Preoperative atelectasis in patients with obesity undergoing bariatric surgery: a cross-sectional study

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Abbreviated Title (Running Head): Preoperative Atelectasis in Bariatric Surgery

Summary Statement: Preoperative atelectasis were highly prevalent in patients with obesity undergoing bariatric surgery. BMI above 45 was associated with a higher relative prevalence and atelectasis percentage coverage which explained ~70% of preoperative SpO2.

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Data Availability: The data that support the findings of this study are openly available in the Harvard Dataverse at https://doi.org/10.7910/DVN/4JZZLB.

Code Availability: The code documenting the analysis in this study is openly available in https://github.com/javimangal/preoperative-atelectasis/ and deposited in https://zenodo.org/doi/10.5281/zenodo.10211241.

Abstract

Background: Atelectasis are present even before surgery in patients with obesity. No study has reported the prevalence of preoperative atelectasis in obese patients to date. We aimed to estimate the prevalence and extension of preoperative atelectasis in patients with obesity undergoing bariatric surgery, and the extent to which atelectasis mediate preoperative SpO2 values.

Methods: Cross-sectional study in a single center specialized in laparoscopic bariatric surgery. Preoperative chest computed topographies were re-assessed by a senior radiologist to quantify the extent of atelectasis coverage as a percentage of total lung volume. Patients were classified as having atelectasis when the affection was ≥2.5% to estimate the prevalence of atelectasis. Crude and adjusted prevalence ratios and odds ratios were obtained to assess the relative prevalence of atelectasis and percentage coverage, respectively, at higher obesity categories. Generalized additive models were built to assess the effect of BMI on preoperative SpO2 and the extent to which atelectasis percentage mediated the effect.

Results: The sample consisted of 236 patients with a median BMI 40.3 (IQR:34.6–46.0, range:30.0–77.3). The overall prevalence of atelectasis was 32.6% (95%CI: 27.0–38.9) and by BMI category: 30-35 (12.9%, 95%CI:6.1–24.4), 35-40 (28.3%, 95%CI:17.2–42.6), 40-45 (12.3%, 95%CI:5.5–24.3), 45-50 (48.4%, 95%CI:30.6–66.6), and ≥50 units (68.8%, 95%CI: 86.7–100). Compared to 30-35, only the categories with BMI ≥45 had significantly higher relative prevalence of atelectasis—45-50 (aPR: 3.44, 95%CI:1.64–7.23) and ≥50 (7.6, 95%CI: 3.9–14.5)—and odds of greater atelectasis percentage coverage—45–50 (aOR=6.0, 95%CI:2.12–16.9) and ≥50 (aOR=104.7, 95%CI:33.6–326.8)—. In univariable analysis, BMI ($p<0.001$, %deviance=38.7), obstructive sleep apnea ($p<0.001$, %deviance=12.4), and atelectasis percent ($p<0.001$,

%deviance=67.0) were related with a decrease in SpO2. In a fully adjusted model (%deviance=68.1), only atelectasis ($p<0.001$) remained associated with SpO2.

Conclusions: The prevalence and extension of atelectasis increased with higher BMI, being significantly higher at BMI ≥45. Preoperative atelectasis mediated the effect of BMI on SpO2.

Keywords: Pulmonary Atelectasis, Perioperative Medicine, Bariatric Surgery, Obesity, Oxygen Saturation

INTRODUCTION

North-American countries have a high prevalence of obesity in adults: USA, 41.9%;[1] Canada, 30.0%;[2] and Mexico, 36.9%.[3] People living with obesity are more susceptible to experiencing complications during the perioperative period due to factors such as reduced functional residual capacity, cephalic displacement of the diaphragm, and increased adipose tissue in the chest wall and abdomen.[4,5] Increasing body mass index (BMI) has been shown to be related to a greater decline in lung vital capacity during anesthesia with a marked exposure-response pattern.[6]

Obesity is an important risk factor for lung complications such as atelectasis in patients undergoing anesthesia as these patients suffer from lung restriction, obstructive sleep apnea (OSA) and obesity hypoventilation syndrome.[7] Perioperative atelectasis are more common in patients with obesity compared to patients with a normal BMI, with the earlier experiencing persistence of atelectasis 24 hours after surgery.[8] Although great attention has been given to postoperative atelectasis, Lagier and cols. recently highlighted that “the direct impact of intraoperative pulmonary atelectasis on postoperative outcomes is still unclear”.[9]

Besides the priorly mentioned mechanisms, altered lung surfactant production induced by obesity could cause atelectasis since animal models with obesity are known to have surfactant deficiency relative to alveolar surface area.[10,11] Obese patients with asthma have reduced surfactant protein (SP)-A levels,[12] a mechanism that would increase surface tension, facilitating alveolar collapse.[13] Noteworthy, weight loss after bariatric surgery has been shown to improve lung function due to normalization of SP-A and SP-C expression.[14]

Despite being less studied, atelectasis are present even before surgery in patients with obesity.[8,15] Nonetheless, no study has estimated the prevalence of atelectasis before surgery in obese patients to date. Thus, the objective of this study was to assess the prevalence and extension of preoperative atelectasis in patients with obesity undergoing bariatric surgery, and the extent to which atelectasis mediate preoperative peripheral saturation of oxygen (SpO2).

METHODS

Study Design and Setting

This was a single-center cross-sectional study conducted in a specialized center for laparoscopic bariatric surgery in Tijuana, Mexico mainly receiving patients from abroad. The study period was the month of June 2020. Adult patients who presented for elective bariatric surgery and underwent chest CT scan screening for COVID-19 were eligible. Exclusion criteria were a CO-RADS score ≥3, positive antibody test against SARS-CoV-2, and a prior history of COVID-19, neuromuscular disease, or bronchiectasis.

This study was reviewed and approved by the ethics committee of Hospital General de Tijuana (CONBIOÉTICA-02-CEI-001-20170526, approval no. 001771).

During this time, a joint initiative between Mexico, Canada and the United States (USA) restricted international non-essential travels due to the COVID-19 emergency,[16] but travelling for elective surgeries was possible. American Society of Anesthesiologists (ASA) recommendations for elective surgeries included that patients were tested against SARS-CoV-2, screened for symptoms of COVID-19, and advised against surgery when symptoms were present.[17] Rapid antigen tests against SARS-CoV-2 were not yet available in Mexico[18] and it was not feasible to perform RT-PCR on patients before surgery due to long waiting times until the result was available. Thus, the hospital committee decided that patients were screened for COVID-19 by a sequential approach consisting of 1) patients were asked for sign and symptoms of COVID-19 prior to arriving to the hospital and advised not to present for surgery if these were present, 2) upon arrival at the hospital, a rapid SARS-CoV-2 antibody testing was performed. If IgM against SARS-CoV-2 was positive, the surgery was postponed. 3) If the antibody test was negative, a chest computed tomography (CT) was performed and a CO-RADS[19] score ≥3 was considered suggestive of COVID-19, leading to cancellation of the surgery.

Since chest CT images were available as part of this screening process, we considered this a unique opportunity to study the prevalence and extent of preoperative atelectasis in patients with obesity undergoing bariatric surgery.

Exposure

Weight was measured in a 90x90 cm platform scale with a maximal capacity of 1,000 kg and a precision of 200 grams (Rhino© PLABA-9 model). For height determination patients are encouraged to stand with the heels together and buttocks, shoulders, and head in contact with a stadiometer (precision 0.1 mm). BMI (kg/m^2) was determined as the ratio of weight (kilograms) and squared height (m^2). Obesity class categories were created from BMI according to WHO criteria[22] into class 1 (30–35), 2 (35–40), and 3 (≥40). Class 3 obesity subgroups were further defined as: (40–45), (45–50), and ≥50 units.

