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Association between Body Mass Index and Risk of Coronavirus Disease 2019 (COVID-19): A Nationwide Case-control Study in South Korea

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Background. Increased body mass index (BMI) has been associated with a higher risk of severe coronavirus disease 2019 (COVID-19) infections. However, whether obesity is a risk factor for contracting COVID-19 has hardly been investigated so far.

Methods. We examined the association between BMI level and the risk of COVID-19 infection in a nationwide case-control study comprised of 3788 case patients confirmed to have COVID-19 between 24 January and 9 April 2020 and 15 152 controls matched by age and sex, who were aged 20 years or more and underwent National Health Insurance Service (NHIS) health examinations between 2015–2017, using data from the Korean NHIS with linkage to the Korea Centers for Disease Control and Prevention data. Our primary exposure of interest was BMI level, categorized into 4 groups: <18.5 (underweight), 18.5–22.9 (normal weight), 23–24.9 (overweight), and ≥25 kg/m^2 (obese).

Results. Of the entire 18 940 study participants, 11 755 (62.1%) were women, and the mean age of the study participants was 53.7 years (standard deviation, 13.8). In multivariable logistic regression models adjusted for sociodemographic, comorbidity, laboratory, and medication data, there was a graded association between higher BMI levels and higher risk of COVID-19 infection. Compared to normal-weight individuals, the adjusted odds ratios in the overweight and obese individuals were 1.13 (95% confidence interval [CI], 1.03–1.25) and 1.26 (95% CI, 1.15–1.39), respectively. This association was robust across age and sex subgroups.

Conclusions. Higher BMI levels were associated with a higher risk of contracting COVID-19.

Keywords. COVID-19; SARS-COV-2; body mass index; obesity.

The ongoing coronavirus disease 2019 (COVID-19) outbreak has led to an unprecedented worldwide health, economic, and social crisis. In South Korea, the first COVID-19 case was confirmed on 20 January 2020 [1]. With proactive containment efforts, comprehensive contact tracing, and extensive testing of symptomatic or suspected individuals for COVID-19, South Korea was able to flatten the curve of new COVID-19 infections by mid-March [1, 2]. However, there are growing concerns of ongoing sporadic community infections spreading via asymptomatic patients or persons with an unknown viral transmission route.

Given the current limited availability of point-of-care COVID-19 testing, identifying and prioritizing testing in individuals at higher risk of severe COVID-19 has been a key emerging issue. From early reports, elderly patients, especially those with comorbidities such as hypertension, diabetes, and cardiovascular disease, had the highest rates of hospitalization [3, 4]. As the prevalences of both obesity itself and obesity-related noncommunicable diseases increase in older adults, it is possible to speculate that obese patients may be more susceptible to developing more serious illness. In fact, several recent studies found that obesity was associated with a more severe course of COVID-19, which included higher risks of intensive care unit admission, tracheal intubation for mechanical ventilation, and death among patients hospitalized for COVID-19 [5–9]. Therefore, obese patients, who comprise around 40% of the US population and around 13% of the world population [10], should be considered as high risk and deserve extra attention and precautions to help improve outcomes in patients requiring hospitalization for severe COVID-19.

Meanwhile, whether obesity is a risk factor for contracting COVID-19 infection is another important issue. It is crucial to identify those individuals who are susceptible to COVID-19 infections in order to contain further COVID-19 transmissions, particularly when testing capacity is limited and in the absence of effective vaccines or antiviral drugs. However, recent studies

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that have included body mass index (BMI) data of patients with COVID-19 have largely focused on the severity and outcomes of infection, and to date there is a paucity of studies that examine the association between BMI and the risk of COVID-19 infection [11, 12]. To address these gaps in knowledge, we sought to determine the association between BMI categories and the risk of COVID-19 infection in a nationwide, population-based, case-control study.

METHODS

Source Population

We obtained data from the Korean National Health Insurance Service (NHIS) database, which is linked to national health screening examination information and Korea Centers for Disease Control and Prevention (KCDC) data. The NHIS covers compulsory health insurance for all citizens in Korea and provides cost-free annual or biennial health screening examinations to all insured individuals. Since Korea has a single-payer national health system, all medical records of covered inpatient and outpatient visits, as well as results from the national health examinations, are centralized in the NHIS database, which includes diagnostic codes, procedures, prescriptions, medical costs, and personal information (eg, age, sex, residential area, income level, and disability) [13, 14]. The KCDC database provides details on all epidemiological investigations for each individual infected with COVID-19, which include date of laboratory confirmation, residential area, and exposure history [15].

