The inverse association between blood pressure and pulse oximetry accuracy: An observational study in patients with suspected or confirmed Covid-19 infection

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KEY MESSAGES

WHAT IS ALREADY KNOWN ON THIS TOPIC

- Although the UK Medical and Healthcare Regulatory Agency cautions on the impact of poor peripheral blood circulation reducing the signal of pulse oximeters in hypovolaemia, there are no data on possible measurement error of oxygen saturation measurements from pulse oximetry across a range of blood pressures.

WHAT THIS STUDY ADDS

- Throughout the range of systolic blood pressures of 80 to 180mmHg, there was an inverse association with the accuracy of pulse oximeters on measuring oxygen saturations. Similar associations were observed for diastolic blood pressure and heart rate.
- The accuracy of pulse oximeters decreases with lower systolic and diastolic blood pressures with a linear relationship, with a tendency to provide overestimates of the true blood oxygen saturation.

ABSTRACT

Background: Pulse oximeters are a standard non-invasive tool to measure blood oxygen levels, and are used in multiple health care settings. It is important to understand factors affecting their accuracy, to be able to use them optimally and safely. This analysis aimed to explore the association of the measurement error of pulse oximeters with systolic blood pressure, diastolic blood pressure and heart rate within ranges of values commonly observed in clinical practice.

Methods: The study design was a retrospective observational study of all patients admitted to a large teaching hospital with suspected or confirmed Covid-19 infection from February 2020 to December 2021. Data on systolic and diastolic blood pressure and heart rate levels were available from the same time period as the pulse oximetry measurements.

Results: Data were available for 3420 patients with 5927 observations of blood oxygen saturations as measured by pulse oximetry and arterial blood gas sampling within 30 minutes. The difference in oxygen saturation using the paired pulse oximetry and arterial oxygen saturation difference measurements was inversely associated with systolic blood pressure, increasing by 0.02% with each mmHg decrease in systolic blood pressure (95% confidence interval; CI: 0.00 to 0.03%) over a range of 80mmHg to 180mmHg. Inverse associations were also observed the error for oxygen saturation measured by pulse oximetry and both diastolic blood pressure (+0.03%; 95% CI: 0.00 to 0.05%) and heart rate (+0.04%; 95% CI: 0.02 to 0.06% for each unit decrease in the heart rate).

Conclusions: Care needs to be taken in interpreting pulse oximetry measurements in patients with lower systolic and diastolic blood pressures, and heart rates, as oxygen saturation is overestimated as blood pressure and heart rate decrease. Confirmation of the oxygen saturation with an arterial blood gas may be appropriate in some clinical scenarios.

Introduction

Over recent decades pulse oximetry has become a very common tool in monitoring patients and informing clinical decision-making. The pulse oximeter provides regular non-invasive measurements of blood oxygenation and is used in a wide range of clinical settings ranging from hospital in-patients, clinical care outside hospital, and also by patients for self-monitoring in the home.

Pulse oximetry uses the difference in the detection of two separate infra-red light wave frequencies through translucent perfused tissue, due to differential light absorption by oxygenated or deoxygenated haemoglobin. The ratio of these differences can be used to calculate blood oxygen saturations in a non-invasive manner [1]. As such, there is a cardio-vascular component to the generation of this signal, as differences in the rate of blood flow to the capillary bed may modify the equilibriums of both oxygen delivery and extraction by metabolically active tissue, and hence the measurement of oxygen saturation generated by the pulse oximeters. The UK Medicine and Healthcare Products Regulatory Agency has identified 'low perfusion' as a factor that may modify the accuracy of pulse oximeters in measuring blood oxygen saturations [2], but no studies have explored how this association may be modified within the normal range of blood pressure measurements in acutely unwell patients. It is important that the evidence-base for the routine use of pulse oximeters as non-invasive measurements of oxygen saturation is well understood, as they contribute to early warning scores that may trigger clinical review and escalation [3], as well as having the large benefit for both patients and staff of minimising the use of arterial blood gases.