Outcomes

The main outcome was the prevalence of atelectasis. The degree of atelectasis coverage as a percentage of lung volume and SpO2 during the preanesthetic assessment were secondary outcomes.

High-resolution chest CT images (1mm slices, 120kV, 50mA, scan time: 0.5sec, FOV L: 240) were obtained with a Toshiba© Aquilion 16 Slice CT Scanner and archived in EvoView PACS (U.M.G. Inc.). A senior radiologist was blinded to the patient's BMI and analyzed chest CT scans in OsiriX© viewer to assess the presence and extent of atelectasis by first measuring the total area of the lung—pixels with density values between –1000 and +100 Hounsfield Units (HU)—. Densities considered to indicate atelectasis were identified in dependent lung regions and calculated by including all pixels within these regions—HU between –100 and +100—.[23] The location was expressed as unilateral or bilateral, whereas the percentage of coverage was registered by rounding to the lower 2.5% category (i.e. values <2.5% were rounded to 0%). Thus, all patients with an atelectasis percentage ≥2.5% were considered as having atelectasis.

SpO2 was determined during the preanesthetic assessment with the patient seating, at rest, and at room air (FiO2: 21%) with a pulse oximeter (Masimo SET®) with precision of 2% at rest in the range of 70-100%.

Confounders

All hypothesized relationships between the exposure, outcomes and confounders were defined a priori and drawn in a directed acyclic graph (DAG) with the *DAGitty* software[24] (**Figure 1**). The diagram was updated by testing implied conditional independencies as described by Ankan, et al.[25] Age, sex and obstructive sleep apnea (OSA) constituted the minimal set of adjustment for the relationship between obesity class and atelectasis percentage. For the relationship between BMI and preoperative SpO2, atelectasis percentage was studied as the mediator of the effect, while the minimal set of confounders was the same as above. Blood serum hemoglobin was considered as an ancestor of the outcome. The mean altitude of the state of residence in meters above sea level (m.a.s.l.) was considered as potentially relevant determinant of SpO2. Due to overspread distribution and inability to model as a non-linear term, this variable was categorized into low (0-1000 m.a.s.l.) and moderate (1000-2500 m.a.s.l.) altitude as per Crocker ME, et al.[26]

Detailed descriptions of all other variables are provided in the **Supplementary Variable Dictionary**.[27]

Sample Size

We did not identify any prior studies reporting the prevalence of preoperative atelectasis in patients with obesity. Thus, we calculated the minimum sample size based on the following assumptions:

1. The PROBESE trial reported that 5.6% of patients in the high PEEP group (12 cmH_2O) and 4.4% in the low PEEP group (4 cmH_2O) had postoperative atelectasis.[5] Assuming a linear relationship between PEEP and atelectasis, patients with no PEEP (0 cmH_2O) could be expected to have a prevalence of atelectasis of 6%.
2. A deviation of 5% in the expected prevalence estimate was selected according to recommendations by Naing et al.[6] for preliminary small-scale studies.
3. Confidence level of 95%.

The minimum sample size obtained was 241 patients.

Statistical analysis

Descriptive characteristics are presented as the mean and standard deviation (SD), median with interquartile range (IQR), and/or range (minimum–maximum) for numerical variables. For categorical variables, absolute frequencies and percentages were calculated. A map of the USA and Canada territories was plotted showing the absolute frequency of patients per state of residence. Categorical variables were summarized in frequency tables and compared with the chi-squared test. Relationships between categorical and numerical variables were assessed through stacked histograms, boxplots, and Q-Q plots and compared with unpaired t-tests or Wilcoxon's test. Scatterplots were used to assess relationships between numeric variables and compared with Spearman's rank test if monotonically increasing/decreasing. When relationships were non-linear, curvatures were first visualized through local regression smooth curves (loess), followed by determining an optimal smooth curvature in a general additive model by increasing the number of knots and comparing against linear terms; if the non-linear term was significantly better than linear, the lowest k with a drop ≥2 in the Akaike information criterion (AIC), plus an adequate visual representation of the relationship, and optimal k-index was selected.

The prevalence of atelectasis and its 95% confidence interval (95%CI) were estimated with a one-sample proportion test with Wilson score intervals for the total sample and BMI categories. Due to zero-inflation and skewness, mean atelectasis percentage was determined by bootstrapping with 10,000 re-samples, and 95%CI with the bias-corrected and accelerated (BCa) method. Relative frequencies of atelectasis percentage by obesity category and class 3 subgroups (40–45, 45–50, and ≥50) are shown in a barplot. Prevalence ratios of atelectasis per obesity class (reference category: class 1) were estimated in a modified Poisson regression model with robust errors as described by Yorlets, et al.[29] and adjusted for age, sex, and OSA.

Atelectasis percentage coverage was modeled in an ordinal logistic regression model.[30] Despite obesity class not meeting the proportional odds assumption, its impact was checked by comparing against partial proportional odds and multinomial models.[31] Since the AIC and McFadden adjusted R2 were better for the main proportional odds model,[32] results of ordinal logistic regression models are presented. Estimates are summarized as the unadjusted and adjusted odds ratio (OR) with Wald 95%CI.

Mean SpO2 was assessed in a fractional regression model by building generalized additive models[33] with a quasibinomial logit link function to assess the extent to which BMI, OSA, atelectasis percentage, and additional covariates (age, sex, mean altitude of the place of residence, and hemoglobin) explained the variation in SpO2. Nine influential outliers were removed according to a Cook's distance greater than 4/n for the two main explanatory variables (BMI n=3, atelectasis percentage n=6); results of analyses keeping all observations are provided in the accompanying reports.[32] OR for the mean SpO2 value with their 95%CI were calculated for all linear and categorical terms, whereas non-linear effects were allowed for BMI (k=8) and atelectasis percent (k=5), which were plotted to show their partial effect on mean SpO2 with 95%CI to assess the extent to which their effect on SpO2 changed when adjusted for other variables. Models were compared by their percentage explained deviance. Predicted values of

SpO2 were obtained from the model including all terms, for all possible combinations of atelectasis percentage and BMI (within the ranges observed in this study) when setting covariates to their reference level or mean value. The relationship between these three variables was visualized in a three-dimensional plot and predicted curves for every unit-decrease in SpO2 were plotted in a two-dimensional plot. Observed SpO2 values were plotted on top of the gradient of predictions to visualize the range at which combinations are likely to be observed in clinical practice.

Complete-case analysis was performed since missing data was <3% for all variables. Statistical significance was defined as p<0.05. P-values are shown rounded to 3 decimals. All analyses and figures were created with R version 4.3.2. Packages used are listed and referenced in the **Supplementary Material**. Details of missing data and statistical assumption checks for every test/model are described in the reports available at https://github.com/javimangal/preoperative-atelectasis/[32]

A data analysis and statistical plan was written and filed with the institutional review board before data were accessed. The dataset[27] and code[32] documenting these analyses are publicly available.

RESULTS

Out of 281 scheduled surgeries, 35 (12.4%) patients decided not to present to the hospital, 3 (1.1%) had a positive SARS-CoV-2 antigen test, and the remaining 243 (86.5%) underwent chest CT screening for COVID-19. After exclusion of 7 patients due to CO-RADS ≥3 (n=4) and who reported prior COVID-19 (n=3), 236 were included for analysis.

