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A B S T R A C T
The recent COVID-19 pandemic poses the general question on how infectious diseases can persistently affect human health. A growing body of literature has found a significant amount of evidence on the long- term adverse effects of infectious diseases, such as influenza, typhoid fever, and yellow fever. However, we must be careful about the fact that little is known about the long-term consequences of the acute diarrheal disease pandemic cholera – *Vibrio cholerae* bacillus – which still threatens the health of the population in many developing countries. To bridge this gap in the body of knowledge, we utilized unique census-based data on army height at age 20 in early 20th-century Japan, with a difference-in-differences estimation strategy using regional variation in the intensity of cholera pandemics. We found that early-life exposure to a cholera pandemic had heterogeneous stunting effects on the final height of men; the magnitude of the stunting effects increased as the intensity of exposure increased.

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1. Introduction

The recent COVID-19 pandemic poses the general question on how infectious diseases can persistently affect human health. In light of this, we must be careful about the fact that cholera (*Vibrio cholerae* bacillus) pandemics still threaten populational health in many developing countries (Harris et al., 2012). On an annual basis, approximately 3 million cases of infections and 100,000 deaths occur worldwide (Ali et al., 2015; Didelot et al., 2015; Hu et al., 2016).

A growing body of literature has examined the long-term adverse effects of early-life exposure to a wide range of infectious diseases on health and socioeconomic outcomes in later life. Examples of recent long-term literature focusing on historical infectious diseases include Barofsky et al. (2015) for malaria, Parman (2015) for pandemic influenza, Beach et al. (2016) for typhoid fever, and Saavedra (2017) for yellow fever. Despite its heavy burden worldwide, little is known about the long-term impacts of early-life exposure to a cholera pandemic on human health.

To estimate the effects, we used a comprehensive conscription dataset covering the entire Japanese male population at age 20, between 1899 and 1910. By utilizing the frequent cholera epidemics from 1879 to 1890 as natural experiments, we employed the difference-in-differences approach to better identify the potential long-term impacts of early-life exposure to cholera on stature. We found that postnatal exposure to a cholera epidemic at age 1 had heterogeneous stunting effects. While the strongest stunting effects (0.25 cm) were observed at the highest decile group of cholera death rates, the effects observed at the 7–8th decile groups were roughly 40% of the maximum stunting effects. Meanwhile, the estimated effects observed at 1–6th groups were close to 0 and not statistically significant. Our results also suggest that while exposure at birth year had such stunting effects at the highest decile group, prenatal exposure to a cholera epidemic had little effect. We have confirmed that these results are robust against alternative specifications, intensity measures, and

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1 Almond and Currie (2011a) and Currie and Vogl (2013) provide comprehensive reviews of these works.

2 While there are a few economic studies analyzing historical cholera infections, such as Acemoglu and Johnson (2007), and Ambrus et al. (2015), neither study has investigated the persistent adverse health effects of early-life exposure to a cholera pandemic.
potentially influential subsamples. Our finding is consistent with the fetal-origin hypothesis that postulates that undernutrition in early life can impose permanent effects on body length as well as induce organ damage (Barker, 1992, 1998).

This study contributes to the literature in the following two ways. First, we estimated the potential long-term effects of early-life cholera exposure on the entire male population at age 20. Most previous studies that have analyzed long-term exposures to infectious diseases have used a wide variety of cross-sectional survey datasets that cover subsamples of each target population (Almond and Currie, 2011a; Currie and Vogl, 2013). By taking advantage of the comprehensive official army records, we used a regiment-preference-level panel dataset that covers most males aged 20 at that time, overcoming the potential sample selection biases in survey datasets. Another advantage is that we could control for a certain proportion of unobservable factors by applying the fixed effects models to our panel dataset.

Second, we estimated the heterogeneity in the treatment effects of early-life cholera exposure. In the growing body of related literature, estimating the heterogeneity in the long-term effects of early-life exposure to shock is considered to be an important research agenda (Currie and Vogl, 2013). However, most of the abovementioned studies have predominantly focused on the overall effects of early-life exposure to infectious diseases. To bridge this gap in the body of knowledge, this study is the first to examine the varying long-term effects of cholera exposure on stature.

