) < 0.001	8.30 (15.39) < 0.001	8.12 (14.29) < 0.001	7.66 (13.42) < 0.001
Density of medical doctors	0.02 (2.10) 0.038	−0.06 (−1.30) 0.196	−0.22 (−2.11) 0.037	−0.04 (−0.70) 0.484	−0.02 (−0.35) 0.729	0.01 (0.17) 0.869
Density of nursing and midwifery personnel	−0.01 (−1.59) 0.113	0.01 (0.15) 0.879	−0.28 (−3.07) 0.003	−0.14 (−2.14) 0.034	−0.16 (−2.44) 0.016	−0.20 (−2.90) 0.004
Current health expenditure per capita	0.04 (3.89) < 0.001	−0.29 (−4.66) < 0.001	−0.47 (−3.03) 0.003	−0.54 (−6.30) < 0.001	−0.55 (−6.21) < 0.001	−0.51 (−5.97) < 0.001
GNI per capita	−0.01 (−0.81) 0.417	0.03 (0.44) 0.657	0.03 (0.15) 0.882	0.17 (1.93) 0.056	0.15 (1.69) 0.093	0.14 (1.52) 0.130
Mean years of female schooling	0.03 (1.36) 0.176	0.26 (2.56) 0.011	−0.26 (−1.33) 0.186	−0.27 (−2.14) 0.034	−0.16 (−1.25) 0.215	−0.18 (−1.35) 0.180
Poverty headcount ratio	−0.03 (−4.02) < 0.001	0.14 (3.06) 0.003	0.25 (2.50) 0.013	0.19 (2.97) 0.003	0.15 (2.40) 0.018	0.11 (1.93) 0.056
n	156	156	156	156	156	156
R^2	0.81	0.74	0.84	0.86	0.84	0.80
F	95.64	76.30	143.45	160.48	130.57	105.18
P	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Table 3 (continued)

	Healthy life expectancy at birth	15 – 60 adult mortality	Maternal mortality	Under-five mortality	Infant mortality	Neonatal mortality
Block II (Regressions weighted by population)						
Constant	4.24	4.51	4.98	6.36	6.23	6.00
	(25.17)	(6.83)	(2.77)	(6.23)	(6.61)	(5.90)
	< 0.001	< 0.001	0.006	< 0.001	< 0.001	< 0.001
Density of medical doctors	< 0.001	−0.03	−0.06	0.12	0.16	0.22
	(0.04)	(−0.55)	(−0.37)	(1.19)	(1.58)	(2.00)
	0.970	0.586	0.714	0.236	0.116	0.047
Density of nursing and midwifery personnel	−0.01	0.13	−0.13	−0.09	−0.11	−0.10
	(−0.70)	(1.64)	(−1.24)	(0.73)	(–0.90)	(−0.66)
	0.486	0.104	0.218	0.465	0.371	0.510
Current health expenditure per capita	0.03	−0.17	−0.46	−0.34	−0.36	−0.36
	(2.06)	(−1.61)	(−1.89)	(−2.28)	(−2.33)	(−1.91)
	0.041	0.110	0.061	0.024	0.021	0.058
GNI per capita	−0.02	0.01	0.31	0.13	0.13	0.14
	(−1.17)	(0.15)	(1.07)	(1.02)	(1.01)	(0.94)
	0.245	0.879	0.288	0.309	0.313	0.351
Mean years of female schooling	0.05	0.11	−0.51	−0.57	−0.51	−0.79
	(1.92)	(0.72)	(−1.82)	(−2.66)	(−2.36)	(−2.85)
	0.057	0.470	0.071	0.009	0.020	0.005
Poverty headcount ratio	−0.07	0.33	0.73	0.52	0.47	0.43
	(−3.70)	(4.13)	(4.46)	(4.48)	(4.47)	(3.76)
	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
n	156	156	156	156	156	156
R^2	0.82	0.72	0.85	0.86	0.85	0.81
F	34.51	16.22	76.27	54.19	45.30	31.01
P	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

All dependent and independent variables were transformed into natural logarithms for the regressions

