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The impact of medical infrastructure on regional innovation: An empirical analysis of China's prefecture-level cities

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ABSTRACT

Because of public health emergencies, such as the COVID-19 pandemic, having an optimal medical infrastructure is an important way to maintain the normal operation of society and stimulate vitality in regional innovation. Based on the data on 260 cities at the prefecture level and above in China from 2001 to 2018, this paper investigates the characteristics and mechanisms of medical infrastructure on regional innovation. After a series of regressions, we robustly find that medical infrastructure has a significantly positive impact on regional innovation. In addition, based on the mediating effect model, the mechanism test shows that medical infrastructure can promote regional innovation through the channels of the natural population growth rate, educational level, and the environmental greening level. Finally, considering the urban heterogeneity, we find that the positive impact of medical infrastructure on regional innovation is reflected mainly in eastern and central cities, non-sub-provincial cities, and non-resource-based cities. These conclusions not only enrich the theoretical research on regional innovation from the perspective of medical infrastructure but also shed light on how to better promote regional innovation for China or even other countries.

1. Introduction

In early 2020, the sudden outbreak of the novel coronavirus (COVID-19) pandemic introduced huge challenges for public health systems and exposed weakness in the construction of a health emergency system and a structured medical service in China. In this pandemic, the surge in patients, shortage of medical staff, and insufficient supply of medical equipment forced us to re-examine the impact of medical infrastructure on the economic and social development (Benjamin, 2020; Jovanović et al., 2020; Kuderer et al., 2020; Sharma et al., 2021).

Regions with well-developed medical infrastructure have relatively healthy and vigorous economic development, and their emergency response and recovery capabilities in public emergencies, such as epidemics and natural disasters, are also relatively sound. Therefore, strengthening the supply of public services and investing in and building medical infrastructure not only promote health equity and improve happiness and security but also help increase employment and stimulate the economy (Sulistyowati, 2014; Benjamin, 2020). In this regard, in recent years, China has implemented several policies and laws that offer a blueprint for the construction of medical infrastructure. For example, in 2016, the State Council issued the “Healthy China 2030” Planning Outline, which pointed out that the medical and health industry should be built into a national pillar industry and strive to build a high-quality and efficient public health service that covers all of society; in June 2020, the “The Basic Medical Hygiene and Health Promotion Law of the People's Republic of China” was implemented, focused on promoting China's medical and health undertakings and trying to provide legal protection for citizens' access to medical and health services. In October 2020, the fifth plenary session of the nineteenth Central Committee also emphasized that protecting public health is a strategic priority, so it is necessary to have a network for public health protection.

Unlike some developed countries, such as the United States and Germany, where private medical service providers play a dominant role in the entire medical system (Kruse et al., 2018), China's medical infrastructure construction is usually led by the government, and the equalization of basic public health services is mainly driven by the implementation of national public health service projects (Yuan et al., 2019). Notably, although China has executed the medical marketization

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Medical infrastructure has a fundamental role in the healthy operation of the national economy (Furman et al., 2002; Sala-i-Martin et al., 2004). Kuderer et al. (2020) and Sharma et al. (2021) show that medical infrastructure has an impact on human health, and personal health is an important factor that affects the mortality rate of the COVID pandemic. Among the many impacts of medical infrastructure on the economy and society, its role in regional innovation should not be overlooked. In recent years, the relationship between innovation and infrastructure has been linked increasingly closely. For example, the impact of transportation infrastructure on innovation and the contribution of new infrastructure to innovation have become important topics of concern to the academia. However, the effect of medical infrastructure on innovation is rarely discussed (Yu and Mi, 2012; Wang et al., 2020). In the post-epidemic era, governments of various countries can be expected to pay attention to the construction of a medical infrastructure, and the economic effects of medical infrastructure will also become the focus of academic attention.

Medical infrastructure is closely related to people's life and health. Innovative activities will be unsustainable in the absence of a healthy life, manifested mainly in two ways. First, in terms of social effects, a sound medical infrastructure can increase convenience for people, protect their rights to life and health, and promote social stability (Tripathi, 2017; Sharma et al., 2021). Second, in terms of economic effects, public health is a guarantee of economic growth and technological innovation (Furman et al., 2002; Aghion et al., 2010; Jiang et al., 2020). Good health is not only a necessary condition for expanding life expectancy but also conducive to enhancing labor skills and increasing individual innovation (Ghosh and Dinda, 2018; Kristanto et al., 2019).

Meanwhile, regions with a high level of medical infrastructure can attract inflows of people seeking medical treatment and high-quality workers who have a higher demand for medical facilities (Baum-Snow and Pavan, 2012). With the reform of China's hukou system, high skilled talents (scientists, engineers, researchers) can more easily obtain a region's registered residence than before, which stimulates its sustainable innovation (Shen and Li, 2022). The requirements of high skilled talents for infrastructure have gone beyond the basic survival needs and turned to medical health and high-quality life (Lin et al., 2021). Hence, to attract more talents, the Chinese local governments always put the priority and convenience of medical service provision on a prominent position of economic development (Zhang and Zhang, 2017; He, 2020; Huang et al., 2021). Therefore, for a region, improving medical infrastructure not only enhances people's physical fitness and promotes human capital but also attracts high-quality resources from other regions, which is conducive to consolidating its foundation for innovation and economic development.