The remainder of this paper proceeds as follows: Section 2 explains the historical background and maternal stressors. Section 3 introduces the data. Section 4 introduces the estimation strategy. Section 5 presents the main results. Section 6 provides several robustness checks. Section 7 discusses the results.

2. Background

2.1. Cholera epidemics in Japan

Cholera infection is caused by Vibrio cholerae, and its incubation period is considered to be approximately 1 to 5 days. After the symptoms start, this acute diarrheal disease causes severe dehydration within hours, which leads to substantial fluid deficit in excess of 10% of the body weight. Cholera case fatality rates exceeded 50% before the establishment of modern approaches to rehydration therapy (Clemens et al., 2017).

In 1877 of the Meiji era, Vibrio cholerae was brought to Japan by a British trading vessel (Japan Water Works Association, 1967, p. 136). Since the first epidemics in 1879, cholera frequently emerged and never subsided throughout the late 19th century. Fig. 1 illustrates the number of infected people and deaths due to cholera between 1877 and 1911. As illustrated in this figure, cholera had been prevalent for approximately 5 years in the late 19th century. Although the Meiji government noticed that polluted water was related to the infections, they could not provide effective prevention for the people. In May 1878, the government issued a public warning concerning drinking water to inform the public about the contamination of wells (Japan Water Works Association, 1967, pp. 137–140). However, this temporary measure was unable to lower the risk of infection, as shown in Fig. 1.3

3 In May 1887, Sensai Nagayo, the head of the Home Department’s Central Sanitary Association, argued for the construction of water and sewerage services to prevent the spread of cholera. In June 1887, the Association drafted its Proposal to Construct Sanitary Plumbing in Tokyo, which was submitted to Prime Minister Hirobumi Ito. However, the project was unable to secure support among local governments and did not find the necessary funds to install water supply systems; moreover, the installation of supply pipes did not proceed (Japan Water Works Association, 1967, pp. 146–147).

Around the beginning of the 20th century, an unmistakable reduction in the number of cholera infections and deaths was finally noted due to the introduction of modern water supply systems in Yokohama, Tokyo, and Osaka (Ogasawara and Matsushita, 2018).

2.2. Maternal stressors

Maternal infection to cholera can cause substantial nutritional deprivation due to the fluid deficit (Ciglenecki et al., 2013; Clemens et al., 2017). The weight of evidence from numerous animal studies shows that inadequate nutrition of the fetus in utero leads to abnormal fetal growth (Barker, 1992, 1998). Almond and Mazumder (2005) suggest that fetal exposure to pandemic influenza can be associated with shorter stature in adulthood. The other possible path is maternal stress from the symptoms of cholera infection. In fact, a set of recent studies have provided evidence on the adverse health effects of mental disorders in pregnant women (Hibino et al., 2009; Stein et al., 2014; Torche, 2011; Yonkers et al., 2014). Nutritional deprivation in the postnatal period may also have adverse health effects on infants (Barreca, 2010; Neelsen and Stratmann, 2011; Ampaabeng and Tan, 2013; Nandi et al., 2016). In this paper, we intend to estimate the overall effects of early-life cholera exposure because we cannot disentangle both channels given the nature of our dataset. Thus, we attempted to assess this point using some specifications in our analyses.

3. Data

3.1. Army height

To measure the adult terminal statures of the males, we drew data from the 1899 to 1910 editions of the Statistical Report of the Army Ministry, published by the Army Ministry, reviewing the regiment-preference-year average height of 20-year-old males.4 Based on the Conscription Ordinance, most men at age 20 took a physical examination for enlistment from 1889 until the end of World War II. Our dataset covers approximately 97% of the male

4 This document reports the number of men in ten height categories on a frequency table. We systematically calculated the average height of men by using the midpoints and frequencies in the height classes (Banerjee et al., 2010). Note also that there is a consensus that adult height is an important biological measure reflecting accumulated nutritional status (Fogel, 1994).
population aged 20 at that time, supporting the representativeness of our analytical sample (Statistics Bureau of the Cabinet, 1911). We could not obtain the height data for the 1904–1905 samples because of the Russo–Japanese War. However, this omission does not cause a selection issue but rather can exclude influential observations that were potentially stunted by the war.