In constructing the study population of this nationwide case-control study, we first identified all 10 237 patients confirmed to have severe acute respiratory syndrome coronavirus 2 (SARS-COV-2) infections by a positive result on a polymerase chain reaction test of a nasopharyngeal or oropharyngeal sample between 24 January 2020 and 9 April 2020 in South Korea. We then excluded 481 patients aged 19 years and younger, and 5945 patients who did not undergo NHIS health examinations between 1 January 2015 and 31 December 2017. We further excluded 23 patients who had missing data for any of the study variables (see following Methods subsections). Thus, a total of 3788 confirmed cases were included. For each case patient, we randomly matched 4 controls by age (5-year intervals) and sex who underwent NHIS health examinations during the same period. Individuals who died before 9 April 2020 or had missing information on key study variables were not selected as controls. Therefore, the final study population comprised 18 940 participants, which included 3788 case patients and 15 152 matched controls (Supplementary Figure 1). The Institutional Review Board of NHIS Ilsan Hospital approved this study and waived the requirement for informed consent, as only deidentified data were used.

Data Collection and Measurements

Baseline data on sociodemographic information, such as age, sex, income level, and residential area, were collected in the year prior to the index date. We defined the index date as the end of the study period (ie, 9 April 2020), for both case patients and matched controls. Comorbidities (eg, diabetes, ischemic heart disease, congestive heart failure, cerebrovascular disease, hemiplegia, dementia, peripheral vascular disease, liver disease, chronic pulmonary disease, connective tissue disease, peptic ulcer disease, chronic kidney disease, and malignancy) were assessed using the International Statistical Classification of Disease and Related Health Problems, Tenth Revision, coding algorithms (Supplementary Table 1), which were ascertained by the presence of at least 2 or more diagnostic codes up to 5 years prior to the index date. The Charlson comorbidity index (CCI) score was also calculated as a proxy of disease burden and illness severity [16]. The use of angiotensin-converting enzyme (ACE) inhibitors, angiotensin-receptor blockers, or dipeptidyl peptidase-4 (DPP-4) inhibitors was defined as a prescription for these medications, identified up to 5 years before the index date.

All anthropometry and laboratory results were collected at every health examination visit between 2015 and 2017, and results were averaged over the 3 years. BMI was calculated as weight in kilograms divided by height in meters-squared. Blood pressure was measured using standardized methods while the participant was sitting on a chair after a 5-minute rest. Serum lipid, glucose, and creatinine levels were measured from specimens collected while fasting. Estimated glomerular filtration rate (eGFR) was estimated by the Chronic Kidney Disease Epidemiology Collaboration equation for creatinine [17].

Statistical Analysis

Our primary exposure of interest was BMI, which was presented as the average of all measurements in each health examination visit between 2015 and 2017. In the study population, the mean and median numbers of BMI measurements that contributed to each BMI value per individual were 1.7 (standard deviation [SD], 0.7) and 2.0 (interquartile range [IQR], 1.0–2.0), respectively, which were equal between case patients and matched controls. Given a possible nonlinear relationship with COVID-19 infection risk, BMI was treated as a categorical variable and divided into 4 categories: <18.5 (underweight), 18.5–22.9 (normal weight), 23–24.9 (overweight), and ≥25 kg/m^2 (obese). Obesity was defined as ≥25 kg/m^2 based on a World Health Organization cut-off point for Asian populations [18]. The normal weight BMI category (18.5–22.9 kg/m^2) was chosen as the reference because it included the largest number of participants and allowed for the most precise comparison with lower and higher BMI categories.

To examine the association between BMI categories and the risk of COVID-19 infection, we used multivariable logistic regression models with 4 incremental levels of adjustment: Model

1 was unadjusted; Model 2 was adjusted for age, sex, residential area, income level, smoking status, and CCI score; Model 3 was adjusted for all covariates in Model 2 plus systolic blood pressure, low-density lipoprotein cholesterol level, triglyceride level, high-density lipoprotein cholesterol level, fasting glucose level, and eGFR; and Model 4 was adjusted for all covariates in Model 3 plus use of ACE inhibitors and/or angiotensin-receptor blockers, and use of DPP-4 inhibitors. To test the robustness of our findings, we further performed subgroup analyses by age (20–39, 40–49, and ≥60 years) and sex (male and female). The risk of developing COVID-19 was expressed as odds ratios (ORs) and 95% confidence intervals (CIs).