Accordingly, does medical infrastructure empirically promote regional innovation? If so, how does medical infrastructure affect regional innovation? In this regard, based on development data on 260 cities at the prefecture level and above in China from 2001 to 2018, this study focuses on the characteristics and impact mechanisms of medical infrastructure on regional innovation. The main conclusion is that medical infrastructure has a significant role in promoting regional innovation, and it mainly affects regional innovation through channels of natural population growth rate, educational level, and environmental greening level. Moreover, this effect has spatial relevance, and it differs depending on the type of city. Our analysis not only explores how to promote regional innovation from the perspective of medical infrastructure but also sheds light on how to restore the vitality of regional innovation from the perspective of health economics.

The remainder of this study is structured as follows. Section 2 reviews the relevant literature and proposes a theoretical hypothesis; Section 3 designs our research, including the construction of regression equation and the description of variables; Section 4 tests the theoretical hypothesis from diverse perspectives; and Section 5 concludes this study and proposes some corresponding recommendations.

2. Literature review and theoretical hypothesis

2.1. Review of the literature

Many factors affect regional innovation. Infrastructure, including medical and health care, is a topic of widespread concern. Our literature review reveals that the extant research on the influence of medical infrastructure on regional innovation mainly focuses on the following aspects.

First, some papers concern the economic growth effect of medical infrastructure. Bhargava et al. (2001) simulate the relationship between the growth rate of the gross domestic product (GDP) and human health and point out that the adult survival rate (ASR) has a positive effect on the GDP growth rate, which indicates that medical infrastructure can prolong life expectancy and increase the ASR. Agenor (2008) affirms the contribution of medical services to the health of workers and holds that medical services can drive economic growth by improving individual productivity. Based on the endogenous growth model, Hosoya (2014) confirms that medical infrastructure can play an important role in economic growth, such as increasing production through labor expansion. Based on 37 years of data from Nigeria and a vector error correction model, Babatunde (2018) finds that expenditures on medical infrastructure, unlike agricultural and natural resource infrastructure, have a positive impact on the country's economic growth. This is consistent with the conclusion of Bakare and Olubokun (2011). Meanwhile, Mukherjee (2017) uses the Euclidean distance function to construct a medical infrastructure index and finds a cointegration relationship between medical infrastructure and economic growth.

Second, some papers also focus on the social development effect of medical infrastructure. Medical infrastructure makes a positive contribution to improving people's quality of life, extending life expectancy, reducing poverty, and increasing employment. Colgrove et al. (2010) emphasize the important role of medical infrastructure on people's health, national security, and social well-being. Sulistyowati (2014) points out that the expansion in health expenditure and medical expenses is beneficial in increasing employment in the service industry and reducing the poverty rate in a region. By constructing a comprehensive index of the stock of infrastructure, Dash and Sahoo (2010) show that the development of infrastructure, including medical and health care in a region, can help eliminate poverty and raise people's living standards. Based on panel data on Indonesian provinces, Kristanto et al. (2019) find that, although the relationship between the availability of health facilities and life expectancy is not significant, the development of health personnel and medical insurance is conducive to prolonging life expectancy.

Third, other papers study the regional innovation effect of medical infrastructure. Infrastructure plays an irreplaceable role in raising the level of regional innovation (Smith, 1997; Furman et al., 2002). Specifically, on the one hand, medical infrastructure can optimize the health of local workers. Aghion et al. (2010) point out that healthier people usually have higher productivity and are better at learning and creating new technologies, which is critical to directly promoting regional innovation. Nelson and Phelps (1966) and Ghosh and Dinda (2018) show that a higher level of medical infrastructure helps in enhancing the physical fitness of workers, thereby raising labor efficiency and human capital levels and further promoting technological innovation. On the other hand, the medical infrastructure in a region has a siphonic effect
on surrounding labor. That is, a region’s medical infrastructure can promote the inflow and agglomeration of labor, especially high-quality labor, which provides solid intellectual support for the region to increase innovation. Concerning how to accelerate rural economic growth in the United States, Oehmke et al. (2007) find that adequate health care services can gather retired talents which is beneficial to rural development. Similarly, in China, talents often regard the availability of high-quality medical facilities as essential in selecting a workplace or choosing a place of residence (Lin et al., 2021). If we increase intellectual capital in healthcare organizations, it can promote innovation and create value (Huang et al., 2021). Additionally, using the principal component analysis method, Guo and Lv (2019) evaluate the ability of a city to attract high skilled workers, pointing out that medical services are an important consideration when high skilled workers determine their employment destination. Baum-Snow and Pavan (2012) also affirm the positive role of medical infrastructure in promoting the attraction of high skilled workers and regional innovation.

To sum up, most of the existing literature evaluates the development of a region’s infrastructure, which includes medical infrastructure, but relatively few papers focus solely on the economic effect of medical infrastructure. In addition, in terms of sample selection, when discussing the relationship between medical infrastructure and regional innovation, most papers tend to select the national or provincial level, and few studies have been done on the innovation level of prefecture-level cities. At the same time, in terms of measurement indicators, most papers choose indicators such as health infrastructure investment or public health expenditure to reflect the construction status of medical infrastructure, which is not comprehensive.