3.1.1. Cholera death rates

We use the cholera death rate as our intensity variable. This rate is defined as the number of cholera deaths per 100,000 people. To obtain data on cholera deaths and the population number, we digitized a set of documents published by the Sanitary Bureau of the Home Department (1912, 1924) and the Statistics Bureau of the Cabinet (1992, 1999, 2000).

To examine the random nature of cholera epidemics in the late 19th century, we illustrate the spatial distribution of the death rates in the prevalent years in Fig. 2. A comparison between Fig. 2a and c suggests that while the severity of cholera in 1879 was greater in the prefectures in western Japan, the prefectures in eastern Japan suffered higher rates in 1886. By contrast, a comparison between Fig. 2b and d indicates that the severity of cholera in 1882 was greater in the prefectures in central Japan, whereas the prefectures in western Japan were the hardest hit in 1890. These nonsystematic patterns of cholera epidemics support the random nature of the cholera pandemics. These figures also confirm that there were substantial spatiotemporal variations in our key intensity variable, cholera death rate. We take advantage of the random variation in cholera epidemics throughout the

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Fig. 2. Cholera death rates in the prevalent years. Notes: The cholera death rate is defined as the number of deaths from cholera per 1000 people. The cholera death rates in 1879, 1882, 1886, and 1890 are illustrated in Figs. a–d, respectively. Sources: Sanitary Bureau of the Home Department (1912, 1924); Statistics Bureau of the Cabinet (1992, 1999, 2000).
Japanese archipelago to identify the effects of early-life cholera exposure.

3.3. Additional control variables

Despite the random nature of our key cholera intensity variable, we further include a few additional variables to control for the potential standard of the public health environment and income effects in each prefecture.\(^5\) We consider the coverage of hospitals, doctors, and midwives per 100 people.\(^6\) Data on the number of hospitals, doctors, and midwives were taken from the Sanitary Bureau of the Home Department (1912, 1924) and the Statistics Bureau of the Cabinet (1992, 1999, 2000).\(^7\) The summary statistics of all variables are reported in Table 1.

4. Estimation strategy

We employ a difference-in-differences approach as our identification strategy by exploiting the differences in epidemic intensity among areas during epidemic years. To evaluate the effects of early-life exposure to cholera on final height in detail, we introduced a categorical variable that varies according to cholera death rate as a measure of epidemic intensity.\(^8\) Our baseline specification is given by

\[
\text{Height}_{ijt} = \alpha + \sum_{k=2}^{10} \beta_k l_{ik} + x_{ijt} \gamma + v_{ij} + \lambda_t + t \theta_t + e_{ijt}
\]

where \(\text{Height}_{ijt}\) is the mean final height of men in region \(i\) of prefecture \(j\) and year \(t\), and \(l_{ik}\) is an indicator variable that takes one if the observation is classified into the \(k\)th decile of the cholera death rate. \(x_{ijt}\) is a vector of the prefecture-year level control variables. \(v_{ij}\) and \(\lambda_t\) represent the regiment-prefecture and year fixed effects, respectively. As some regiments consist of areas in two prefectures, we used the regiment-prefecture fixed effect, rather than the simple regiment \((v_i)\) or prefecture fixed effects \((v_j)\). \(t \theta_t\) is the regiment-prefecture specific time trend, and \(e_{ijt}\) is a random error term.

Our key variable can capture the heterogeneity of the lingering effects depending on the epidemic intensity. To fully investigate the long-term effects of pandemics in early-life periods, we used the cholera intensity variable during the 1 year before birth to the 2 years after birth. The estimated parameter \(\beta_k\), which is of interest, is interpreted as the effect of cholera exposure on final height at the \(k\)th decile of the cholera death rate relative to the 1st decile group. The cholera death rate at the 8–10th decile groups was mostly observed in the pandemic years (Appendix). Hence, we expect that \(\beta_k\) is negative and statistically significant when \(k\) is over 7.