For sensitivity analyses, we additionally assessed the optimal cut-off point of BMI value for predicting COVID-19 diagnosis, based on the area under the receiver operating characteristic curve (AUROC). To compare predictive performance of BMI, we also calculated the net reclassification improvement (NRI) and integrated discrimination index (IDI) between adjusting models with and without BMI.

Data from descriptive analyses were summarized using means (SD), medians (IQR), or numbers (proportions), as appropriate, and were compared using independent-sample *t*-tests or chi-square tests, respectively. All analyses were conducted using SAS version 9.4 (SAS Institute Inc., Cary, NC). A *P* value < .05 was used as the threshold for statistical significance for any tests.

RESULTS

Clinical Characteristics of Study Population

Clinical characteristics of the 3 788 case patients with COVID-19 and 15 152 matched controls who met the eligibility criteria for the study are shown in Table 1. The mean age of the study participants was 53.7 years (SD, 13.8), among whom 62.1% were women, 87.0% were urban residents, and 13.7% had 1 or more comorbidities based on the CCI components. The mean and median BMI values were 24.0 kg/m^2 (SD, 3.4) and 23.8 kg/m^2 (IQR, 21.6–26.0), respectively, in case patients and 23.8 kg/m^2 (SD, 3.4) and 23.5 kg/m^2 (IQR, 21.5–25.7), respectively, in matched controls. Overall, case patients were more likely to reside in rural areas, have lower income levels, have a higher prevalence of comorbidities, and be prescribed DPP-4 inhibitors. In contrast, matched controls were more likely to be current smokers and have higher systolic blood pressure, lipid levels, and eGFR.

Association Between BMI and Risk of COVID-19

In logistic regression models that were adjusted for sociodemographic, comorbidity, laboratory, and medication data, there was a graded association between higher BMI levels and higher risk of COVID-19 infection (Figure 1). Specifically, compared to normal-weight individuals, we observed 13% and 25% higher risks of COVID-19 in overweight and obese individuals, respectively, with adjusted ORs in Model 3 of 1.13 (95% CI, 1.03–1.25) and 1.25 (95% CI, 1.14–1.38), respectively (Model 3 in Table 2). It should be noted that these associations remained largely unchanged despite additional adjustments for medications known to potentially influence ACE2 expression, including ACE inhibitors or angiotensin-receptor blockers, and DPP-4 inhibitors (Model 4 in Table 2). In contrast, underweight individuals tended to trend toward an increased risk of contracting COVID-19 infections, but this was not statistically significant.

Subgroup Analyses

We then examined the association between BMI category and risk of COVID-19 across clinically relevant subgroups. In subgroup analyses, a stepwise increase in the risk of COVID-19 infection associated with an incrementally higher BMI was largely consistent across all age categories and sex (Figure 2). Of note, the magnitude of adjusted ORs in obese individuals was much stronger in gradually younger age categories, which were 1.53 (95% CI, 1.18–1.99), 1.26 (95% CI, 1.10–1.44), and 1.19 (95% CI, 1.02–1.39) in the 20–39, 40–59, and ≥60 years age categories, respectively (Table 3).

Sensitivity Analyses

Next, we determined the optimal cut-off points for predicting COVID-19 diagnosis based on the AUROC, and found that optimal threshold levels of BMI were different across the whole population and various subgroups; these were lowest (21.8 kg/m^2 of BMI) in patients aged 40–59 years (AUROC, 0.525; 95% CI, .510–.539) and women (AUROC, 0.525; 95% CI, .512–.538), and highest (25.9 kg/m^2 of BMI) in elderly patients aged 60 years and older (AUROC, 0.518; 95% CI, .500–.536) and men (AUROC, 0.520; 95% CI, .503–.537; Supplementary Table 2). When we compared the predictive ability of BMI for the risk of COVID-19 by calculating NRI and IDI values, positive NRI or IDI values indicated that models incorporating BMI were statistically superior to corresponding models without BMI (Supplementary Table 3).