Accordingly, this study makes the following contributions to the literature. On the one hand, unlike other studies that mainly focus on the effect of transportation, communication, or other infrastructures on innovation, we investigate the role of medical infrastructure in regional innovation, especially combining the background of the COVID-19 pandemic. Moreover, we empirically explore the characteristics and mechanisms between medical infrastructure and regional innovation. On the other hand, unlike extant studies that generally measure the improvement of medical infrastructure by the amount of medical and health investment or expenditure, we comprehensively calculate the level of medical infrastructure in a city, based on the number of hospitals and health centers per capita, the number of hospital beds per capita, and the number of practicing or assistant physicians per capita.

2.2. Proposed hypothesis

In order to clarify the role of medical infrastructure in regional innovation, combining the existing literature, we attempt to propose some theoretical hypotheses.

In general, the sound medical infrastructure in a region can provide perfect medical conditions and facilities for its people (Babatunde, 2018; Kristanto et al., 2019; Jovanović et al., 2020), and help these people to focus on research and development and technological innovation without seeking medical treatment everywhere (Aghion et al., 2010; Ghosh and Dinda, 2018; Jiang et al., 2020). In addition, a region’s excellent medical infrastructure also helps to enhance its attraction to enterprises, capital and talents, so as to provide industrial foundation, capital investment, and intellectual support for its innovative development (Baum-Snow and Pavan, 2012; Ghosh and Dinda, 2018; Guo and Lv, 2019; Sharma et al., 2021). Therefore, we can propose our first hypothesis.

**Hypothesis 1.** Generally, medical infrastructure can promote regional...
innovation.

It is meaningful to explore how medical infrastructure affects regional innovation. First, medical infrastructure can affect the innovation vitality of a region through the natural population growth rate. Sound medical infrastructure provides complete medical security, which enhances the physical fitness and willingness of workers to bear children and helps them remain healthy, and reduces the mortality rate (Tripathi, 2017; Sharma et al., 2021). The high natural population growth rate not only provides a sufficient labor pool for innovation but also affords a big market scale and intellectual support for product innovation (Dakhli and De Clercq, 2004; Desmet and Parente, 2010). Additionally, it can also create more intensive intellectual contacts and knowledge spillovers for technological change (Kuznets, 1960; Cheung and Ping, 2004; Brandt and Rawski, 2008).

Second, medical infrastructure can influence regional innovation by attracting highly educated workers. Highly educated or skilled workers are the main engines of innovation, and high-quality labor is the cornerstone and source of innovation in a region (Nelson and Phelps, 1966; Dakhli and De Clercq, 2004; Guo and Lv, 2019). The health of the highly educated labor force is a prerequisite for innovation. In addition, whether a region has high-quality medical resources is an important factor that high-quality talents consider when choosing a place to live (Kaiser et al., 2015; Frenkel et al., 2013). Having a complete medical infrastructure facilitates the inflow of R&D talents and promotes regional innovation through knowledge transfer, spillover, and sharing (Dash and Sahoo, 2010; Ghosh and Dinda, 2018). Therefore, the medical infrastructure can raise the quality of educated workers by optimizing their stock and increment, thereby enhancing regional innovation (Hosoya, 2014; Kaiser et al., 2015).

Finally, medical infrastructure can affect regional innovation through the channel of the environmental greening level. The environment in which medical infrastructure is located is an important part of the living environment (Smith, 1997; Sulistyowati, 2014; Sapci and Shogren, 2018). A high environmental greening level is beneficial for physical and mental health and has a good inhibitory effect on bodily functions such as breathing. Therefore, regions with relatively sound medical infrastructure often focus on improving the quality of the surrounding environment (Tripathi, 2017; Jovanović et al., 2020; Le Tourneau, 2020). This not only reduces pollution, improves the investment environment and living conditions, and provides a good environmental guarantee for regional innovation (Vigicantalar and Lonnqvist, 2013; Zhao et al., 2021) but also attracts more high-quality resources and promotes a region as a preferred place of innovation and entrepreneurship (Sapci and Shogren, 2018; Jiang et al., 2020).

Accordingly, we can propose our second theoretical hypothesis:

**Hypothesis 2.** Medical infrastructure promotes regional innovation mainly through the channels of natural population growth rate, educational level, and the environmental greening level.

3. Model specification

3.1. Equation

Based on the first theoretical hypothesis stated, we can construct the following empirical equation to examine the impact of medical infrastructure on regional innovation:

$$\ln innovation = \alpha_0 + \alpha_1 Medi + \alpha_2 X_i + \delta \epsilon + \epsilon,$$

where $i$ is the city, $t$ is the year, $innovation$ is regional innovation, $Medi$ is medical infrastructure, $X$ is control variables, $\delta$ is the individual effect, and $\epsilon$ is the random disturbance.

3.2. Variables

The explained variable is regional innovation. Following Cheung and Ping (2004) and Jinji et al. (2015), we proxy it with the total number of patents granted per capita. Fig. 1 shows that in China between 2001 and 2018 the average level of regional innovation is unbalanced.