Taking advantage of the structure of our data, we included the fixed effects in the regression model. The regiment-prefecture fixed effect controls for all unobserved time-constant factors, such as geographical characteristics and meteorological features that might be correlated with the risk of infectious diseases. The year fixed effect controls for all unobserved factors that are constant across the regiment-prefecture cell in both the birth and measured years, such as the macroeconomic picture and technological developments. In addition, the regiment-prefecture specific time trend was included to relax the common trend assumption with respect to cholera intensity. Thus, our specification is flexible despite the limited availability of data in 19th-century Japan.

Inter-prefecture migration was negligible during the prewar period (Nakagawa, 2001). Nevertheless, we considered the potential sorting effects due to migration by clustering the standard error at the level of nine larger areas.\(^7\) Therefore, our standard errors are robust for heteroskedasticity across areas and heteroskedasticity and correlation within areas.

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\(^5\) In fact, Bassino (2006) shows the importance of income and access to health care services for adult heights in postwar Japan. See also Bassino and Kato (2010) for a discussion on children’s growth in postwar Japan.

\(^6\) In the late nineteenth-century Japan, cholera epidemics were not likely to affect the size of birth cohort or the risk of fetal deaths (Ogasawara and Inoue, 2018). Thus, the potential mortality selection effects could be negligible.

\(^7\) There are some missing values. For instance, the data on doctors in Kagoshima prefecture in 1881 are not used, because of a mistake in the material. In the case of prefectures that split off from other prefectures between 1879 and 1890, we use the data on the original prefectures before independence.

\(^8\) Most of the related studies use the difference between affected cohorts and non-affected surrounding cohorts to investigate the effects of early-life health shocks on outcomes. This strategy tends to ignore the differences in shock intensity among units in affected cohorts, which might obscure the effects of treatment.

\(^9\) We used the conventional geographical classifications of Japan to systematically divide the prefectures into nine larger areas: Hokkaido (northernmost), Tohoku (eastern), Kanto (eastern-central), Chubu (western-central), Kansai (southern-central), Chugoku (westernmost), Shikoku (southwest island of main island), Kyushu (southwest island), and Okinawa (southernmost).
Fig. 3. Heterogeneity in the effects of exposure to cholera on final height. Notes: The horizontal axis indicates the 2nd to 10th decile of the cholera death rate. The 1st decile is not included because the results indicate effects relative to the 1st decile group. The dotted and solid lines indicate the estimates and their 90% confidence intervals, respectively. Standard errors are clustered at the 9-area level.

5. Main results

Fig. 3 presents our main results. Fig. 3a–d show the effects of cholera exposure from 1 year before birth to 2 years after birth, respectively.\(^\text{10}\) As shown in Fig. 3a and d, the estimated coefficients are not significantly negative, regardless of the cholera intensity, both 1 year before birth and 2 years after birth.\(^\text{11}\) This result suggests that exposure to a cholera epidemic at these times does not have long-term impacts on final height. As for the results in the birth year (Fig. 3b), the estimated coefficient at the 10th decile is \(-0.182\) and statistically significant at the 10% level, suggesting that the severest cholera epidemic was associated with stunting. The magnitude of the effect indicates that the final mean height of infants who experienced cholera exposure at the 10th decile, with a mean value of 4.7\(\text{cm}\), was 0.182 cm lower than that of infants classified into the 1st decile group; that is, those who were not exposed to cholera. In addition, the impacts of cholera exposure at the 8th and 9th deciles, which were observed in the epidemic years, are insignificant but negative and relatively large.