DISCUSSION

In this nationwide, population-based, case-control study, we found a graded association between higher BMI levels and higher risk of COVID-19 infections. In particular, obese individuals showed the highest susceptibility to COVID-19, even after adjusting for potential confounding factors, including sociodemographic, comorbidity, laboratory, and medication data. This association was robust across age and sex subgroups. These findings suggest that BMI could be an important consideration in estimating an individual's risk of acquiring

Table 1. Clinical Characteristics of Case Patients and Matched Controls

		Study Participants		
	Overall	Case Patients	Matched Controls	
Characteristics	n = 18 940	n = 3788	n = 15 152	*P*
Age, mean (SD), years	53.7 (13.8)	53.7 (13.8)	53.7 (13.8)	1.000
Age intervals, n (%)	…	…	…	1.000
20–29 years	1160 (6.1)	232 (6.1)	928 (6.1)	
30–39 years	1820 (9.6)	364 (9.6)	1456 (9.6)	
40–49 years	3750 (19.8)	750 (19.8)	3000 (19.8)	
50–59 years	5685 (30.0)	1137 (30.0)	4548 (30.0)	
60–69 years	4195 (22.2)	839 (22.2)	3356 (22.2)	
≥70 years	2330 (12.3)	466 (12.3)	1864 (12.3)	
Sex, n (%)				
Men	7185 (37.9)	1437 (37.9)	5748 (37.9)	1.000
Women	11 755 (62.1)	2351 (62.1)	9404 (62.1)	
Residential area, n (%)	…	…	…	<.001
Large city	13 909 (73.4)	2791 (73.7)	11 118 (73.4)	
Small city	4081 (21.6)	733 (19.4)	3348 (22.1)	
Rural area	950 (5.0)	264 (7.0)	686 (4.5)	
Income quantiles, n (%)	…	…	…	<.001
First quantile, lowest	4202 (22.2)	1057 (27.9)	3145 (20.8)	
Second quantile	2790 (14.7)	562 (14.8)	2228 (14.7)	
Third quantile	3268 (17.3)	584 (15.4)	2684 (17.7)	
Fourth quantile	4053 (21.4)	716 (18.9)	3337 (22.0)	
Fifth quantile, highest	4627 (24.4)	869 (23.0)	3758 (24.8)	
Comorbidities, n (%)				
Diabetes	1010 (5.3)	268 (7.1)	742 (4.9)	<.001
Ischemic heart disease	336 (1.8)	73 (1.9)	263 (1.7)	.425
Heart failure	124 (.7)	24 (.6)	100 (.7)	.857
Cerebrovascular disease	490 (2.6)	135 (3.6)	355 (2.3)	<.001
Hemiplegia	101 (.5)	36 (1.0)	65 (.4)	<.001
Dementia	136 (.7)	66 (1.7)	70 (.5)	<.001
Peripheral vascular disease	83 (.4)	17 (.4)	66 (.4)	.912
Liver disease	234 (1.2)	87 (2.3)	147 (1.0)	<.001
Chronic pulmonary disease	411 (2.2)	101 (2.7)	310 (2.0)	.019
Connective tissue disease	97 (.5)	25 (.7)	72 (.5)	.154
Peptic ulcer disease	554 (2.9)	107 (2.8)	447 (3.0)	.682
Chronic kidney disease	45 (.2)	7 (.2)	38 (.3)	.456
Malignancy	555 (2.9)	121 (3.2)	434 (2.9)	.281
CCI scores, n (%)	…	…	…	<.001
0	16 351 (86.3)	3159 (83.4)	13192 (87.1)	
1	1 334 (7.0)	301 (7.9)	1033 (6.8)	
2	697 (3.7)	167 (4.4)	530 (3.5)	
≥3	558 (3.0)	161 (4.3)	397 (2.6)	
Smoking status, n (%)	…	…	…	<.001
Never	13 728 (72.5)	2931 (77.4)	10 797 (71.3)	
Former	2566 (13.5)	733 (14.7)	2007 (13.2)	
Current	2646 (14.0)	264 (7.9)	2348 (15.5)	
Prescribed medications, n (%)				
ACE inhibitor or ARB	4169 (22.0)	834 (22.0)	3335 (22.0)	.993
DPP-4 inhibitor	929 (4.9)	252 (6.7)	677 (4.5)	.044
BMI, mean (SD), kg/m^2	23.8 (3.4)	24.0 (3.4)	23.8 (3.4)	<.001
SBP, mean (SD), mmHg	121.6 (13.9)	121.0 (14.2)	121.8 (13.9)	.005
LDL-C, mean (SD), mg/dL	114.7 (34.3)	114.6 (31.6)	114.7 (35.0)	.087
HDL-C, mean (SD), mg/dL	57.5 (16.5)	56.7 (14.2)	57.7 (17.0)	<.001
Triglyceride, mean (SD), mg/dL	123.0 (86.2)	120.4 (78.9)	123.7 (87.9)	.026
Fasting glucose, mean (SD), mg/dL	99.1 (22.7)	99.8 (22.3)	99.0 (22.8)	.039
eGFR, mean (SD), mL/min/1.73m^2	91.0 (18.1)	90.4 (17.8)	91.1 (18.2)	.022

