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Do solar cycles explain the emergence of COVID-19? Neutron count comparison between the solar minima of 2008–2009 and 2019–2020
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Abstract
Cosmic rays are believed to be mutagenic and can stimulate virus mutation through point mutations. Neutron count on Earth ground stations is a reliable proxy to quantify cosmic ray flux. A previous study reported that the maximum flux of cosmic rays in November 2019 could be related to the emergence of COVID-19 (late November to early December). Using the latest neutron count data, this study investigated if the data from 2019 to 2020 could specifically explain the emergence of pandemic (COVID-19). The results indicate that there is no significant difference between the previous two last solar minima datasets (2008–2009 and 2019–2020; \( n = 24, p = 0.60 \)). This suggests that the solar minima of 2019–2020 did not experience an increase in cosmic rays and the emergence of COVID-19 could not be solely explained by cosmic ray flux caused by solar cycles (space weather change).

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Introduction
COVID-19 is one of the pandemics of the modern age [1–5] that causes a severe upper respiratory tract syndrome [6,7]. The fatality rate of COVID-19 is estimated to be around 4% before the vaccination was available [8,9]. Although the exact origin of COVID-19 is not concluded yet, SARS-CoV-2 likely emerged from a horseshoe bat, hence, COVID-19 is considered as a zoonotic disease [10–15]. It is critical to investigate the trigger factor and rapid mutation of SARS-CoV-2 to prevent and prepare for possible future outbreaks. There are many studies that linked COVID-19 to environmental and metrological factors [16–24]. For example, Carleton et al. [19] reported that daily ultraviolet (UV) radiation lowers the cumulative daily growth rate of COVID-19 cases over the subsequent two and half weeks. Srivastava [24] stated gaseous pollutant (PM10, PM2.5, BC, NOx, SO2, CO and VOCs concentration) and COVID-19 cases are positively correlated, and higher temperature is negatively correlated. These studies focusing on the transmission and environment factors are useful in terms of preventing the spread of COVID-19. However, questions still remain; what originally triggered the outbreak of COVID-19? Why does SARS-CoV-2 mutate rapidly? Would it be possible for us to control trigger factors of COVID-19?

Interestingly, one hypothesis is a correlation between pandemic outbreaks and the number of sunspots [25–29]; Figure 1. Wickramasinghe [27] suggested a 11-year cycle of sunspot minima and a 100-year cycle of sunspot deep minima decrease the solar magnetic field thus increases the total amount of mutagenic cosmic radiation that reaches Earth. On the other hand, Nasirpour et al. [29] stated that both solar maxima and minima could cause pandemics on Earth. They stated the same mechanism for solar minima as Wickramasinghe [27]. As to solar maxima, they suggest an increase in the solar magnetic field causing stronger solar winds that brings solar charged particles to Earth and cause point mutations in virus RNA.

Influence of cosmic rays might extend to viral hosts as well (e.g., human). It has been suggested an increase in cosmic rays influence virus replication in host organisms via NF-κB (protein complex regulating the expression of immune response genes) [30] as NF-κB can be activated in response to cosmic rays [30–34]. Zaporozhan and Ponomarenko [30] stated that any Earth organisms and their living conditions can be influenced by high-energy cosmic radiation comprised of electrons, protons, ultraviolet and gamma-rays. For
example, NF-kB signaling in infected host cells plays an important role in differential regulation of influenza virus RNA synthesis. Indeed, many studies reported the correlation between solar cycles and influenza outbreaks [35–37]. This study evaluated the strength of cosmic rays reaching to Earth since 1964, which were measured by neutron count on an Earth ground station. The newest data was used (up to June 2021) to find the possible relation among Sun, Earth, and the ongoing COVID-19 pandemic. The focus of study is to test; if the amount of mutagenic cosmic rays measured by neutron count on an Earth ground station is the highest during 2019–2020 and can explain the outbreak of COVID-19.

**Methods**

**Data**
The cosmic ray data from 1964 to 2021 was extracted from Oulu Cosmic Ray Station Neutron Monitor Database (URL: https://cosmicrays.oulu.fi/). It has been reported that the neutron monitor at Sodankylä Geophysical Observatory located in Finland (67° 22’ N, 26° 38’ E) is one of the most stable and reliable stations of the World Neutron Monitor Network [38]. Neutron count (average count per minute) is a method to quantify cosmic rays (i.e., proxy for cosmic ray flux). As cosmic rays collide with particles in the Earth’s atmosphere, they create secondary particles such as neutrons [39–43]. Historical pandemic data was identified from Piret and Boivin [44] and Liu et al. [2].

**Statistical analysis**
The difference between the dataset of 2008–2009 and 2019–2020 was tested using Student’s t-test. For linear regression analysis, the past 24 month data from the highest peak during 2008–2009 and 2019–2020 were analyzed to investigate the neutron increase trend. The trend of neutron data was calculated by linear regression followed by ANCOVA to test if the slopes of these two linear equations are significantly different. All the calculations were conducted using R ver. 3.6.1 (R Core-Team, 2019).

**Results**
Based on the neutron count (NC) per minute, cosmic rays peaked in April 2020 (NC = 6813) which was close to the start of the pandemic. However, there was a peak in December 2009 (NC = 6844), and its value was slightly higher than the data in April 2020 (Figure 1) and indeed December 2009 was the highest since 1964. Therefore, this study focused on the detailed difference between the year of last two solar minima 2008–2009 and 2019–2020 to compare how these two high neutron count peaks were different.

The duration of high peak (NC > 6800) lasted for nine months during 2008–2009 (from April 2009—December 2009) while it lasted only one month (April 2020) during 2019–2020. The cumulative neutron count were 161,606 and 161,832 for 2008–2009 and 2019–2020 (Figure 2) respectively. There were no significant
differences among these two datasets (monthly data of 2008–2009 and 2019–2020; n = 24, p = 0.60).