Fig. 3c shows clearer long-term effects of cholera exposure, 1 year after birth, on final height. At the 2nd to 6th decile, the estimated coefficients stay close to 0. In contrast, the coefficients are significantly negative and gradually become larger from the 7th to 10th decile. Cholera death rates classified into the 8–10th decile groups were observed in epidemic years; these results support that exposure to a cholera epidemic results in a short stature. In addition, the estimation result at the 7th decile group suggests that severe cholera exposure had adverse long-term effects even in non-epidemic years. The magnitudes of the estimated effect of cholera exposure, 1 year after birth, on final height are \(-0.093\), \(-0.102\), \(-0.214\), and \(-0.246\) cm at the 7th, 8th, 9th, and 10th deciles, respectively.

We briefly compared the effects of exposure in the birth year (Fig. 3b) with exposure, 1 year after birth (Fig. 3c), to determine the vulnerable timing. At the 10th decile, the impact size in the birth year is smaller than that at the 9th decile, as well as the 10th decile, 1 year after birth. Moreover, in contrast to exposure in the birth year, exposure 1 year after birth has a significant effect at the 7th decile group; that is, high intensity in non-epidemic years. These results suggest that infants are likely to be more sensitive to cholera exposure 1 year after birth than in the birth year.

In the baseline specification, the key measure is a categorical variable that varies according to the cholera death rate. To confirm

\(^\text{10}\) We have confirmed that the estimated effects of cholera exposure, three and four years after birth, are close to zero and statistically insignificant in most cases. Since including decile dummies exacerbates the efficiency in the estimation, we do not prefer to include these exposure variables.

\(^\text{11}\) Although the estimated effect at the 10th decile is positive and significant, two years after birth (Fig. 3d), this may be due to scarce observations (only 1.8% of the total observations).
that our estimation results remain stable if cholera intensity is defined based on another index, we used the decile of cholera incidence rate as an alternative measure of intensity. Fig. 4 presents the results. As shown in Fig. 4a, the results for cholera exposure in the birth year are similar to those in Fig. 3b. The estimated coefficient at the 10th decile is −0.169 and significant at the 10% level. Fig. 4b shows that the effects of exposure 1 year after birth are also broadly similar to the main results shown in Fig. 3c. Although the estimated coefficients at the 7th and 10th deciles (−0.094 and −0.244) are insignificant, the differences in value from the main results are only 0.001 and 0.002, respectively. These results, using the alternative measure, support that our findings are not disturbed by the definition of the cholera intensity variable.

To summarize, our main results suggest that cholera exposure in the birth year and 1 year after birth have adverse effects on final height. Furthermore, we found that the magnitude of the effects increased as the intensity of exposure increased.

6. Robustness

6.1. Alternative specification

We check the robustness of our main results in several ways, focusing on exposure in the birth year and 1 year after birth. First, we verified the robustness in terms of the randomness of our cholera variable. If cholera intensity was correlated with intensity in the previous year, the estimated effects of exposure in the birth year may be confounded with those of exposure 1 year after birth. We confirmed that this potential issue would not affect our estimation results by employing a specification that included the cholera intensity variables in both the birth year and 1 year after birth. The specification is given by

$$\text{Height}_{ijt} = \alpha + \sum_{k=2}^{10} \beta_k l_{ijk} + \sum_{k=2}^{10} \delta_k I_{ij(t+1)k} + X_{ijt} + v_j + \lambda_t + \tau_l + e_{ijt}$$

(2)

where \(l_{ijk}\) and \(I_{ij(t+1)k}\) indicate cholera intensity in the birth year and 1 year after birth, respectively. As Eq. (1), this specification controls for the additional control variables, the regiment-prefecture and year fixed effects, and the regiment-prefecture specific time trend.

Fig. 5 shows the results. Although the effects of cholera exposure in the birth year and 1 year after birth on final height were estimated at the same time, these are not different from the main results. The estimated coefficient of the 10th decile dummy of cholera death rate is significantly negative in the birth year and has significant adverse effects at the 7–10th deciles 1 year after birth. These results indicate that our baseline estimates accurately capture the long-term effects of exposure to cholera in both timings.