The explanatory variable is medical infrastructure. Following Yan et al. (2020), Calderon and Serven (2004), and Li et al. (2017), we construct an index to comprehensively reflect a region’s medical infrastructure, which is based on standardization in the number of hospitals and health centers per capita, the number of hospital beds per capita, and the number of practicing or assistant physicians per capita. Its spatial distribution, illustrated in Fig. 2, is unbalanced as well, and the soundest medical infrastructure is concentrated in East China.

We follow the relevant literature (Feng and Yuan, 2021; Gössling and Ruten, 2007; Lakshmanan, 2011; Griffith et al., 2006; O’Sullivan, 2005) regarding the control variables. For example, economic growth ($gdp$) is measured by the gross domestic product (GDP) per capita. Road infrastructure (road) is measured by the paved road area per capita. Fiscal expenditure (expenditure) is measured by the proportion of local general public budget expenditure in GDP. Financial development (finance) is measured by the ratio of “balance of loans” over GDP. R&D expenditure ($rd$) is measured by the proportion of science and technology expenditure in GDP. Research personnel (researcher) is measured by the number of employees in scientific research comprehensive technical service industry per 10,000 people.

In view of the availability of the data, we collect development data on 260 cities in China at the prefecture level and above from 2001 to 2018. Notably, data on the level of urban innovation comes from the China National Intellectual Property Administration (www.cnipa.gov.cn), and the remaining data mainly comes from the China City Statistical Yearbook and the statistical yearbooks of provinces. The descriptive statistics of each variable are reported in Table 1. The standard deviation is controlled within a certain range, indicating that its distribution is relatively concentrated.

To avoid regression bias caused by multicollinearity between the variables, we carry out a multicollinearity test. In Table 2, the VIF (variance inflation factor) of each variable is less than 10, which indicates the absence of multicollinearity between them.

4. Empirical results

4.1. Baseline regression

Accordingly, we use STATA16.0 to conduct a panel regression. We perform the Hausman test to clarify whether we should employ a random-effects (RE) model or a fixed-effects (FE) model. As seen in Table 3, the result of the Hausman test is 286.92, which rejects the null hypothesis, and implies that we should adopt the FE model. Hence, in column (1) of Table 3, the coefficient of the effect of medical infrastructure on regional innovation is 0.1247, at the 1 % significance level, which implies that medical infrastructure can significantly promote regional innovation. This confirms our theoretical hypothesis. Additionally, the regression results of the control variables are all positively significant and exceed the statistical level of at least 1 %, except for fiscal expenditure (inexpenditure) and R&D expenditure (inrd), which are insignificant. The main reason may be that higher fiscal expenditure and R&D expenditure mean higher government intervention, which tends to distort the effect of innovation and deviate from the original intention of innovation (Brandt and Rawski, 2008; Feng and Yuan, 2021).

4.2. Considering endogeneity

The regressions might have endogeneity caused by two-way causality between medical infrastructure and regional innovation. To mitigate endogeneity, we employ the two-stage least squares (2SLS) for regression, with slope as an instrumental variable (IV) of medical
The main reason is as follows. On the one hand, slope can affect the construction of medical infrastructure, that is, the steeper the slope of city, the less suitable it is for human habitation (Feng et al., 2021). Moreover, steep terrain is not conducive to the stationing of medical staff or for visits to doctors by patients (Le Tourneau, 2020). Therefore, medical and health institutions are more likely to be built on flatter terrain. However, as a natural geographical factor, slope is not directly related to the level of regional innovation. Since slope is a geographical variable, and our sample consists of panel data, we divide slope by annual time to make it dynamic. The reason for this treatment is that, over time, the hindrance to medical infrastructure from geographic factors will diminish. Columns (3)–(4) of Table 4 show the regression results of the 2SLS. Notably, the F-statistic in the first-stage regression is greater than 10, indicating the absence of a weak IV.

Meanwhile, we employ the generalized method of moments (GMM) approach for further regression. The non-autocorrelation test of the

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**Fig. 2.** The spatial distribution of medical infrastructure in China, 2001–2018.

**Table 1**

Descriptive statistics of the variables.

| Variable  | Mean  | St. dev. | Min.    | Max.   | p25   | Median | p75   |
|-----------|-------|----------|---------|--------|-------|--------|-------|
| lninnovation | 0.3003 | 1.6830   | -4.5173 | 5.7272 | -0.9685 | 0.2580 | 1.4331 |
| Medi      | 0.0111 | 0.7443   | -1.4767 | 6.0496 | -0.4775 | -0.1196 | 0.3003 |
| lnprgdp   | 10.0192 | 0.9099   | 4.5951  | 13.1338 | 9.3543 | 10.0717 | 10.6785 |
| lnroad    | 2.1557 | 0.6757   | -1.9661 | 4.6856 | 1.7299 | 2.1994 | 2.6090 |
| lnexpenditure | -2.1200 | 0.7205 | -5.9252 | 1.7985 | -2.4568 | -2.0913 | -1.7202 |
| lnfinance | 0.0036 | 0.5865   | -2.5842 | 3.2108 | -0.4022 | -0.0343 | 0.3459 |
| lnresearcher | 2.3966 | 1.0104   | -1.6183 | 8.4658 | 1.7283 | 2.3064 | 2.9026 |
| lnrd      | -4.6269 | 2.0521   | -13.017 | 0.0000 | -4.5226 | -3.8481 | -3.4418 |
| lngrowth  | 5.5924 | 5.1154   | -16.6400 | 113.0000 | 2.7600 | 5.1800 | 7.9100 |
| lnedu     | -6.2819 | 1.3549   | -16.6475 | 0.0000 | -7.0434 | -6.3027 | -5.3973 |
| lnenvironment | 8.8403 | 3.3836 | -2.7045 | 17.3221 | 8.3940 | 9.6617 | 10.5743 |