All participants were residents of the USA and Canada (**Figure 2**). The mean age of participants was 40.3 (SD: 9.87) years and 90.7% were women (n=214). Most patients had a CO-RADS score of 1 (n=230, 97.5%), while the remaining 2.5% (n=6) had CO-RADS 2. Patients with a diagnosis of OSA constituted 7.6% (n=18) of the sample. The median BMI was 40.3 (IQR: 34.6–46.0, range: 30.0–77.3). Most patients were in the class 3 obesity category (n=121, 51.3%), followed by class 1 (n=62, 26.3%) and 2 (n=53, 22.5%). Characteristics of the sample stratified by obesity class are shown in **Table 1**.

Age had a weak negative correlation with BMI (rho= -0.155, p=0.017). The median BMI was not significantly different between men (43, IQR: 37.9–46.2) and women (39.9, IQR: 34.5–45.5) (p=0.154). The median BMI was significantly higher in participants with OSA (44, IQR: 40.1–49.2) than those without (39.8, IQR: 34.5–45.1) (p=0.014). OSA was more frequent among men than women (p<0.001).

Preoperative atelectasis

The overall prevalence of preoperative atelectasis was 32.6% (95%CI: 27.0–38.9), being greater in higher obesity classes (p<0.001): class 1 (n=8/62), 12.9% (95%CI: 6.1–24.4); class 2 (n=15/53), 28.3% (95%CI: 17.2–42.6); and class 3 (n=54/121), 44.6% (95%CI: 35.7–53.9). Of those who had atelectasis, the most frequent presentation was unilateral n=53 (68.8%), compared to bilateral n=24 (31.2%). When examining this by obesity class, laterality was not significantly different for those with class 1, 2, and 3 obesity categories: n=7 (87.5%), n=10

(66.7%), and n=36 (66.7%), respectively (p=0.484). Atelectasis percentage showed a non-monotonic non-linear relationship with BMI (**Figure 3A**). A marked increase in atelectasis percentage occurred at BMI higher than ~45. The mean atelectasis percentage coverage in the sample was 2.66% (95%CI:2.08–3.26) and according to WHO categories: class 1 (0.93%, 95%CI:0.32–1.81), class 2 (1.55%, 95%CI:0.75–2.45), and class 3 (4.04%, 95%CI:3.06–5.02). Within class 3 subgroups, the mean atelectasis percentage was 0.7% (95%CI:0.22–1.27) in the 40–45 group; 3.63% (95%CI:2.18–5.0), in 45–50; and 10.44% (95%CI:8.83–12.5), in the ≥50 subgroup. The relative frequencies of the extent of coverage were significantly higher with increasing obesity class (p<0.001) (**Figure 4A**), with greater heterogeneity and increasing percentage coverage within class 3 obesity subgroups (**Figure 4B**).

Age was similarly distributed among patients without atelectasis (40.6, SD:10.1) and those with atelectasis (39.6, SD:9.3) (p=0.498). The differences in atelectasis occurrence between men (45.5%) and women (31.3%) were not statistically significant (p=0.178). Patients with a diagnosis of OSA had atelectasis more frequently (94.4%, n=17/18) than those without (27.5%, n=60/218) (p<0.001). The location of atelectasis was not different among patients with and without OSA (p=0.313). Unadjusted and adjusted prevalence ratios of atelectasis by obesity class are shown in **Table 2**.

Ordinal logistic regression models were fitted to assess the relationship between explanatory variables and increases in the extent of atelectasis percentage. The results of univariable and multivariable models for obesity class and confounder variables are shown in **Table 3**. Compared to class 1 obesity, class 2 obesity was not significantly associated with a greater atelectasis percentage coverage (aOR=2.25, 95%CI: 0.86–5.90), whereas class 3 obesity was associated with a 5-fold increase in the odds of a greater extent of atelectasis percentage (aOR=5.29, 95%CI: 2.29–12.25).

Due to the heterogeneity observed in atelectasis percentage in the class 3 category, post-hoc analyses were conducted to assess differences in subgroups. The prevalence of atelectasis in the 40–45, 45–50, and ≥50 subgroups was 12.3% (95%CI: 5.49–24.29), 48.4% (95%CI: 30.56–66.60), and 68.75% (95%CI: 86.66–100.00), respectively. Prevalence ratios are shown in **Table 2**. Ordinal logistic regression analyses showed that compared to the 30–35 category, the odds of a higher atelectasis percentage did not increase in the 40–45 group (aOR=0.63, 95%CI: 0.19–2.02), whereas the odds of higher atelectasis affection increased in several orders of magnitude in the 45–50 (aOR=6.00, 95%CI: 2.12–16.94), and ≥50 (aOR=104.7, 95%CI: 33.55–326.8) groups (**Supplementary Table 1**).

SpO2 during the pre-anesthetic assessment

The median SpO2 was 96% (IQR: 93–97), with a minimum value of 88%. A total n=146 (61.9%) had normal SpO2 (above 94%), whereas n=75 (31.8%) had a value in the 90–94% range, and n=15 (6.4%) had ≤90%. BMI exhibited a negative non-linear non-monotonic relationship with SpO2 (**Figure 3B**). SpO2 was significantly lower in patients with atelectasis (92, IQR: 91–93) compared to those without (97, IQR: 96–98) (p<0.001), and lower in patients with bilateral atelectasis (91.5, IQR: 90–92) compared to those with unilateral atelectasis (92, IQR: 92–93) (p=0.006). There was a decreasing trend in SpO2 with higher atelectasis percentage extension (**Figure 3C**). Patients with sleep apnea had a lower median SpO2 (92, IQR: 91–93) than those without (96, IQR: 93–97) (p<0.001). SpO2 was not correlated (rho= -0.065, p=0.32) with the values of hemoglobin (mean:14.5, SD:1.21 g/dL) observed in this study. Similarly, mean altitude of the place of residence (range: 31–1861 m.a.s.l.), age (rho= 0.022, p=0.74), and sex (p=0.413) were not significantly associated with SpO2.

Generalized additive models were created to model the non-linear relationship between BMI and SpO2, allowing the incorporation of additional linear and categorical terms (**Supplementary

Table 2). BMI ($p<0.001$, %deviance=38.7, **Figure 5A**), OSA ($p<0.001$, %deviance=12.4), and atelectasis percent ($p<0.001$, %deviance=67.0, **Figure 5D**) were significantly associated with SpO2 in univariable analyses. However, a model including these three variables together showed that only atelectasis percentage remained associated with SpO2 (OSA, $p=0.3$; BMI, $p=0.2$; atelectasis percent, $p<0.001$; %deviance=67.3). BMI adjusted for covariates (not atelectasis) had an explained deviance of 45.8% (BMI, $p<0.001$; **Figure 5B**). Atelectasis percent adjusted for covariates (not BMI) had an explained deviance of 68% (atelectasis percent, $p<0.001$; **Figure 5E**). A fully adjusted model including both BMI and atelectasis percent (%deviance=68.1, **Figure 5C and 5F**) showed only atelectasis percentage ($p<0.001$) remained significantly associated with SpO2. Predicted SpO2 values from this model are shown in **Figure 6A** and plotted alongside observed SpO2 values (**Figure 6B**). The 3-dimensional relationship between SpO2 predictions by BMI and atelectasis percentage is shown in **Figure 7**.