6.2. Falsification test

Second, we conducted a placebo test using the categorical variable and capturing the cholera intensity 2 years before birth. As fetuses could not be affected by an epidemic 2 years before birth, the variable should not have any significant effects on their final
height. Fig. 6 shows the results of our placebo test. The cholera intensity is measured by the death rate in Fig. 6a and the incidence rate in Fig. 6b. As expected, the estimated coefficients are near 0 and not statistically significant, regardless of the intensity. These results provide evidence that our baseline specification is valid.

6.3. Influential subsamples and clustering issue

Third, we checked the robustness using subsamples. The Japanese government enacted the Rentaiku shireibu jyorei (Regulation for Regimental District Office) to reorganize the regiments in 1907. As this reform might have influenced our main estimates, we conducted a regression analysis excluding all regiments affected by the reform to check the sensitivity of our results. Fig. 7 presents the results. Overall, these results are consistent with our main results. Although the effects of cholera exposure in the birth year on final height are not significant, the estimated coefficient is negative and large at the 10th decile relative to the other deciles. As for the exposure to cholera 1 year after birth, the results are close to our baseline results. Thus, these results confirm that the reform in 1907 does not disturb our main estimates.

Finally, we conducted an estimate using standard errors clustered at the prefecture level and fixed effects at the 9-area level in order to confirm that our classification does not have substantial effects on our main results. Fig. 8 shows the results, which are not really different from our main results; the estimated effects are statistically significant at the 10th decile group in the birth year and at the 9–10th decile groups, 1 year after birth. These results provide evidence of robustness against our cluster of standard error.

7. Discussion

By utilizing a comprehensive conscription dataset on the Japanese adult male population using the difference-in-differences approach, we estimated the heterogeneity in the treatment effects of early-life exposure to a cholera epidemic. We found that exposure to a cholera epidemic at age 0 reduced adult height by 0.25 cm at a maximum, and such stunting effect decreased as the intensity of exposure decreased. The estimates also suggest evidence of the timing of exposure. While exposure during the birth year might have stunting effects, the magnitude of prenatal exposure was close to 0 and statistically insignificant across all

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12 We also confirmed that our results are robust if the standard errors are adjusted for spatial correlation and serial correlation based on Conley (1999). The results are displayed in Fig. A.2 in Appendix.
decile groups. Overall, our results are consistent with the studies that show the negative relationships between disease environments during rapid economic growth and adult heights (e.g., Haines et al., 2003; Carson, 2020).

Our estimates indicate that exposure to a cholera epidemic at ages 0 to 1 led to an approximately 0.2–0.3 cm decline in the final height of men. Does this kind of stunning effect matter? One must be careful not to neglect the smaller magnitude of the effect on final height. In fact, Mazumder et al. (2010) provide evidence that a 0.1 cm decline in final height can be associated with a higher risk of cardiovascular disease in old age. Lawlor et al. (2002, 2004) also show evidence of shorter stature and higher risk of diabetes, heart disease, and osteoarthritis. Moreover, our estimates are similar to those estimated in previous studies focused on prewar Japan: Early-life exposure to the influenza epidemic of 1918–1920 led to roughly 0.1–0.3 cm declines in the height of the juvenile population (Ogasawara, 2017). To summarize, our findings on the negative impacts of early-life exposure to pandemics of cholera is consistent with the growing body of studies that have reported the importance of the childhood environment (Almond and Currie, 2011a).

In contrast, our results provide little evidence on the adverse effects of cholera exposure during the prenatal period and early infancy (two-year old) on the final height. One possible interpretation of this result is that the high fatality rate of a cholera epidemic culled most unhealthy infants in utero who are vulnerable to severe and acute dehydration due to cholera infection (Katja et al., 2006), and shifted the distribution of initial health endowments to the left at the same time (Trivers and Willard, 1973). This means that the surviving infants are still unhealthy compared with the surrounding cohorts, and thus we could observe the clear stunning effects of exposure at ages zero to one. At the same time, unhealthy infants are more likely to be culled by the infections, which eventually shifts the distribution of health endowments to the right, two years after birth. The unclear effects of early infancy exposure at age two can also be explained by the acquisition of immunity for cholera (Lyer et al., 2016).