Data are presented as means (SDs) or numbers (%).

Abbreviations: ACE, angiotensin-converting enzyme; ARB, angiotensin-receptor blocker; BMI, body mass index; CCI, Charlson comorbidity index; DPP-4, dipeptidyl peptidase-4; eGFR, estimated glomerular filtration rate; HDL-C, high-density lipoprotein cholesterol; LDL-C, low-density lipoprotein cholesterol; SBP, systolic blood pressure; SD, standard deviation.

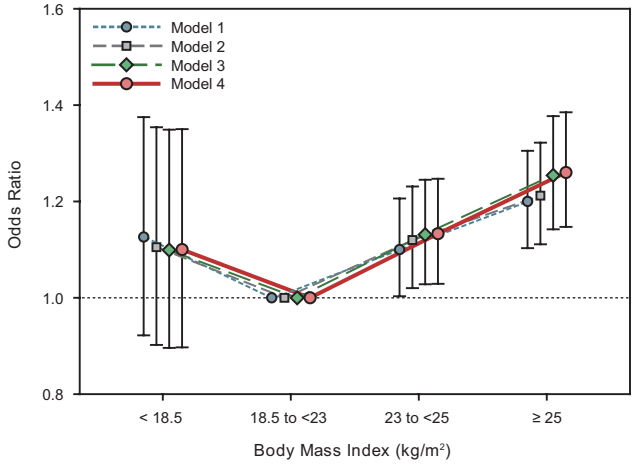

Figure 1. Associations between BMI and risk of COVID-19 infection. Model 1 was unadjusted; Model 2 was adjusted for age, sex, residential area, income level, smoking status, and Charlson comorbidity index score; Model 3 was adjusted for all covariates in Model 2 plus systolic blood pressure, low-density lipoprotein cholesterol level, triglyceride level, high-density lipoprotein cholesterol level, fasting glucose level, and estimated glomerular filtration rate; and Model 4 was adjusted for all covariates in Model 3 plus use of angiotensin-converting enzyme inhibitors or angiotensin-receptor blockers, and use of dipeptidyl peptidase-4 inhibitors. Abbreviations: BMI, body mass index; COVID-19, coronavirus disease 2019.

COVID-19, and in devising strategies that could contain the further spread of COVID-19 at a population level.

While obesity is a well-recognized risk factor for various cardiometabolic diseases, its role in infection must not be ignored [19]. During the 2009 H1N1 influenza A virus pandemic, obesity emerged as a novel, major, predisposing factor in both the transmission and severe course of viral disease [20–22]. Obesity not only prolonged the duration of influenza virus shedding, but was also linked to higher risks of hospitalization and mortality [23–25]. Furthermore, impaired immune responses to vaccination in obese individuals have also been reported in several types of viral infections, such as influenza, hepatitis B, and tetanus [26–28].

By analogy to other viral infections, obesity may play an important role in COVID-19 transmission, but this hypothesis has hardly been investigated so far. In the present study, using a national cohort of 18 940 case patients and matched controls, we found a significant relationship between incrementally higher BMI and the risk of COVID-19 infection, in which obese individuals with a BMI of more than 25 kg/m^2 were associated with a 26% higher risk of contracting COVID-19 than normal-weight individuals. More importantly, these associations were consistent even after adjusting for sociodemographic factors, comorbidities, cardio-metabolic components, and medications, which suggests that obesity may be an independent risk factor in acquiring COVID-19 infection. To our knowledge, although several observational studies have reported a higher risk for severe COVID-19 associated with obesity, this is the first case-control study to confirm the relationship between obesity and the risk of COVID-19 acquisition. From the preventive perspective, our study findings are particularly informative, in that obesity is not only a risk factor for a severe course of COVID-19 disease, but also for acquiring the virus itself. Thus, not only should BMI be a major consideration in informing treatment strategies, but also in preventive strategies for COVID-19. Of note, the Infectious Disease Society of America recently developed recommendations for diagnostic testing prioritization, with priorities given to critically ill patients, health-care workers, immunocompromised patients, and elderly patients [29]. Based on our findings, future recommendations could include individuals with higher BMI levels. Moreover, although the results of prediction testing in this study may be insufficient to provide concrete guidance for diagnostic testing prioritization and preventive strategies, this study could serve as a starting point for future investigations that could potentially look into the causal relationship between BMI and the risk of contracting COVID-19 infections.