DISCUSSION

In this study, we sought to study the prevalence of preoperative atelectasis in patients with obesity undergoing bariatric surgery, and to study the extent of atelectasis percentage coverage on chest CT and its relationship with SpO2 during the preoperative assessment. Our results show that atelectasis are present in a high percentage of obese patients before surgery (32.6%), with increasing prevalence with higher obesity class: class 1 (12.9%), class 2 (28.3%), and class 3 (44.6%). Subgroup analysis of the class 3 obesity category showed that the prevalence in subgroups was heterogeneous: 12.3% in the 40–45 group; 48.4%, in 45–50; and 68.75% in patients with a BMI ≥50. Adjusted prevalence ratios showed that an increased risk of higher atelectasis compared to the class 1 obesity category was only confidently evidenced at BMI ≥45.. Since our study only included patients with a BMI ≥30 it is likely that these prevalence ratios are even higher when setting overweight or normal BMI as the reference categories since prior studies have shown that atelectasis are more frequently found in obese patients than normal-BMI patients before surgery.[8] Thus, our results only allow us to conclude on an increased relative risk of atelectasis at BMI ≥45 compared to obese patients in the lowest BMI category for obesity (30-35).

Although the prevalence of atelectasis in our study may seem high compared to other studies reporting low proportions of atelectasis even during the postoperative period—for instance, 0.4% in the BOLD registry[34] and 4.4 to 5.6% in the PROBESE trial[21]—, atelectasis assessment has been based on reporting of atelectasis after indication of an imaging study upon clinical suspicion. Therefore, patients in whom imaging is not performed are assumed not to have atelectasis, which biases the estimate towards the null. Here, we propose a definition of atelectasis (≥2.5% of atelectasis coverage on chest CT as a fraction of total lung volume) which could be used in future prospective studies to homogenize outcome assessment and reporting of atelectasis.

Regarding the extent of coverage of atelectasis on chest CT before surgery, we found a mean overall atelectasis percentage (as a fraction of total lung volume) of 2.66% (95%CI:2.08–3.26), which is close to the 2.1% reported by Eichenberger, et al.[8] Reinius and cols. reported lower numbers (0.4 ± 0.7%),[15] although their measurement was at the end of espiration and their estimate could be biased to the null due to zero-inflation as suggested by the SD which includes negative values. Atelectasis coverage in our study increased at higher BMI: class 1 (0.93%), class 2 (1.55%), and class 3 (4.04%). Within class 3 subgroups, mean atelectasis coverage was 0.7% in the 40–45 subgroup; 3.63%, in 45–50; and 10.44% at BMI ≥50. When modelling BMI as a continuous variable, we were able to see that a marked increase in atelectasis percentage occurs around a cutoff point close to 45, which is consistent with what we observed in analyses by BMI categories. Furthermore, ordinal logistic regression analyses confirmed that the odds of having a higher atelectasis percentage coverage is higher in 5 orders of magnitude in the class 3 obesity category, but not statistically significant in the class 2 obesity subgroup despite the point estimate being greater than 1 (aOR=2.25, 95%CI: 0.86–5.90). When examining subgroups of class 3 obesity, we observed that only categories above 45 had a significantly higher odds of increased atelectasis percentage coverage con chest CT after adjusting for confounders. The reason why the prevalence of atelectasis and atelectasis percentage coverage increased in class 2 obesity and then decreased again to levels comparable to class 1 obesity in the 40-45 subgroups could be due to outliers and a latent possibility of residual confounders driving these increases which were non-statistically significant.

As a secondary objective, we studied the extent to which SpO2 measured during the preoperative assessment could be due to BMI alone or mediated by atelectasis percentage. Strikingly, the plots of atelectasis percent vs BMI (Figure 1A) and SpO2 vs BMI (Figure 1B) are nearly mirror-images, which suggests a strong correlation between them. Since these variables were non-monotonically related (not only increasing/decreasing at the entire length of the x-axis) but exhibited clear non-linear relationships, we modelled their effect on SpO2 in a generalized additive model. We observed that BMI, OSA, and atelectasis percentage were all significantly associated with SpO2 in univariable models. Nonetheless, when adjusted for atelectasis percentage, only atelectasis percentage remained significantly associated with atelectasis percentage. Furthermore, atelectasis percent alone had a percentage explained deviance of 67.0% which only increased in one unit (68.1%) in a model including BMI and covariates. The attenuation of the effect of BMI on SpO2 is evident from the plots shown in figure 2, whereas the effect of atelectasis percentage persists after adjustment. Therefore, these results show that the effect of BMI on SpO2 was largely mediated by atelectasis percentage alone.

Noteworthy, there was heteroskedasticity in the residuals of adjusted models, with very low error at SpO2 ≤95% and increasing error at higher SpO2 values, possibly reflecting that explanation of low SpO2 values with these variables was very good, but that SpO2 values >96% were not well explained by these terms. This is something that is reflected in the predictions plot presented in Figure 3 since only the curves for SpO2 values between 89-96% are well represented. While it would not be possible to extend the y-axis to values lower than 0% to predict SpO2 >96%, it would be possible to extend the y-axis to higher atelectasis percentage values, meaning that SpO2 values lower than 88% could likely be predicted. We found these results encouraging since they show that predicting preoperative atelectasis without the need of performing a chest CT is possible and something that could be implemented in future studies aiming to compare atelectasis before, during, or after surgery. As this is only a proof-of-concept analysis, we advise against implementing our results into practice and we instead encourage researchers to aim to develop and validate a prediction model of atelectasis percentage coverage on large-scale, sufficiently powered, and representative studies.[35]

Strengths of our study include the large sample of patients with obesity, including extreme BMI, and the availability of chest CT scans before surgery due to the COVID-19 pandemic that allowed us to study the prevalence of preoperative atelectasis. Furthermore, we were able to show the effect of BMI on preoperative atelectasis and SpO2 through robust DAG-informed modelling which is the currently the recommended approach to study potentially causal relationships. We found strikingly strong effects of increasing BMI on both atelectasis percentage and SpO2, the latter of which was largely mediated by atelectasis. Additionally, the participation rate in our study was 84% of all programmed surgeries.

Limitations of our study include that the atelectasis percentage variable was rounded to the lowest 2.5% category, which caused loss of information for the variable. This could have led to an underestimation of the prevalence of atelectasis and its effect on BMI. Thus, our results are likely conservative which is pertinent for a preliminary study like this. Another limitation is that there could be residual confounding as we did not have good documentation in medical records of other potential confounders like recent respiratory infections or heart disease. Although COVID-19 could be an additional potential confounder, we exclude participants who declared a prior history of COVID-19 or who had suggestive findings of current SARS-CoV-2 infection according to CO-RADS. One additional limitation is that our study is poorly representative of men since 90.7% were women, although this is a common situation in studies conducted in bariatric surgery (70-79% women).[8,15,36] Additionally, our sample was overall younger than other large representative studies which could explain why the prevalence of comorbidities like hypertension and diabetes were lower than what has been reported.[36]

CONCLUSION

The overall prevalence of preoperative atelectasis in patients with obesity undergoing bariatric surgery was 32.63% (95%CI: 26.97–38.85) and increased with higher BMI categories. The mean atelectasis percentage coverage in lung CT was 2.66% (95%CI:2.08–3.26) and similarly increased with higher BMI. The risk of having a greater prevalence and extension of atelectasis were significantly higher at BMI ≥45. Preoperative atelectasis mediated the effect of BMI on preoperative SpO2, with atelectasis alone explaining nearly 70% of the variability in SpO2.

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Table 1. Clinical characteristics of patients, according to WHO obesity categories—class 1 (30-35), class 2 (35-40), and class 3 (≥40) obesity—.