However, we must excuse the fact that our data on height are aggregated annually in nature. This kind of aggregation might have attenuated the observed stunning effects. Despite this, this study contributes to the literature in a few points. As explained in the introduction, investigating the heterogeneity in the long-run effects is an important agenda in the literature (Currie and Vogl, 2013). Our findings provide suggestive evidence on the long-run heterogeneous effects of early-life cholera exposure, using unique historical data on final height in an Asian country. In addition, related previous studies have mainly focused on developed countries (Almond and Currie, 2011b). As this point, it is important that the cholera epidemics in South and East Asia are known as pathogenic reservoirs and sources of international transmissions (Didelot et al., 2015). This study offers a useful suggestion on the potential long-run health effects of a cholera epidemic in developing countries, especially in Asia. This is a case study of industrializing Japan, a past-developing Asian country in which the public health environment is known to be similar to those in current developing countries (van der Eng and Sohn, 2019).

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Conflicts of interest

There are no conflicts of interest to declare. Ryo Nagaya provided excellent research assistance.

Appendix A.

Our key measure of cholera intensity is based on the decile of the cholera death rate, between 1879 and 1890. Fig. A.1 presents the proportions of observations classified into each decile group by birth year. Evidently, most observations experienced cholera exposure from the 7th to 10th deciles of intensity in the epidemic years, namely 1879, 1882, 1886, and 1890.

We checked the robustness of our main results using the standard errors adjusted for spatial and serial correlation suggested by Conley (1999). The estimates are based on Hsiang (2010). The spatial correlation is assumed to vanish at 400 km, and the serial correlation is assumed to vanish at 3 years. Fig. A.2 presents the results, indicating that our main results are robust. Our results remain stable if we set 300 km or 500 km as the distance for spatial correlation and/or set 2 years as the period for serial correlation (not reported).

Fig. A.3 shows the relationship between residuals and the cholera death rates. In 1879–1890, higher death rates due to cholera were observed in Toyama, Ishikawa, Osaka, Nara, Tokyo,

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13 We also note that we used the census-based, regiment, district, year-level army height data in this study. In such aggregate data, the treatment assignments become relatively rough, implying that our obtained estimates are considered to be the lower bound of the true unobservable treatment effects.
**Fig. A.1.** Proportions of observations by the cholera death rate in birth year, 1879–1890. Notes: The legend indicates the 1st to 10th decile of the cholera death rate.

**Fig. A.2.** Robustness check: Estimates using standard error adjusted for spatial autocorrelation. Notes: The horizontal axis indicates the 2nd to 10th decile of the cholera death rate. The 1st decile is not included because the results indicate effects relative to the 1st decile group. The dotted and solid lines indicate the estimates and their 90% confidence intervals, respectively. Standard errors are adjusted for spatial autocorrelation.

**Fig. A.3.** Scatter diagram of residuals against the cholera death rates. Notes: The labels stand for following prefectures: HK (Hokkaido), AO (Aomori), FT (Iwate), MG (Miyagi), AK (Akita), YC (Yamagata), FS (Fukushima), IB (Ibaraki), TC (Tochigi), GI (Gunma), ST (Saitama), CB (Chiba), TY (Tokyo), KN (Kanagawa), NI (Niigata), TM (Toyama), IS (Ishikawa), FI (Fuku), YN (Yamanashi), NA (Nagano), GI (Gifu), SZ (Shizuoka), AI (Aichi), ME (Mie), SI (Shiga), KY (Kyoto), OS (Osaka), HG (Hyogo), NR (Nara), WA (Wakayama), TT (Tottori), SM (Shimane), OY (Okayama), HS (Hiroshima), YA (Yamaguchi), TK (Tokushima), KA (Kagawa), EH (Ehime), KO (Kochi), FO (Fukuoka), SG (Saga), NS (Nagasaki), KU (Kumamoto), OI (Oita), MI (Miyazaki), KG (Kagoshima), and OK (Okinawa).

and Hokkaido. The residuals remain largely stable regardless of the cholera intensity.

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