**Table 2**

Multicollinearity test.

| Variable  | VIF  | 1/VIF |
|-----------|------|-------|
| Medi      | 1.82 | 0.5500 |
| lnprgdp   | 2.62 | 0.3813 |
| lnroad    | 1.69 | 0.5928 |
| lnexpenditure | 3.21 | 0.3111 |
| lnfinance | 1.76 | 0.5694 |
| lnresearcher | 1.96 | 0.5100 |
| lnrd      | 2.85 | 0.3506 |
| Mean VIF  | 2.27 |       |
level. Robust standard errors in parentheses are clustered at the city

Notes: *, **, and *** indicate statistical significance at 10 %, 5 %, and 1 % levels, respectively. Robust standard errors in parentheses are clustered at the city level.

disturbance term is carried out with the difference-GMM and system-GMM methods. The results show that the p-value of AR (1) is less than 0.05, whereas the p-value of AR (2) is greater than 0.1, indicating that the model has first-order autocorrelation, but no second-order auto-correlation. Additionally, the results of the Sargan test rejects the null hypothesis of over-identification of the IVs. Therefore, regardless of whether we use the 2SLS method or the GMM method, the impact of medical infrastructure on regional innovation is significantly positive at the 1 % statistical level, which confirms our hypothesis once again.

Table 3
Regression results based on the RE and FE models.

|          | (1) Inovation | (2) Inovation |
|----------|---------------|---------------|
| Medi     | 0.1247***     | 0.1426***     |
| loggdpp  | 0.2051***     | 0.481***      |
| lnrealad | 0.079**       | 0.11**        |
| lnexpenditure | 0.0219     | -0.0042       |
| lnfinance | 0.2011***     | 0.3959***     |
| lnresearcher | 0.1594***   | 0.2256***     |
| lnresearcher | -0.0322     | -0.0114       |
| constant | -3.3455***    | -5.3785***    |
| Year effect | Yes          | Yes           |
| Province effect | Yes        | Yes           |
| Province × year effect | Yes   | Yes           |
| Observations | 4680        | 4680          |
| R-squared | 0.7726        | 0.9273        |

Notes: *, **, and *** indicate statistical significance at 10 %, 5 %, and 1 % levels, respectively. Robust standard errors in parentheses are clustered at the city level.

Table 4
Regression results based on the 2SLS and GMM methods.

|          | (1) Inovation | (2) Inovation | (3) Inovation | (4) Inovation |
|----------|---------------|---------------|---------------|---------------|
| Medi     | 0.5029***     | 0.1344***     | 0.1274***     |
| Inslope  | -0.3115***    | (0.0700)      | (0.0333)      | (0.0207)      |
| lnlnnovation | 0.2422***    | 0.4554***     |
| AR (1)   | 4.12***       | 4.2749***     |
| AR (2)   | 1.1887        | 0.7597        |
| Sargan   | 189.4054      | 211.9928      |
| Control variables | Yes        | Yes           | Yes           |
| Year effect | Yes          | Yes           | No            |
| Province effect | No         | No            | No            |
| Province × year effect | Yes   | Yes           | No            |
| Observations | 4680        | 4680          | 4420          |
| R-squared | 0.4187        | 0.9212        | -             |

Notes: *, **, and *** indicate statistical significance at 10 %, 5 %, and 1 % levels, respectively. Robust standard errors in parentheses are clustered at the city level.

Table 5
Regression results based on replacing dependent variable.

|          | (1) lnnovation | (2) lnnovation | (3) lnnovation |
|----------|---------------|---------------|---------------|
| Medi     | 0.2237***     | 0.1212***     | 0.1681***     |
| Year effect | Yes         | Yes           | Yes           |
| Province effect | Yes    | Yes           | Yes           |
| Province × year effect | Yes | Yes           | Yes           |
| Control variables | Yes     | Yes           | Yes           |
| Observations | 4680        | 4680          | 4680          |
| R-squared | 0.7726        | 0.9273        | 0.7520        |

Notes: *, **, and *** indicate statistical significance at 10 %, 5 %, and 1 % levels, respectively. Robust standard errors in parentheses are clustered at the city level.

4.3. Robustness tests

4.3.1. Replacing the variables

To check the robustness of the regression results, we substitute the main variables. First, we replace the explained variable with the number of invention patents granted per capita (lninnovation1), the number of utility model patents per capita (lninnovation2), and the number of design patents per capita (lninnovation3), respectively. The results are reported in columns (1)–(3) of Table 5, showing that the influence of medical infrastructure on these three alternative variables is positive at the 1 % statistical significance level at least, which indicates that our findings are robust.