	Total (n=236)	**Class 1 Obesity** (n=62)	**Class 2 Obesity** (n=53)	**Class 3 Obesity** (n=121)
Sex				
Woman	214 (90.7%)	60 (96.8%)	48 (90.6%)	106 (87.6%)
Man	22 (9.3%)	2 (3.2%)	5 (9.4%)	15 (12.4%)
Age (years)				
Mean (SD)	40.3 (9.87)	42.1 (10.3)	40.8 (9.25)	39.1 (9.82)
Weight (kilograms, kg)				
Median [Q1, Q3]	111 [97.4, 130]	88.8 [84.2, 95.7]	107 [102, 112]	128 [114, 142]
Height (meters, m)				
Mean (SD)	1.67 (0.08)	1.66 (0.06)	1.69 (0.09)	1.67 (0.09)
BMI (kg/m^2)				
Median [Q1, Q3]	40.3 [34.6, 46.0]	33.0 [31.5, 33.8]	38.3 [36.6, 39.1]	45.6 [42.2, 51.1]
Surgical procedure				
SG	189 (80.1%)	52 (83.9%)	41 (77.4%)	96 (79.3%)
RYGB	6 (2.5%)	1 (1.6%)	1 (1.9%)	4 (3.3%)
OAGB	5 (2.1%)	1 (1.6%)	1 (1.9%)	3 (2.5%)
LBGS	31 (13.1%)	5 (8.1%)	9 (17.0%)	17 (14.0%)
ARISCAT risk group				
Low Risk	175 (74.2%)	44 (71.0%)	41 (77.4%)	90 (74.4%)
Intermediate Risk	61 (25.8%)	18 (29.0%)	12 (22.6%)	31 (25.6%)

	Total (n=236)	**Class 1 Obesity** (n=62)	**Class 2 Obesity** (n=53)	**Class 3 Obesity** (n=121)
SpO2 (%)				
Median [Q1, Q3]	96.0 [93.0, 97.0]	97.0 [95.0, 97.8]	96.0 [94.0, 97.0]	94.0 [92.0, 97.0]
Mean altitude (meters)[1]				
Median [Q1, Q3]	519 [519, 806]	519 [313, 806]	519 [519, 885]	519 [519, 806]
Hypertension				
No	177 (75.0%)	52 (83.9%)	40 (75.5%)	85 (70.2%)
Yes	59 (25.0%)	10 (16.1%)	13 (24.5%)	36 (29.8%)
Diabetes				
No	211 (89.4%)	58 (93.5%)	48 (90.6%)	105 (86.8%)
Yes	25 (10.6%)	4 (6.5%)	5 (9.4%)	16 (13.2%)
Obstructive sleep apnea				
No	218 (92.4%)	60 (96.8%)	50 (94.3%)	108 (89.3%)
Yes	18 (7.6%)	2 (3.2%)	3 (5.7%)	13 (10.7%)
Hypothyroidism				
No	213 (90.3%)	55 (88.7%)	50 (94.3%)	108 (89.3%)
Yes	23 (9.7%)	7 (11.3%)	3 (5.7%)	13 (10.7%)
Dyslipidemia				
No	218 (92.4%)	58 (93.5%)	48 (90.6%)	112 (92.6%)
Yes	18 (7.6%)	4 (6.5%)	5 (9.4%)	9 (7.4%)
Use of antidepressants				
No	142 (60.2%)	36 (58.1%)	33 (62.3%)	73 (60.3%)
Yes	94 (39.8%)	26 (41.9%)	20 (37.7%)	48 (39.7%)

	Total (n=236)	Class 1 Obesity (n=62)	Class 2 Obesity (n=53)	Class 3 Obesity (n=121)
CO-RADS				
CO-RADS 1	230 (97.5%)	61 (98.4%)	51 (96.2%)	118 (97.5%)
CO-RADS 2	6 (2.5%)	1 (1.6%)	2 (3.8%)	3 (2.5%)
Glucose (mg/dL)				
Median [Q1, Q3]	83.0 [74.0, 92.0]	83.0 [77.0, 90.0]	81.0 [70.0, 92.0]	83.0 [74.0, 92.0]
Creatinine (mg/dL)				
Mean (SD)	0.76 (0.15)	0.77 (0.12)	0.74 (0.14)	0.76 (0.16)
Urea (mg/dL)				
Mean (SD)	21.4 (6.70)	22.9 (6.08)	20.5 (6.77)	21.1 (6.89)
Hemoglobin (g/dL)				
Mean (SD)	14.5 (1.21)	14.5 (1.20)	14.5 (1.17)	14.6 (1.24)
Hematocrit (%)				
Mean (SD)	42.8 (3.33)	42.6 (3.32)	42.6 (3.22)	42.9 (3.41)
WBC count (10^3/μL)				
Mean (SD)	7.83 (1.76)	7.81 (1.74)	7.71 (1.76)	7.89 (1.78)
Neutrophils (10^3/μL)				
Mean (SD)	4.97 (1.42)	4.94 (1.39)	4.83 (1.39)	5.04 (1.46)
Lymphocytes (10^3/μL)				
Mean (SD)	2.70 (0.811)	2.71 (0.802)	2.70 (0.920)	2.69 (0.771)
Monocytes (10^3/μL)				
Mean (SD)	2.70 (0.811)	2.71 (0.802)	2.70 (0.920)	2.69 (0.771)
Platelets (cells/μL)				

	Total (n=236)	Class 1 Obesity (n=62)	Class 2 Obesity (n=53)	Class 3 Obesity (n=121)
Mean (SD)	316 (64.4)	307 (67.6)	319 (63.2)	320 (63.2)

Abbreviations: Assess Respiratory Risk in Surgical Patients in Catalonia (ARISCAT), body-mass index (BMI), coronavirus disease (COVID-19) Reporting and Data System (CO-RADS), lap-band to gastric sleeve (LBGS), one anastomosis gastric bypass (OAGB), peripheral saturation of oxygen (SpO2), roux-en-Y gastric bypass (RYGB), sleeve gastrectomy (SG), white blood cell (WBC), 25th percentile (Q1), 75th percentile (Q3), percentage (%), standard deviation (SD).

[1]Mean altitude of the state of residence.

Table 2. Crude and adjusted prevalence ratio of atelectasis according to obesity class category.

Category	PR	SE	95%CI	aPR[1]	SE	95%CI
Class 1 Obesity		Reference			Reference	
Class 2 Obesity	2.19	0.40	1.01—4.76	1.97	0.37	0.95—4.09
Class 3 Obesity	3.46	0.35	1.76—6.8	3.15	0.33	1.66—5.97
Subgroups (Class 3 Obesity)						
[40,45)	0.97	0.48	0.37—2.5	0.72	0.45	0.3—1.76
[45,50)	3.81	0.38	1.81—8.01	3.44	0.38	1.64—7.23
≥50	7.88	0.33	4.12—15.05	7.55	0.33	3.94—14.46

[1]Adjusted for age, sex, and obstructive sleep apnea.