Robust standard errors were reported in all regression equations

The numbers in the cells are *b* (regression coefficient), t_b (t value of *b*), and *p*-value skilled health workers, medical doctors, and nursing and midwifery personnel were different between low-, lower-middle-, upper-middle-, and high-income countries. Third, as eTable 10, eFig. 3, and eFig. 4 show, after plugging the average level of density of health workforce of high-income countries into the computational models of six health outcomes for low-, lower-middle-, and upper-middle-income countries, ceteris paribus, the estimated health outcomes in low-, lower-middle-, and upper-middle-income countries, especially the low-income countries, were still much lower than those of high-income countries; after simultaneously plugging the average levels of density of health workforce, current health expenditure per capita, GNI per capita, mean years of female schooling, and the poverty headcount ratio of high-income countries into those models, these estimated health outcomes in low-, lower-middle-, and upper-middle-income countries became further closer to those of high-income countries.

3.5 Correlation between Health Workforce and Covid-19 Excess Deaths

Results of population-unweighted and population-weighted univariate Pearson correlations estimated between density of health workforce and COVID-19 excess deaths per 100 K people are shown in Table 4. COVID-19 excess deaths per 100 K people were significantly negatively correlated with density of skilled health workers (r: –0.230, p-value: 0.039) and density of nursing and midwifery personnel (r: –0.259, p-value: 0.019), unweighted by population. Population-weighted correlations of COVID-19 excess deaths per 100 K people with density of skilled health workers, density of medical doctors, and density of nursing and midwifery personnel were not significant.

4 Discussion

In the context of global efforts to meet the SDGs, our study uses multiple health outcomes and the latest WHO dataset on health workforce to investigate the association between health workforce and health outcomes, providing an update and extension of previous cross-country studies (Amiri & Solankallio-Vahteri, 2019; Anand & Bärnighausen, 2004; Cochrane et al., 1978; Farahani et al., 2009; Hertz et al., 1994; Kim & Moody, 1992; Muldoon et al., 2011; Or et al., 2005; Pinzón-Flórez et al., 2015; Robinson & Wharrad, 2001; Robinson & Wharrad, 2000). Our results underscore the importance of accounting for poverty and the broader social determinants of health when studying the association of health outcomes with the health workforce, and the distinction between cross-individual

Table 4 Correlations between density of the health workforce (per 100 K population) and COVID-19 excess deaths per 100 K people, unweighted and weighted by population

	Pearson correlation coefficient (95% CI), p-value	
	Unweighted by population	Weighted by population
Density of skilled health workers	−0.230 (−0.427 to −0.013), 0.039	−0.136 (−0.344 to 0.085), 0.228
Density of medical doctors	−0.061 (−0.276 to 0.159), 0.586	0.119 (−0.102 to 0.328), 0.292
Density of nursing and midwifery personnel	−0.259 (−0.452 to −0.043), 0.019	−0.204 (−0.404 to 0.015), 0.068

and cross-country disparities, given the importance of developments in populous low- and middle-income countries like China and India.

From a global perspective, the data underscores the wide disparities in health outcomes between different countries, especially between those most and least advantaged. For example, the healthy life expectancy at birth in the Central African Republic was 44.9 years, and it reached 76.2 years in Singapore. In addition, there were significant disparities in the average levels of six health outcomes between countries in different income categories. The global average levels of maternal mortality ratio, under-five mortality rate, and neonatal mortality rate had not met the minimum targets set in the health-related SDGs by 2030 (World Health Organization, 2015), i.e., 70 deaths per 100,000 livebirths, 25 deaths per 1000 livebirths, 12 deaths per 1000 livebirths for maternal, under-five, and neonatal mortality rates, respectively. Of these countries that did not met the minimum targets, the most ($\geq$77.8%) were low- and lower-middle-income countries. In terms of health workforce, the density of skilled health workers, density of medical doctors, and density of nursing and midwifery personnel also varied widely between countries. For example, Somalia had 8.4 skilled health workers per 100,000 population and Monaco had 2682.4 per 100,000 population. Besides, the global average levels of densities of skilled health workers, medical doctors, and nursing and midwifery personnel had reached the WHO minimum recommendations (World Health Organization, 2016b), i.e., 4.45, 1.27, and 3.18 per 1000 population for density of skilled health workers, density of medical doctors, and density of nursing and midwifery personnel, respectively, that were related to the median achievement level (25%) attainment of 80% coverage for health-related SDGs. However, 50.8%, 49.2%, and 51.8% of all countries had not met that recommendations for densities of skilled health workers, medical doctors, and nursing and midwifery personnel, respectively.