Second, we replace the explanatory variables. We decompose the medical infrastructure (Medi) into three sub-variables, namely, the number of hospitals and health centers per capita (Medi1), the number of hospital beds per capita (Medi2), and the number of assistant physicians per capita (Medi3). Additionally, we employ the methodology of principal component analysis (PCA) (Guo and Lv, 2019) to generate a composite indicator (Medi4) by synthesizing these three factors. The results are reported in Table 6, showing that the coefficients of these four variables on regional innovation are all positive at the 1 % statistical significance level, which again confirms the robustness of our findings.

4.3.2. Deleting extreme outliers

In China, unlike ordinary prefecture-level cities, the four municipalities directly under the central government (Beijing, Tianjin, Shanghai, and Chongqing) have particularities in terms of economic development, political status, and population size, so they are excluded from the results reported in column (1) of Table 7.\(^3\) In addition, considering the influence of statistical biases or special events that lead to extreme values and cause regression biases, we reduce the sample range by 1 % in the regression results shown in column (2) of Table 7. The impact of medical infrastructure on regional innovation remains significantly positive, indicating that our earlier results are still robust.

\(^3\) After deleting extreme outliers, it may raise an issue about the noise model and the character of the resulting residuals. Accordingly, we conduct regressions before and after removing the outliers, and find that whether the samples of municipalities administered by the central government are deleted or not, the value of sigma e is 0.3218, which means that there is no significant change in the residuals. Therefore, removing outliers does not affect the normal distribution of variables, and it is reasonable to employ the fixed-effects (FE) model of panel data for regression. Many thanks to the anonymous reviewer for valuable suggestions.
### 4.4. Mechanism tests

Identifying the mechanism in which medical infrastructure affects regional innovation helps us to further understand their relationship. Based on the mediating effect model (Baron and Kenny, 1986; Hayes, 2017), we investigate the three mechanisms mentioned in the part of the theoretical hypothesis: the natural population growth rate, the educational level, and the environmental greening. The regression results are reported in Tables 9-11. Notably, in these three tables, column (1) shows the results of the benchmark regression; column (2) shows the results of the effect of medical infrastructure on the mediating variables; and column (3) shows the effect of medical infrastructure and mediating variables on regional innovation. In addition, the mediating effect depends on some requirements (Feng et al., 2021). That is, if the coefficients of the medical infrastructure on mediating variables and regional innovation are both significant, then a mediating effect exists. However, if at least one of these two coefficients is insignificant, their joint significance can be tested with the bootstrap sampling method, and if the 95 % confidence interval does not contain 0, the mediating effect is present. Otherwise, the existence of a mediating effect is not supported.

First, we investigate the mechanism of the natural population growth rate as a mediating variable. Table 9 shows that the coefficient of the effect of medical infrastructure on the natural population growth rate is 0.0656, but is not significant at the 10 % level. However, the coefficient of the effect of the natural population growth rate on regional innovation is 0.0551, and it exceeds the 5 % statistical significance level at least. According to the principle of the mediating effect model (Baron and Kenny, 1986; Hayes, 2017), we need to perform a bootstrap test. The results show that the value of the bootstrap test is absent from the 95 % confidence interval. Thus, the mediating effect exists, which implies that medical infrastructure can promote regional innovation through the channel of the natural population growth rate. It is because sound medical infrastructure in a region is conducive to increasing the birthrate and reducing the death rate (Bhargava et al., 2001; Colgrove et al., 2010; Hosoya, 2014). This not only provides a labor pool for production, operations, and innovation but also improves the health and the quality of the labor force, which provides adequate human resources for regional innovation.

Second, we investigate the mechanism of educational level as a mediating variable. Table 10 shows that the coefficient of the effect of medical infrastructure on educational level is 0.0325, and the coefficient of the effect of educational level on regional innovation is 0.0270, both of which exceed the 5 % statistical significance level. This means that the mediating effect exists and implies that medical infrastructure can promote regional innovation through the channel of educational level because, as a critical factor in innovation, where highly educated people choose to settle depends on the local infrastructure, education environment, and cultural atmosphere (Frenken et al., 2013; Feng and Yuan, 2021). High-quality medical infrastructure is conducive to guaranteeing highly educated workers the opportunity to engage in innovative activities and stimulating the innovation effect of educational level.