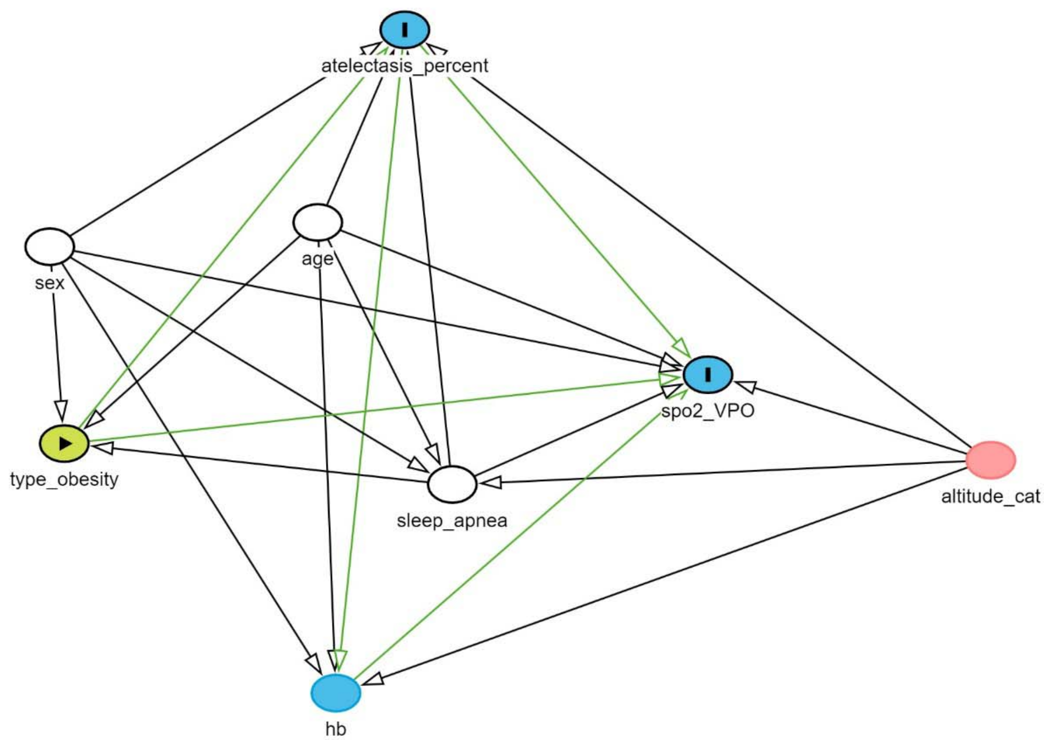
Abbreviations: 95% confidence interval (95%CI), adjusted prevalence ratio (aPR), prevalence ratio (PR), standard error (SE).

Table 3. Univariable and multivariable ordinal logistic regression models of lung atelectasis percentage coverage.

Characteristic	OR	95%CI	aOR	95%CI
Obesity category[1]				
Class 1		Reference		Reference
Class 2	2.38	0.93—6.11	2.25	0.86—5.90
Class 3	5.87	2.59—13.34	5.29	2.29—12.25
Age	0.84	0.55—1.29	0.92	0.58—1.45
Sex				
Woman		Reference		Reference
Man	1.89	0.81—4.40	0.67	0.25—1.84
Obstructive sleep apnea				
No		Reference		Reference
Yes	8.96	3.86—20.74	9.02	3.53—23.04

Abbreviations: 95% confidence interval (95%CI), adjusted odds ratio (aOR), odds ratio (OR).

Figure 1. Directed acyclic graph (DAG).



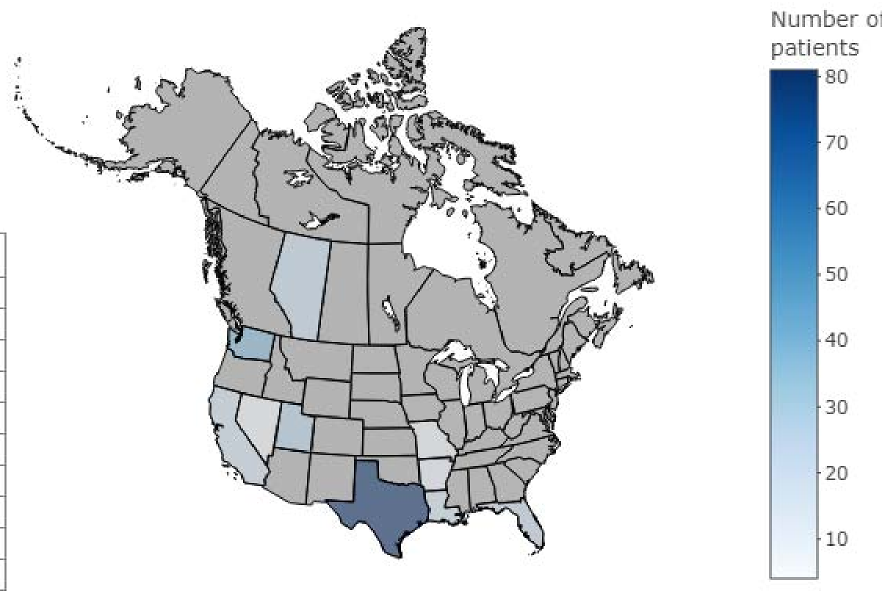
Each circle (node) is used to present a variable. The node in green with an arrowhead inside is the exposure of interest (obesity class), while nodes filled in blue with an "I" inside are the outcomes of interest (atelectasis and SpO2 during the preoperative assessment). White nodes (age, sex, and sleep apnea) correspond to the minimal set of confounders needed to adjust for to remove biasing pathways. The blue node (hemoglobin) is an ancestor of the Spo2 outcome. The pink node (altitude category) is a covariate for which no biasing pathways are latent.

Black arrows show the direction of association between variables, while green arrows present the potential causal paths between exposure and outcome variables.

This figure was generated in https://www.dagitty.net/dags.html; the model code is available at https://github.com/javimangal/preoperative_atelectasis.

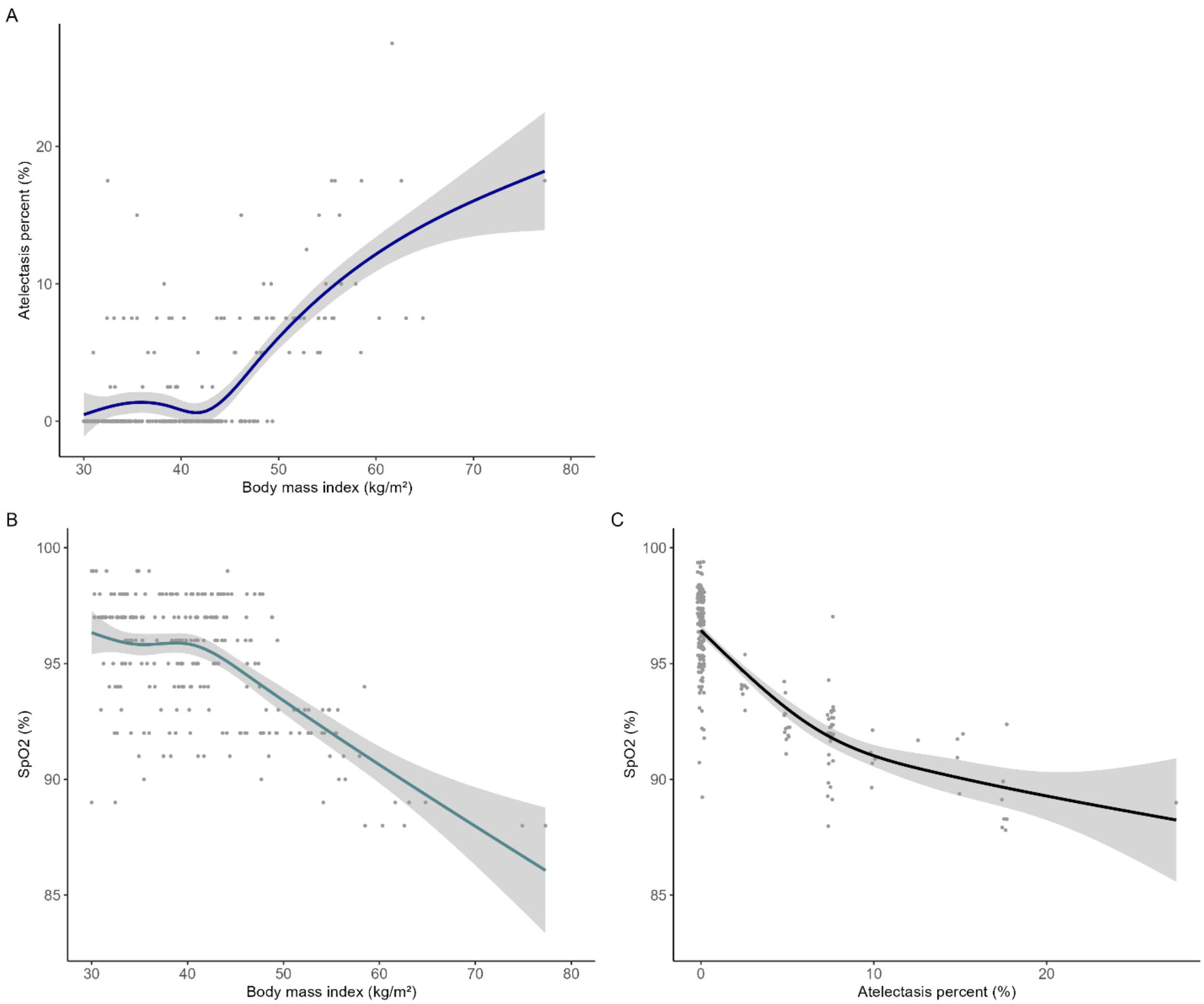
Figure 2. State of residence of participants.