The regression analysis showed that the overall the neutron count is increasing since 1964 to present (Figure 3a). The increase was sharper during 2008–2009 compared to the one during 2019–2020 (Figure 3b). The liner equations for the data from 2008 to 2009, and the data from 2019 to 2020 were y = 11x + 6596 (R² = 0.93, p < 0.001), and y = 4x + 6675 (R² = 0.65, p < 0.001), respectively. This difference in these two slopes was statistically significant as a result of ANCOVA (F (1, 44) = 60.37, p < 0.001).

Discussion

The cosmic ray peak detected from this analysis shared similarity with the neutron count from 1962 to 2019 reported by Wickramasinghe [27]. In their study, neutron count from the Moscow Neutron Monitor showed the maximum flux of cosmic rays reaching Earth in November 2019, and they reported it was the highest record since 1962. Therefore, they concluded that the maximum flux of cosmic rays in November 2019 correlated with the emergence of COVID-19 (late November to early December). On the contrary, this study extended the time period of the data from 2019 to 2021, and found that April 2009 was indeed higher than 2019. Thus, the maximum flux of cosmic rays could not be directly related to the emergence of COVID-19. Such a regional difference in the cosmic ray flux can be simply explained by altitude and geomagnetic latitude [26].

Although our analysis found that the cumulative neutron count in 2008–2009 showed a lower value than 2019–2020, Student’s t-test showed that there was no statistically significant difference between the data of 2008–2009 and 2019–2020. The linear regression analysis indicated that neutron count showed an increasing trend since the early 1960’s, and the increase was indeed significantly sharper during 2008–2009 compared to 2019–2020 (F (1, 44) = 60.37, p < 0.001). Therefore, the solar minima of 2019–2020 is not causing a sharper increase in neutron count compared to the previous solar minima of 2008–2009. From the discussion above, there is no evidence to support that the solar minima of 2019–2020 experienced a significant increase in neutron count, which is the proxy for cosmic rays.

The direct monitoring of solar irradiance from space missions support that there is no significant difference between the 2008–2009 and 2019–2020 solar minima as well. Finsterle et al. [45] reported that two NASA
space missions measuring solar irradiance, Precision Monitoring of Solar Variability (PREMOS), and Variability of Irradiance and Gravity Oscillations (VIRGO), showed no significant change (i.e., $-0.17 \pm 0.29 \text{ W/m}^2$) during the two most recent solar minima in 2008–09 and 2019–20. Thus, it is reasonable to assume that cosmic ray data driven by solar minima cannot solely provide enough evidence to treat 2019–20 peak differently from 2008 to 09 peak to discuss the emergence of COVID-19. This does not deny the possible effects of cosmic rays on COVID-19 as many studies report the correlations between solar cycles and pandemics (Figure 1). However, this study suggests that there must exist other factors such as climatology and/or environmental variables that triggered the emergence of COVID-19.

For example, the variables related to bat ecology should be considered. The surface temperature anomaly data from NOAA (URL: https://www.ncdc.noaa.gov/cag/global/time-series) reports a sharp temperature increase trend from 2010 to 2019. This indicates that the temperature increase is driven by anthropogenic factors such as CO$_2$ emission as reported from previous studies.
According to the EPA (URL: https://www.epa.gov/climate-indicators/climate-change-indicators-us-and-global-temperature), global average surface temperature has risen at an average rate of 0.09 °C per decade since 1901 while it is 0.17 °C per decade since 1979. Also, IPCC [49] reports the increase in global average temperature over the course of this century levels up to at least 2 °C relative to 1850–1900. Intriguingly, Beyrer et al. [12] reported that the rapid temperature increase shifted the global distribution of bats. They reported that the southern Chinese Yunnan province and neighboring regions in Myanmar and Laos form a global hotspot of climate change-driven increase in bat richness. Also, Wu [50] stated that bat species distributions in China have primarily shifted northward due to temperature increases for the past 50 years. As mentioned in Section 1, SARS-CoV-2, likely emerged from bats. Liu et al. [51] and Wacharapluysadec et al. [52] reported that bat-origin RaTG13 virus is currently the most phylogenetically related virus to SARS-CoV-2. Letko et al. [53] stated that bats carry 10,756 reported viruses from at least 28 diverse viral families and they stated that Ebola virus, Marburg virus, Nipah virus, Hendra virus, SARS-CoV, MERS-CoV, and SARS-CoV-2, are all linked to various bat species.

Identifying the dominant environmental or climatological variables that triggered the emergence of COVID-19, is beyond the scope of this article; however, the factor that altered bat distribution should be further investigated. It should be also noted that the increasing trend in neutron count will continue until the end of 2053 owing to decreasing in solar activity [54], which allows mutagenic radiation to penetrate to Earth. The latest IPCC full report [49] is predicting a global temperature increase of 1.2–3.0 °C by 2060. In case the combination of space weather and Earth’s climatology and environmental variables were the triggers of severe pandemic, more pandemics during 2030–31, 2041–42, and 2052–2053 are possible scenarios.

Conclusion
This study suggests that the emergence of the COVID-19 pandemic cannot be explained solely by solar minima (space weather) and is related to climatology and environmental variables on Earth. For example, redistribution of the bat population owing to surface temperature changes or a combination of such a factor and space weather can be considered. To further elucidate the molecular mechanisms of rapid SARS-CoV-2 mutation and cosmic radiation, laboratory experiments will be needed to support the relevance between solar cycles and virus point mutation.

Declaration of competing interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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