Our findings of the significant positive association of a high density of aggregate measure of health workforce with reduced maternal mortality ratio, under-five mortality rate, infant mortality rate, and neonatal mortality rate in a global perspective (unweighted by population) are in accordance with the study of Anand and Bärnighausen (2004). Meanwhile, we found the elasticity of maternal mortality ratio with respect to density of skilled health workers was higher than those of under-five, infant, and neonatal mortality rates. A potential explanation was that a qualified health workforce may be able to address more conditions that put mothers at immediate risk of death compared with children, infants, or newborns (Anand & Bärnighausen, 2004). However, these significant associations of density of skilled health workers with maternal, under-five, infant, and neonatal mortality rates were not robust to different empirical specifications and became insignificant after weighted by the population of each country, reflecting the important distinction between cross-individual and cross-country disparities, and the importance of developments in populous low- and middle-income countries like China and India. Meanwhile, there were no significant associations between density of skilled health workers and healthy life expectancy at birth or the 15 – 60 adult mortality rate, unweighted and weighted by population. No related cross-country study has been found to analyze the association of an aggregate density of health workforce with healthy life expectancy at birth or adult mortality rate. This finding indicates that other factors such as the broader social determinants of health, health expenditure per capita, and the poverty rate account for much of the variation in these two health outcomes, as well as underlying improvements in the aggregate health workforce itself. Using limited data available from 81 countries, we identified a significant and negative correlation between density of skilled health workers and COVID-19 excess deaths when unweighted by population, which indicates the potential importance of health workforce under the current COVID-19 pandemic.

In addition to the aggregate measure of health workforce, we included density of medical doctors and density of nursing and midwifery personnel separately in a parallel set of regressions. From a global perspective, we found that among six health outcomes, the density of medical doctors had a significant positive association with healthy life expectancy at birth and maternal mortality ratio when unweighted by population, which are consistent with the studies of Robinson et al. (2001) and Kim et al. (1992), partly consistent with those of Anand et al. (2004), Or et al. (2005), Hertz et al. (1994), and Pinzón-Flórez et al. (2015), and inconsistent with those of Robinson et al. (2000), Farahani et al. (2009), and Muldoon et al. (2011) Unlike the density of medical doctors, density of nursing and midwifery personnel had a significant and positive association with maternal, under-five, infant, and neonatal mortality rates, after controlling for all four confounders and unweighted by population, which reject earlier findings about nursing invisibility in those studies of Robinson et al. (2000), Anand et al. (2004) Muldoon et al. (2011), and Kim et al. (1992) These differences between our study and previous cross-country studies in the associations of densities of medical doctors and nursing and midwifery personnel with these health outcomes may arise from different times' database and not exactly the same confounders and analytic strategies. Our study updates the evidence in previous studies and highlights the significance of density of medical doctors and density of nursing and midwifery personnel for multiple health outcomes. Similar with aggregate density of health workforce, we did not identify robust significant associations of density of medical doctors and density of nursing and midwifery personnel with these health outcomes after weighted by the population. Meanwhile, we identified a negative correlation of density of nursing and midwifery personnel with COVID-19 excess deaths per 100 K people across countries when unweighted by population. Although the association was not robust and became insignificant after weighted by the population, it could indicate a certain degree of importance of the nursing and midwifery personnel under the current COVID-19 pandemic.