State	n
Texas	81
Washington	39
Utah	27
Alberta	21
Florida	20
California	16
Louisiana	16
Arkansas	7
Missouri	5
Nevada	4



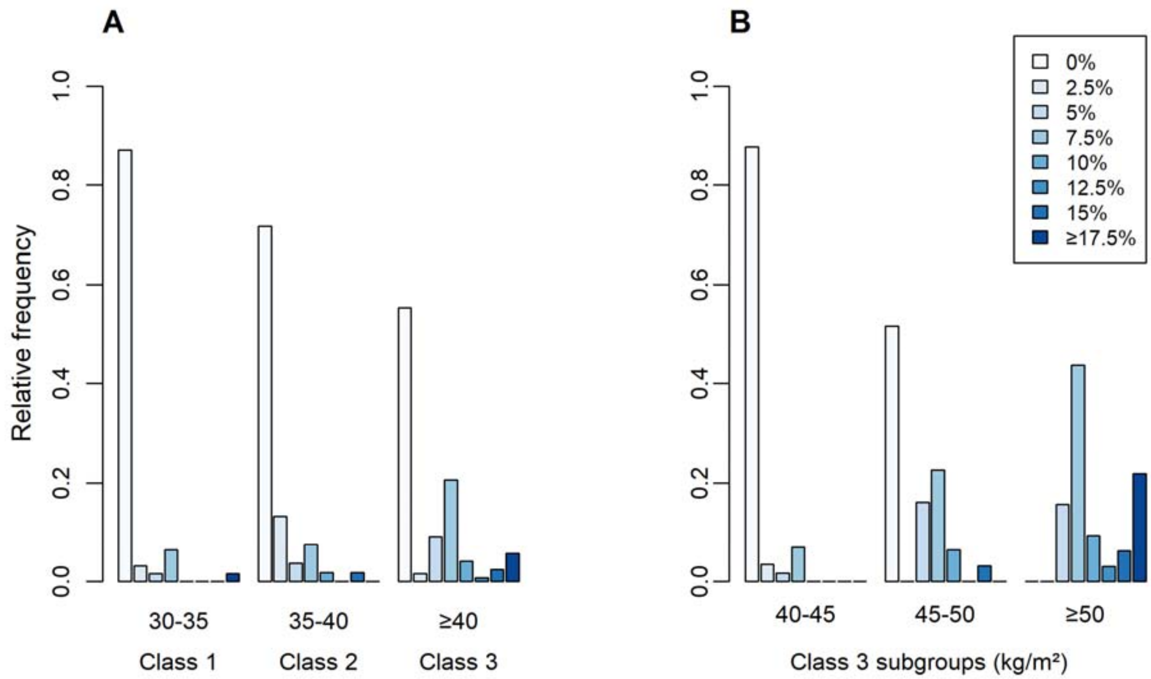
Absolute frequency of patients per state of residence in the USA and Canada.

Figure 3. Pairwise non-linear relationships between body mass index, preoperative SpO2, and preoperative atelectasis percentage coverage on chest CT scan.



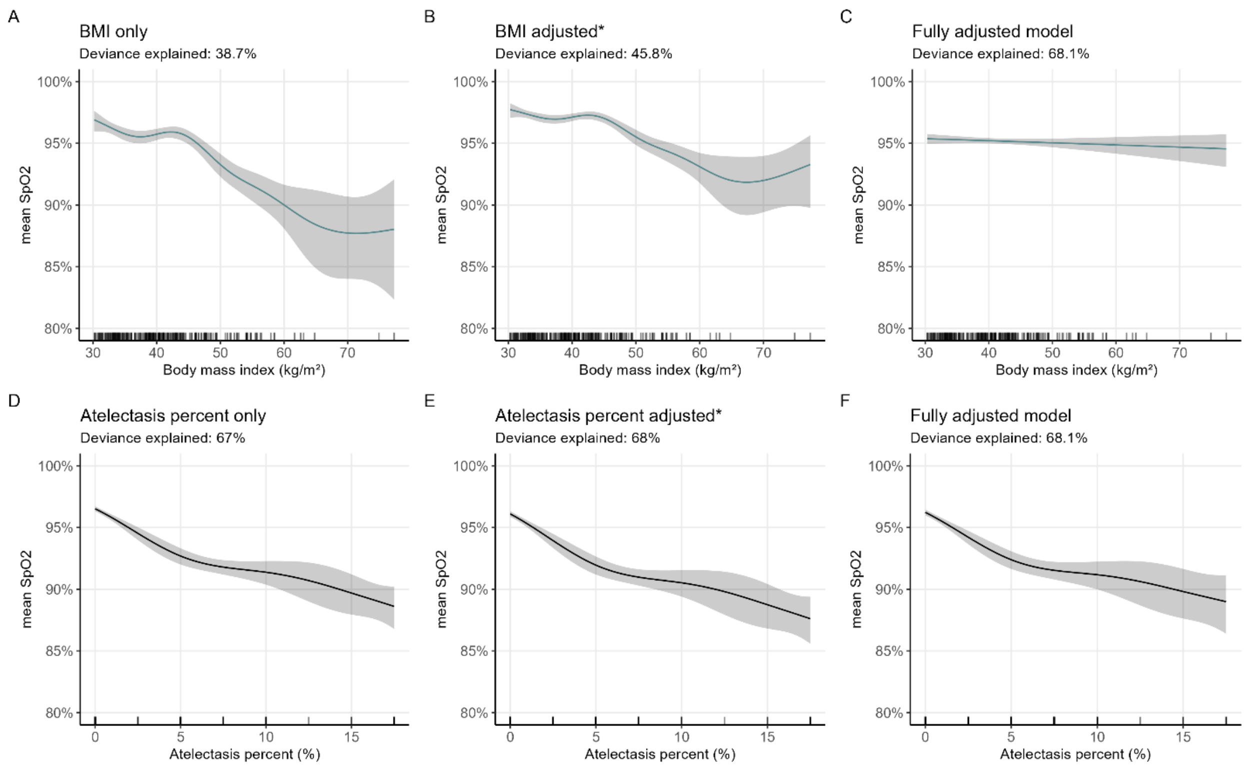
Dots represent individual patient observations. Curves represent the fitted smoothed non-linear relationship. The shaded area corresponds to the 95% confidence interval. **A)** Atelectasis percentage as a function of BMI. **B)** SpO2 as a function of BMI. **C)** SpO2 as a function of atelectasis percentage.