Finally, we investigate the mechanism of the environmental greening level as a mediating variable. Table 11 reports that the coefficient of the effect of medical infrastructure on the environmental greening level is 0.1654, and the coefficient of the effect of the environmental greening level on regional innovation is 0.0224, at the 5 % statistical significance level at least, which implies that the mediating effect exists. This means that regions with a higher level of medical infrastructure pay more attention to environmental greening and protection, which raises the efficiency of regional innovation (Hosoya, 2014; Ghosh and Dinda, 2018; Jiang et al., 2010), because, in general, regions with a higher level of medical infrastructure also attach greater importance to public health, and due to the needs of sustainable development, the location of

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4 Generally, a city’s natural population growth consists of the birth of new residents, the migration of other citizens to the region, and the reduction of morbidity or mortality. However, the data on population migration in China is unavailable, so we adopt the natural growth rate which equals the birth rate minus the mortality rate. Sound medical infrastructure can not only increase the birth rate and provide sufficient labor reserves but also reduce the mortality rate and improve labor quality, which is beneficial for regional innovation. We will consider the impact of population migration on regional innovation when its data are available. Many thanks to the anonymous reviewer for valuable suggestions.
Table 8
Regression results based on spatial econometric models.

| Method          | Innovation | Environment | ln Innovation | ln Environment |
|-----------------|------------|-------------|---------------|----------------|
| Spatial geographic matrix | SDM        | SAR         | SEM           | SDM            | SAR           | SEM           |
| Medi            | 0.1235***  | 0.1471***   | 0.1526***     | 0.1333***      | 0.1789***     | 0.2083***     |
| (0.0423)        | (0.0449)   | (0.0472)    | (0.0428)      | (0.0475)       | (0.0525)      |
| Control variables | Yes        | Yes         | Yes           | Yes            | Yes           | Yes           |
| Observations    | 4680       | 4680        | 4680          | 4680           | 4680          | 4680          |
| R-squared       | 0.8719     | 0.8524      | 0.8244        | 0.8606         | 0.8469        | 0.8257        |

Notes: *, **, and *** indicate statistical significance at 10 %, 5 %, and 1 % levels, respectively. Standard errors are in parentheses.

Table 9
Regression results based on the channel of natural population growth rate.

| Method          | Innovation | ln Innovation |
|-----------------|------------|---------------|
| Medi            | 0.1247***  | 0.0656        |
| (0.0132)        | (0.1257)   |
| Year effect     | Yes        | Yes           |
| Control variables | Yes        | Yes           |
| Observations    | 4680       | 4645          |
| R-squared       | 0.9349     | 0.9353        |

Notes: *, **, and *** indicate statistical significance at 10 %, 5 %, and 1 % levels, respectively. Robust standard errors in parentheses are clustered at the city level.

Table 10
Regression results based on the educational level channel.

| Method          | Innovation | ln Edu         | ln Innovation |
|-----------------|------------|---------------|---------------|
| Medi            | 0.1247***  | 0.0325*       | 0.1239***     |
| (0.0132)        | (0.0172)   | (0.0132)      |
| Year Effect     | Yes        | Yes           | Yes           |
| Control variables | Yes        | Yes           |
| Observations    | 4680       | 4680          | 4680          |
| R-squared       | 0.9349     | 0.9112        | 0.9350        |

Notes: *, **, and *** indicate statistical significance at 10 %, 5 %, and 1 % levels, respectively. Robust standard errors in parentheses are clustered at the city level.

4.5. Further discussion

Because of differences in the distribution of medical infrastructure and innovation across regions in China (Feng et al., 2021; Feng and Yuan, 2021), we sort 260 cities at the prefecture level and above into eastern, central, western, and northeastern regions, based on the medical infrastructure leads to higher requirements for its surrounding environment. Consequently, having medical infrastructure can drive innovative activities through the channel of the environmental greening level.

Table 11
Regression results based on the channel of the environmental greening level.

| Method          | Innovation | ln Environment |
|-----------------|------------|----------------|
| Medi            | 0.1247***  | 0.1654**       |
| (0.0132)        | (0.0804)   |
| Year effect     | Yes        | Yes            |
| Control variables | Yes        | Yes           |
| Observations    | 4680       | 4680           |
| R-squared       | 0.9349     | 0.9355         |

Notes: *, **, and *** indicate statistical significance at 10 %, 5 %, and 1 % levels, respectively. Robust standard errors in parentheses are clustered at the city level.

“Methods for the Division of Eastern, Central, Western, and Northwestern Regions” issued by the National Bureau of Statistics in 2011. The results, reported in Table 12, show that medical infrastructure has a significantly positive impact on innovation in the eastern and central regions, but it is insignificant in the western region. The reason might be that the western region has a weaker innovation foundation and its medical level is somewhat behind, compared with the eastern and central regions. Many high-quality medical resources have flowed to the east and the center, so the western region has difficulty in driving regional innovation through medical infrastructure (Brandt and Rawski, 2008). This means that, to achieve coordinated regional development, China should pay greater attention to reducing the imbalanced regional distribution of medical resources. Notably, the impact of medical infrastructure on regional innovation in the northeast is significantly

Table 12
Regression results for different regions.

| Region   | Innovation | ln Innovation |
|----------|------------|---------------|
| East     | 0.2586***  | 0.2534***     |
| (0.0701) | (0.0342)   |
| Central | 0.0025      | 0.0031        |
| (0.0438) | (0.0438)   |
| West     | -0.0881*   | -0.0881*      |
| (0.0891) | (0.0891)   |
| Northeast | -0.0881*  | -0.0881*      |
| (0.0891) | (0.0891)   |

Notes: *, **, and *** indicate statistical significance at 10 %, 5 %, and 1 % levels, respectively. Robust standard errors in parentheses are clustered at the city level.
negative, perhaps because of its history as a traditional heavy industry base. The historical influence of the planned economy and the constraints of heavy social expenditure have slowed transformation and upgrading in the three northeastern provinces (Heilongjiang, Jilin, and Liaoning), and the northeast has suffered outmigration and brain drain (Brandt and Rawski, 2008; Feng and Yuan, 2021). Additionally, although these three provinces have also built medical infrastructure, their development in general lags significantly behind that of other regions, especially the Yangzi River Delta and the Pearl River Delta which are the two main economic growth poles in China. Therefore, in the northeastern region, the medical infrastructure is stagnant and does not effectively drive regional innovation.