Table 2. Associations Between Body Mass Index Categories and Risk of Coronavirus Disease 2019 Infection

	Study Participants, n (%)		Odds Ratio (95% CI)			
	Case Patients	Controls				
BMI, kg/m^2	n = 3788	n = 15 152	Model 1	Model 2	Model 3	Model 4
<18.5	132 (3.5)	512 (3.4)	1.13 (.92–1.38)	1.11 (.9–1.35)	1.10 (.9–1.35)	1.10 (.9–1.35)
18.5 to <23	1414 (37.3)	6173 (40.7)	1.00	1.00	1.00	1.00
23 to <25	933 (24.6)	3704 (24.5)	1.10 (1.00–1.21)	1.12 (1.02–1.23)	1.13 (1.03–1.25)	1.13 (1.03–1.25)
≥25	1309 (34.6)	4763 (31.4)	1.20 (1.10–1.31)	1.21 (1.11–1.32)	1.25 (1.14–1.38)	1.26 (1.15–1.39)

Model 1 was unadjusted; Model 2 was adjusted for age, sex, residential area, income level, smoking status, and Charlson comorbidity index score; Model 3 was adjusted for all covariates in Model 2 plus systolic blood pressure, low-density lipoprotein cholesterol level, triglyceride level, high-density lipoprotein cholesterol level, fasting glucose level, and estimated glomerular filtration rate; and Model 4 was adjusted for all covariates in Model 3 plus use of angiotensin-converting enzyme inhibitors or angiotensin-receptor blockers, and use of dipeptidyl peptidase-4 inhibitors.

Abbreviations: BMI, body mass index; CI, confidence interval.