Besides, we further compared the associations of densities of skilled health workers, medical doctors, and nursing and midwifery personnel with six health outcomes between countries in different income categories by conducting interaction analyses. Regardless of the level of significance, the elasticities of all six health outcomes with respect to density of skilled health workers, density of medical doctors, and density of nursing and midwifery personnel varied between countries in different income categories, and they were larger in high-income countries than those in middle- and low-income countries. It provides evidence of inequalities in health between high-, middle- and low-income countries, that a higher level of density of health workforce among high-income countries was associated with better health outcomes there. A potential explanation is that individuals of higher socio-economic status adopt health-related behavioral improvements first (such as understanding the harms of smoking), with lower-income populations adopting such societal changes later (Victora et al., 2000; Wagstaff, 2002). However, results of the counterfactual scenario analyses show that it was not possible to address health disparities in these health outcomes between countries at different income levels only by improving the density of health workforce in middle- and low-income countries. Taking the density of skilled health workers for example, by plugging the average level of density of skilled health workers of high-income countries into the computational models of six health outcomes for low-income countries, that were built on basis of results of interaction analyses, ceteris paribus, the estimated health outcomes in low-income countries were still far from the average levels of six health outcomes of high-income countries. However, when plugging the average levels of density of skilled health workers and all other variables including current health expenditure per capita, GNI per capita, mean years of female schooling, and poverty headcount ratio among high-income countries into previous computational models simultaneously, the estimated health outcomes of low-income countries became closer to those of high-income countries. Although we cannot interpret these statistical associations as causal effects, our findings, to some extent, suggest that in addition to the health workforce, many other factors should be taken into account simultaneously for improving the health outcomes.

Moreover, our study confirms the importance of socio-economic factors for health outcomes, as proxied by our included explanatory variables of current health expenditure per capita, GNI per capita, poverty headcount ratio, and mean years of female schooling. First, we note that higher health expenditure per capita was significantly associated with better health outcomes, i.e., increased healthy life expectancy at birth and reduced 15 – 60 adult, maternal, under-five, infant, and neonatal mortality rates, though not robust enough after weighted by population. Our findings differ to some extent from those in previous cross-country studies. For example, both Muldoon et al. (2011) and Pinzón-Flórez et al. (2015) reported that health expenditure per capita was significantly associated with the maternal mortality ratio, but not with under-five and infant mortality rates; and Houweling et al. (2005) noted a significant association of public health expenditure per capita with the under-five mortality rate. Arguably, spending on the broader social determinants of health as well as health financing are as important as the health workforce in contributing to resilient health systems and better population health. Fittingly, the WHO identifies both health finance and health workforce as the building blocks that contribute to the strengthening health systems (World Health Organization (Ed.), 2010).

In terms of the GNI per capita, we did not identify its significant and robust associations with six health outcomes, that is a finding that differs from previous cross-country studies (Anand & Bärnighausen, 2004; Farahani et al., 2009; Houweling et al., 2005; Kim & Moody, 1992; Robinson & Wharrad, 2001; Robinson & Wharrad, 2000). This discrepancy may arise because none of these previous studies included health expenditure per capita or other health financing indicators in their analyses, and our finding probably points to the strong association between the amount of funding earmarked for health care (i.e., current health expenditure per capita) and health outcomes, controlling for a country's average economic status (i.e., GNI per capita).

In contrast with average income, the poverty headcount ratio was identified to have significant and robust associations with all six health outcomes. Specifically, a lower poverty headcount ratio was associated with a longer healthy life expectancy at birth, a lower 15 – 60 adult mortality rate, a lower maternal mortality ratio, a lower under-five mortality rate, a lower infant mortality rate, and a lower neonatal mortality rate. These findings highlight the importance of improving outcomes for the least advantaged or most vulnerable within a given society, and their significance for measured average outcomes. Although Anand et al. (2004) did not find significant associations between income poverty rate and maternal, infant, and under-five mortality rates across 83 countries in 2004, our findings further highlight the importance of eradicating poverty which is also set as the SDG 1 by the United Nations (United Nations, 2015).

Female education, i.e., mean years of female schooling, had significant coefficients in some of the regression models for 15 – 60 adult mortality rate, under-five mortality rate, infant mortality rate, and neonatal mortality rate. However, these associations were not robust enough before and after weighted by population, showing how inter-connected these factors are and defying facile accounts of causal effects. There are mixed results regarding the associations of female education with these health outcomes in previous cross-country studies as well, suggesting the importance of microeconomic studies with well-identified casual effects. Robinson et al. (2000), Schell et al. (2007), and Sartorius et al. (2014) noted a significant association of female education measured by female literacy/illiteracy rate or mean years of female adult education with infant mortality rate and under-five mortality rate; however, the studies of Robinson et al. (2001), Anand et al. (2004), and Pinzón-Flórez et al. (2015) reported that female education was not significantly associated with maternal, under-five, and neonatal mortality rates. Nevertheless, we cannot entirely dismiss the importance of female education for these health outcomes, but must take into account its inter-relationship with poverty and the broader social determinants of health.