In addition, based on the different characteristics of sub-provincial and non-sub-provincial cities and resource-based and non-resource-based cities (Feng and Yuan, 2021; Zhao et al., 2021), we further divide and regress our samples. The results are shown in Table 13. Notably, we consider a city to be a resource-based city if it is listed as such in the “National Resource-based City Sustainable Development Plan (2013-2020)” issued by the State Council in 2013. Similarly, we consider a sub-provincial city based on the “Opinions on Several Issues Concerning Vice-Provincial Cities.”

In columns (1) to (2) of Table 13, it is reported that medical infrastructure has an insignificant impact on the innovation of sub-provincial cities, while it has a significantly positive impact on the innovation of non-sub-provincial cities. This is mainly because sub-provincial cities are composed of provincial capitals and cities specifically designated in the state plan. They have economic management authority equivalent to cities at the provincial level, thus they are more easily influenced and intervened by the central government, which is vulnerable to distorting their normal innovation progress.

In addition, the regression results for resource-based cities and non-resource-based cities, as shown in columns (3) to (4) of Table 13, show that the impact of medical infrastructure on regional innovation is significantly positive, with coefficients of 0.0948 and 0.2028, respectively. This implies that medical infrastructure has a smaller positive effect on regional innovation in resource-based cities than in non-resource-based cities, mainly because resource-based cities are prone to the “resource curse” (Auty, 1993; Sachs and Warner, 1995). That is, in the process of mining resources, resource-based cities not only cause serious environmental pollution but also do not use the economic revenues obtained from resource endowments to develop their local economy (Brandt and Rawski, 2008; Feng and Yuan, 2021; Zhao et al., 2021). Therefore, medical infrastructure in resource-based cities still lags behind, so they are less attractive for advanced production factors, which hinders progress in regional innovation.

5. Conclusions

Like “cardiotonic agents,” high-quality medical infrastructure is critical in promoting regional innovation. Based on data on 260 cities in China at the prefecture level and above from 2001 to 2018, we explore the characteristics and mechanisms of the effect of medical infrastructure on regional innovation. The main conclusions are as follows. First, medical infrastructure has a significantly positive effect on regional innovation, which remains even after considering endogeneity and spatial relevance and conducting a series of robustness checks. Second, the impact of medical infrastructure on regional innovation is mainly through the channels of the natural population growth rate, the educational level, and the environmental greening level. Third, the role of medical infrastructure in promoting regional innovation is regionally diverse. That is, medical infrastructure plays a significant and positive role in the eastern and central regions, but its role is insignificant in the western region and significantly negative in the northeast region. In addition, the effect of medical infrastructure on regional innovation is affected by the type of city: the promotional effect is greater in non-sub-provincial cities and non-resource-based cities than in sub-provincial cities and resource-based cities.

This study investigates the impact of medical infrastructure on regional innovation. Our conclusions not only enrich the relevant research on innovation theory but also shed light on how to promote innovation in the post-epidemic era. For example, it is advisable to foster high-end medical resources and promote the development of health-care industries. Meanwhile, it is necessary to enhance the supply of high-quality and efficient medical services, train professional and high-level medical personnel, increase the number of hospital beds and other equipment, and prepare for public health emergencies, and so forth. Furthermore, it is important to pay attention to differences in medical infrastructure between regions and to achieve coordinated development.

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CRediT authorship contribution statement

All authors are involved in writing the manuscript and have all proved the submitted form.

Declaration of competing interest

There is no conflict of interest in regard to the content discussed in this article.

Data availability

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Table 13

|                      | Innovation | Innovation | Innovation | Innovation |
|----------------------|------------|------------|------------|------------|
|                      | Sub-provincial | Non-sub-provincial | Resource-based | Non-resource-based |
| Medi                 | 0.1269 (0.1973) | 0.1211*** (0.0579) | 0.0948** (0.0471) | 0.2028*** (0.0554) |
| Year effect          | Yes         | Yes        | Yes        | Yes        |
| Province effect      | Yes         | Yes        | Yes        | Yes        |
| Province × year effect | Yes       | Yes        | Yes        | Yes        |
| Control variables    | Yes         | Yes        | Yes        | Yes        |
| Observations         | 270         | 4410       | 1854       | 2826       |
| R-squared            | 0.9908      | 0.9352     | 0.9449     | 0.9436     |

Notes: *, **, and *** indicate statistical significance at 10 %, 5 %, and 1 % levels, respectively. Robust standard errors in parentheses are clustered at the city level.

6 http://www.gov.cn/zfwj/2013-12/03/content_2540070.htm.
6 http://www.reformdata.org/1995/0219/21183.shtml.
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