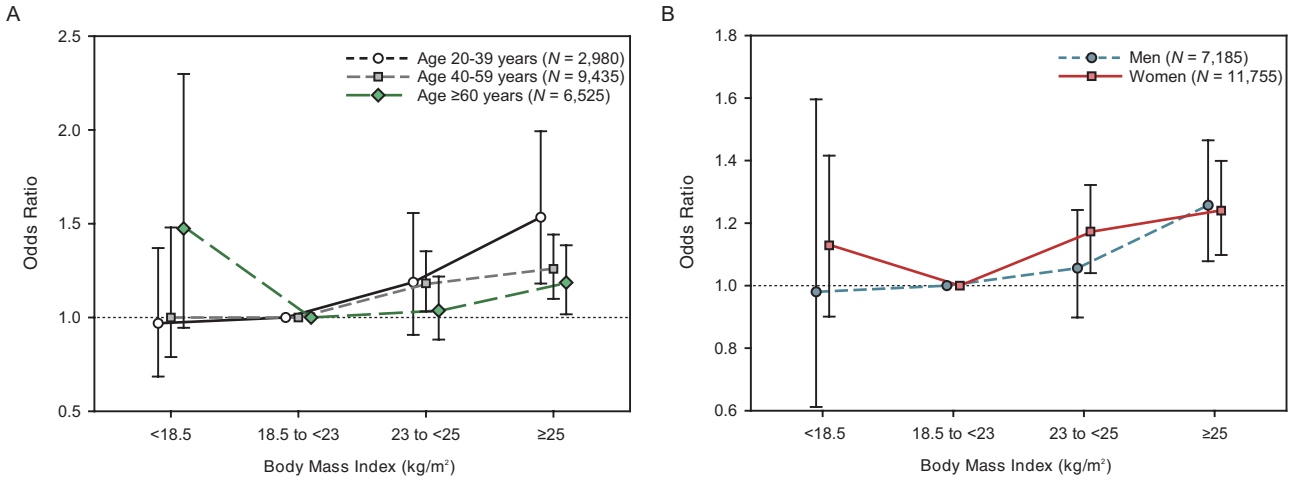

Figure 2. Associations between BMI and risk of COVID-19 infection across subgroups, stratified by (*A*) age and (*B*) sex. All models were adjusted for age, sex, residential area, income level, smoking status, Charlson comorbidity index score, systolic blood pressure, low-density lipoprotein cholesterol level, triglyceride level, high-density lipoprotein cholesterol level, fasting glucose level, estimated glomerular filtration rate, use of angiotensin-converting enzyme inhibitors or angiotensin-receptor blockers, and use of dipeptidyl peptidase-4 inhibitors. Abbreviations: BMI, body mass index; COVID-19, coronavirus disease 2019.

Due to a paucity of data at this time, the underlying mechanisms responsible for the association between obesity and COVID-19 infection are unclear, but several plausible explanations could be contemplated. First, COVID-19 is known to have a high affinity for human ACE2, which acts as the putative receptor of entry of COVID-19 into host cells [30]. Notably, ACE2 expression levels are actually higher in adipose tissue than in other organs, including the lungs, heart, and the kidneys. Obese individuals with more adipose tissue therefore have more ACE2-expressing cells and a larger amount of ACE2, and thus greater vulnerability to COVID-19 [31, 32]. Second, by analogy with other viral agents, such as human adenovirus Ad-36, influenza A virus, human immunodeficiency virus, and cytomegalovirus [32, 33], adipose tissue can also act as a reservoir and host entry point for COVID-19. Finally, the metabolic inflammation associated with obesity potentially impairs immune responses to viral infections. For example, obesity appears to confer an inadequate immune response to viral infections, such as H1N1 influenza or hepatitis B, and a greater vulnerability to overwhelming sepsis following viral illness [26, 34, 35]. All of these possible mechanisms suggest that studies into the pathogenesis of COVID-19 should not merely consider the microbiologic aspects, but also the metabolic aspects of the viral disease.

The strengths of this study include the availability of detailed patient-level information on sociodemographic, comorbidity, anthropometry, and laboratory data from a large national cohort; the utilization of an age- and sex-matched population cohort; and the vigorous adjustment for potential confounders of obesity and related infection risk. However, several limitations of our study bear mention. First, potential selection bias cannot be excluded, given our restriction of analyses to participants who underwent NHIS health examinations between 2015 and 2017, capturing only a third of total confirmed COVID-19 cases between 24 January and 9 April 2020, in South Korea. This proportion of complete health check-ups was particularly low compared to that of the entire population, which was approximately 77% during the same period. Second, rather than changes in BMI over time, the averaged BMI was assessed in this study. However, a BMI substantially changing during the 5 years of follow-up in our study was deemed unlikely. Third, our findings may not be generalizable to populations outside of South Korea, given the social factors, environmental exposures, national health-care policies, and chronic disease burdens, including of obesity, that may be distinct from other countries. For instance, the small sample size of case patients with a BMI of over 30kg/m^2, which is a frequently defined obesity threshold in Western countries, makes it difficult to further categorize our BMI groups to include higher levels.

In conclusion, a higher BMI was associated with a higher risk of COVID-19 infection. As the COVID-19 pandemic evolves, continued investigation into the interplay between metabolic health, especially obesity, and the risk of COVID-19 is warranted in order to inform control strategies for COVID-19. While awaiting further evidence supporting a causal relationship between obesity and the risk of COVID-19 infections, individuals with a higher BMI could be potentially classified as high risk, and thus prioritized in COVID-19 testing.

Table 3. Associations Between Body Mass Index Categories and Risk of Coronavirus Disease 2019 Infection Across Subgroups, Stratified by Age and Sex