There are several practical implications of our findings. Our cross-country results confirm the importance of health workforce in affecting multiple health outcomes. Therefore, investment in health workforce should be an integral part of the strategies to improve health outcomes and achieve health-related SDGs for every country, especially for these low- and lower-middle-income countries, as which account for about eighty percent of the countries that have not met the minimum targets set in the health-related SDGs by 2030. Meanwhile, from the global perspective, it's an urgent task and needs a lot of attention to strengthen the construction of health workforce as about half of the WHO's member countries do not reach the WHO minimum recommendations related to the median achievement level attainment of 80% coverage for health-related SDGs. Besides, as our study finds that it's difficult to improve current disparities in health outcomes between countries in different income categories by improving the density of the health workforce alone, achieving non-health SDGs related to poverty alleviation and expansion of female education and improving the health expenditure per capita should be included simultaneously in strategies to achieve health-related SDGs, especially for low- and middle-income countries.

Several limitations of our study should be addressed. First, health workforce can be discussed from four dimensions, i.e., availability, accessibility, acceptability, and quality (World Health Organization, 2015). Our study only focused on the significance of the first and the most basic level, i.e., availability, of the health workforce for multiple health outcomes. Second, in addition to skilled health workers, medical doctors, and nursing and midwifery personnel included in our study, there are other types of health workforce like community health workers and traditional and complementary medicine personnel that are also important to population health; although statistics on these health workers are lagging and discordant across countries, they exist in many countries and are being statistically available (World Health Organization, 2018), which could be included into the aggregate health workforce for more analyses. However, as the quantity of these types of health workforce is relatively small and their relative proportions of the total health workforce are low and differ across countries, their omission in our study should not bring a large extent of bias on the significance of aggregate health workforce for multiple health outcomes (Wooldridge, 2010). Third, due to the constraints of data availability, we used the most recent data from 2007 to 2017 for densities of skilled health workers, medical doctors, and nursing and midwifery personnel in our study, which might bias their coefficients related to these health outcomes. Besides, as the data of these variables used in our study were not available for all countries at the time of analyses, when we introduced all variables in our analyses, only 156 countries were included, that means our findings cannot necessarily be generalized to all countries in the world. Fourth, our data were cross-sectional and could not provide information of health workforce and health outcomes across multiple periods, that means our study could not reflect the actual effect of density of health workforce on health outcomes, i.e., the associations of densities of skilled health workers, medical doctors, and nursing and midwifery personnel with six health outcomes in our study cannot be concluded as causal relationships. More detailed analyses would be possible to undertake based on time-series data within or across countries. Fifth, it should be acknowledged that the importance of uncontrolled factors in our study to health outcomes cannot be excluded, such as adequate and appropriate nutrition, access to clean water and sanitation services, medical products, vaccines, and technologies.

5 Conclusions

In sum, our study underscores that the relationship between health workforce and health outcomes is both the cause and effect of broader socio-economic and health-system developments. A strong health workforce contributes to better health outcomes and is itself a manifestation of a country's previous investments that reduced poverty, improved health outcomes, and laid the foundation for a robust health system. Investment in health workforce should be an integral part of strategies to achieve health-related SDGs, and achieving non-health SDGs related to poverty alleviation and expansion of female education are complementary to achieving both sets of goals, especially for low- and middle-income countries. In light of the strains on the health workforce during the current COVID-19 pandemic, more attention should be paid to health workforce to strengthen health system resilience and long-term improvement in health outcomes.

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Author Contributions JL and KE designed the study. JL constructed the dataset, cleaned, and analyzed the data. JL prepared the first draft of the manuscript and KE commented and revised it. JL and KE finalized the manuscript.

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Availability of data and material The datasets used in this study are available online.

Declarations

Conflict of Interest We have no conflict of interest to disclose.

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