Figure 4. Atelectasis percentage on chest CT by obesity category.



Relative frequency of atelectasis percentage coverage by BMI categories. **A)** World Health Organization obesity class categories. **B)** Class 3 obesity subgroups.

Figure 5. Partial effect of body mass index (BMI) and chest CT atelectasis percent coverage on the mean SpO2 during the preoperative assessment.



Solid lines represent the partial effect on mean SpO2 for increasing BMI (blue green) and atelectasis percent coverage on mean SpO2 (black), with 95% confidence intervals (shaded area). **A)** Model including only a smoothed term for BMI ($p<0.001$). **B)** Model including a smoothed term for BMI ($p<0.001$) adjusted for confounders*. **C)** Model including a smoothed term for BMI ($p=0.4$) adjusted for confounders* plus atelectasis percentage. **D)** Model including only a smoothed term for atelectasis percentage ($p<0.001$). **E)** Model including a smoothed term for atelectasis percentage ($p<0.001$) and adjusted for confounders*. **F)** Model including a smoothed term for atelectasis percentage ($p<0.001$) and adjusted for confounders* plus BMI.

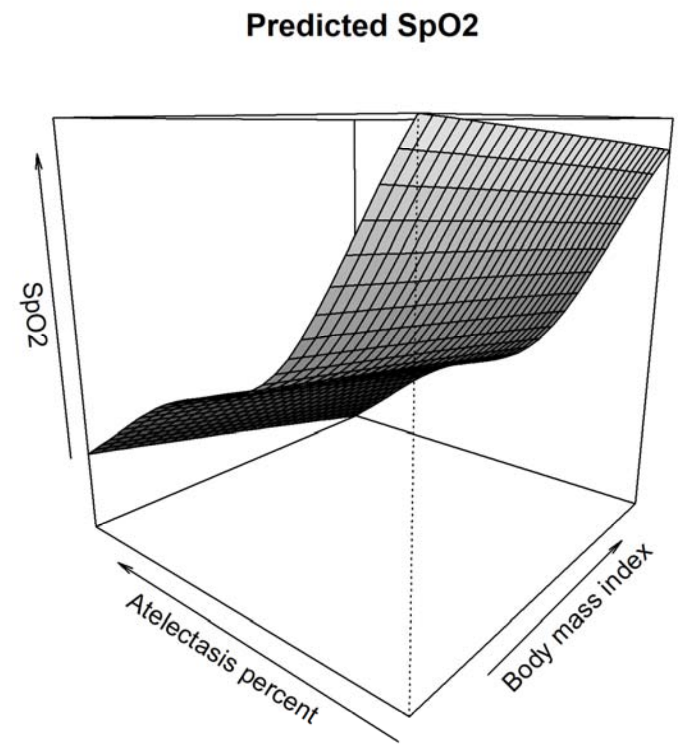
*Adjusted for age, sex, obstructive sleep apnea, mean altitude at the place of residence, and hemoglobin.

Figure 6. Predicted and measured SpO2 values by body mass index (BMI) and atelectasis percentage on chest CT scan.

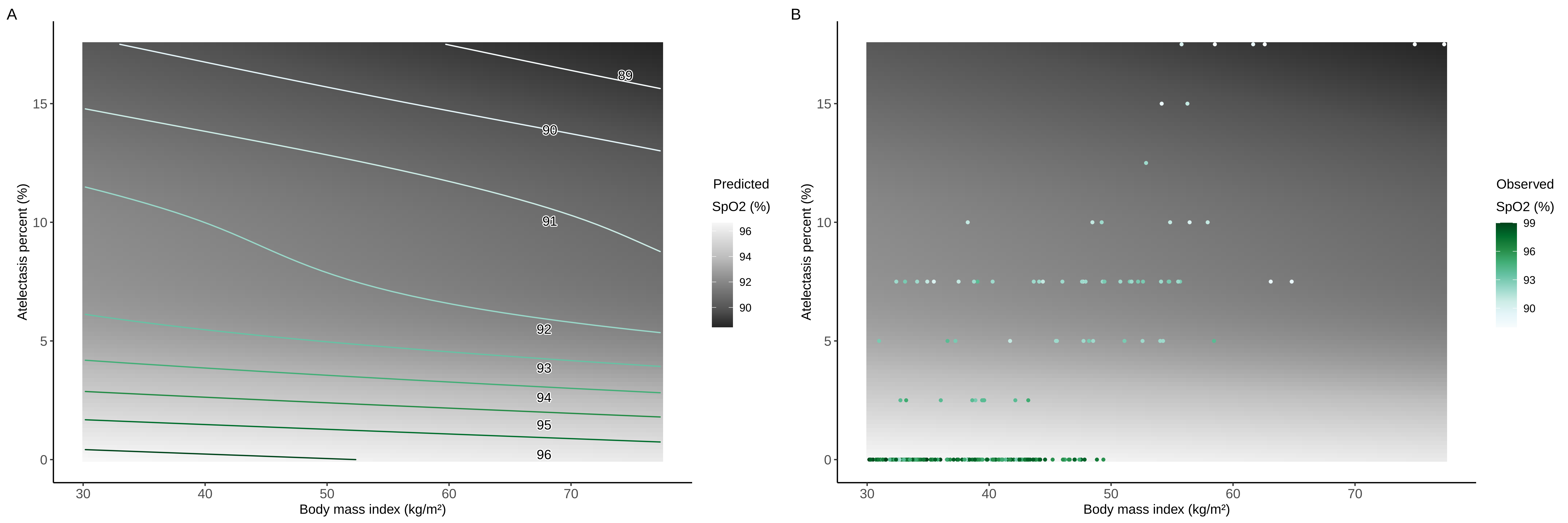
Insert figure here

A) Predicted SpO2. Curved lines correspond to SpO2 values that are predicted by BMI and atelectasis percentage. The background grid on a gray scale corresponds to predicted values of SpO2 for every possible combination of atelectasis percentage and BMI, adjusted for age, sex, obstructive sleep apnea, hemoglobin, and mean altitude at the state of residence. **B)** Observed SpO2. Every dot corresponds to an individual patient observation located at the exact BMI and atelectasis percentage measured, colored according to the observed SpO2 value

Figure 7. Preoperative SpO2 predictions for every combination of atelectasis percentage coverage on chest CT and BMI.



The grid on a gray scale corresponds to predicted values of SpO2 for every possible combination of atelectasis percentage and BMI, adjusted for age, sex, obstructive sleep apnea, hemoglobin, and mean altitude at the state of residence.



A
B
89
90
91
92
93
94
95
96
Atelectasis percent (%)
Body mass index (kg/m²)
Predicted
SpO2 (%)
Observed
SpO2 (%)