	Study Participants, n (%)		Odds Ratio (95% CI)			
	Case Patients	Controls				
BMI kg/m^2	n = 3788	n = 15 152	Model 1	Model 2	Model 3	Model 4
Age, 20–39 years						
<18.5	49 (8.2)	204 (8.5)	1.03 (.74–1.45)	1.01 (.71–1.42)	.97 (.68–1.37)	.97 (.69–1.37)
18.5 to <23	268 (45.0)	1153 (48.4)	1.00	1.00	1.00	1.00
23 to <25	104 (14.4)	419 (17.6)	1.07 (.83–1.38)	1.13 (.87–1.48)	1.20 (.91–1.57)	1.19 (.91–1.56)
≥25	175 (29.4)	608 (25.5)	1.24 (1.00–1.53)	1.33 (1.05–1.67)	1.53 (1.17–1.98)	1.53 (1.18–1.99)
Age, 40–59 years						
<18.5	54 (2.9)	221 (2.9)	1.08 (.79–1.47)	1.10 (.80–1.50)	1.08 (.79–1.48)	1.08 (.79–1.48)
18.5 to <23	735 (38.9)	3238 (42.9)	1.00	1.00	1.00	1.00
23 to <25	467 (24.8)	1765 (23.4)	1.17 (1.02–1.33)	1.16 (1.01–1.32)	1.18 (1.06–1.35)	1.18 (1.03–1.35)
≥25	631 (33.4)	2324 (30.8)	1.20 (1.06–1.35)	1.18 (1.04–1.34)	1.25 (1.09–1.43)	1.26 (1.10–1.44)
Age, ≥60 years						
<18.5	29 (2.2)	87 (1.7)	1.45 (.94–2.23)	1.43 (.92–2.23)	1.47 (.94–2.29)	1.47 (.95–2.30)
18.5 to <23	411 (31.5)	1782 (34.1)	1.00	1.00	1.00	1.00
23 to <25	362 (27.8)	1520 (29.1)	1.03 (.88–1.21)	1.04 (.89–1.22)	1.04 (.88–1.22)	1.04 (.88–1.22)
≥25	503 (38.5)	1831 (35.1)	1.19 (1.03–1.38)	1.17 (1.01–1.36)	1.18 (1.02–1.38)	1.19 (1.02–1.39)
Men						
<18.5	23 (1.6)	97 (1.7)	1.03 (.65–1.64)	.98 (.60–1.59)	.98 (.60–1.60)	.98 (.60–1.60)
18.5 to <23	408 (28.4)	1770 (30.8)	1.00	1.00	1.00	1.00
23 to <25	371 (25.8)	1569 (27.3)	1.03 (.88–1.20)	1.04 (.89–1.22)	1.05 (.89–1.24)	1.06 (.90–1.24)
≥25	635 (44.2)	2312 (40.2)	1.19 (1.04–1.37)	1.21 (1.05–1.39)	1.24 (1.07–1.45)	1.26 (1.08–1.47)
Women						
<18.5	109 (4.6)	415 (4.4)	1.15 (.92–1.44)	1.14 (.91–1.43)	1.13 (.90–1.42)	1.13 (.90–1.42)
18.5 to <23	1006 (42.8)	4403 (46.8)	1.00	1.00	1.00	1.00
23 to <25	562 (23.9)	2135 (22.7)	1.15 (1.03–1.29)	1.16 (1.03–1.30)	1.17 (1.04–1.32)	1.17 (1.04–1.32)
≥25	674 (28.7)	2451 (26.1)	1.21 (1.08–1.34)	1.19 (1.07–1.33)	1.24 (1.10–1.40)	1.24 (1.10–1.40)

Model 1 was unadjusted; Model 2 was adjusted for age, sex, residential area, income level, smoking status, and Charlson comorbidity index score; Model 3 was adjusted for all covariates in Model 2 plus systolic blood pressure, low-density lipoprotein cholesterol level, triglyceride level, high-density lipoprotein cholesterol level, fasting glucose level, and estimated glomerular filtration rate; and Model 4 was adjusted for all covariates in Model 3 plus use of angiotensin-converting enzyme inhibitors or angiotensin-receptor blockers, and use of dipeptidyl peptidase-4 inhibitors.

Abbreviations: BMI, body mass index; CI, confidence interval.

Supplementary Data

Supplementary materials are available at *Clinical Infectious Diseases* online. Consisting of data provided by the authors to benefit the reader, the posted materials are not copyedited and are the sole responsibility of the authors, so questions or comments should be addressed to the corresponding author.

Notes

Author contributions. T. I. C. and D. W. K. have full access to all data in the study and take responsibility for the integrity of the data and accuracy of the analysis. C.-Y. J. and T. I. C. created the study concept and design and drafted the manuscript. T. I. C., H. P., and H. L. acquired, analyzed, or interpreted the data. T. I. C. and H. P. conducted the statistical analysis. D. W. K., J. H. C., Y. J. C., and S. W. K. provided administrative, technical, or material support. T. I. C., Y. J. C., and S. W. K. supervised the study. All authors critically revised the manuscript for important intellectual content.

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