We used data from a cohort of patients with Covid-19 infection who were admitted to a large UK based teaching hospital to explore the differential in blood oxygen levels as measured by pulse oximetry and arterial blood gases and how this changes with systolic blood pressure, diastolic blood pressure and heart rate, within the ranges of values that are commonly observed in clinical scenarios.

Methods

The study design was a retrospective cohort study using routinely collected electronic data for all consecutive patients admitted to Nottingham University Hospitals NHS trust between 1 February 2020 and 31 December 2021 with either suspected or confirmed Covid-19 infection. Oxygen saturations from ward oximetry measurements are recorded routinely electronically using NerveCentre (http://nervecentresoftware.com/), and arterial blood gas measurements are automatically uploaded to the hospital enterprise data warehouse.

Pulse oximetry measurements with a paired blood gas measurement within a 30-minute time window were used as the primary outcome, with a sensitivity analysis restricting to a 10 minute interval. The intervals allow time for the travel between ward where the patient was situated to the blood gas analyser followed by the processing of the sample. Oximetry measurements within Intensive Care Units (ICUs) were not included in this study as these were not available electronically. Complete case only analyses were performed on only those patients with arterial blood gases available, and multiple paired arterial blood gases and pulse oximetry measurements were allowed where available per patient. Patients without arterial blood gases being taken were likely to be too different from this complete case cohort, and therefore imputation would have been invalid for this study.

Mean and standard deviation for differences between pulse oximetry and arterial blood gas oxygen saturation were stratified by patient demographics recorded at baseline admission. Paired pulse oximetry and arterial oxygenation saturation measurements were matched with cardiovascular parameters taken during the same time period as the pulse oximetry. As the aim of the study was to study the accuracy of the pulse oximetry measurements across the range of systolic and diastolic blood pressures observed in routine clinical practice, the range of interest was 80 to 180mmHg for systolic blood pressure, 50 to 110mmHg for diastolic blood pressure and 50 to 120 beats per minute for heart rate.

The pulse oximetry arterial oxygen saturation difference (pulse oximetry minus arterial blood gas oxygen saturation) from paired blood samples was calculated and this was the outcome measure of interest. This difference was then plotted against each cardiovascular parameter as a continuous variable to visually assess the shape of the relationship, and linearity checked by comparing the fit of the linear model against a categorical model that used quartiles of the cardiovascular exposures and a likelihood ratio test to compare the fit of the models. As the associations were linear ($p = 0.82$ for systolic blood pressure, $p = 0.86$ for diastolic blood pressure, $p = 0.20$ for heart rate; bootstrapped general likelihood ratio tests), linear models were used for the main statistical analysis.

Mixed effect models of the association between the difference between pulse oximetry and blood gas oxygen saturation with each cardiovascular parameter were fitted using a random intercept for each patient to allow for repeated measurements. The continuous cardiovascular parameters were fitted as a linear variable. These mixed effect models were then adjusted sequentially for age, sex, and BMI, smoking and ethnicity (fixed effects) and any covariate that altered the association

between each cardiovascular parameter and the difference in saturation by more than 10% was considered a confounding factor and added to the final model. The analysis used version 4.1.2 of the R programming language (R project for Statistical Computing; R Foundation) with the lme4 package. A smoothing term was fitted using a general additive model with cubic splines (k = 10) using the mgcv package in R [4] with ggplot2 [5] to provide a graphical representation of the data.

Approval for this work was granted via an NUH Clinical Effectiveness Team audit (reference: reference: 21-294C) and IRAS (REC: 20/WM/0142, project ID: 282490, amendment No. SA02 20/07/21).

Results

Data were available for 3420 eligible patients (Figure 1), with 5927 paired oxygen saturations recorded within 30 minutes of an arterial blood gas (Table 1). A median of 2 paired measurements (IQR 1 to 3 measurements) were observed per patient with a median time difference of 13 minutes (IQR 5-20 minutes). Of these paired saturation measurements 5864 had systolic blood pressure measurements of which 318 were excluded as being outside the range of 80 mmHg to 180 mmHg; 5864 had diastolic blood pressure measurements of which 274 were excluded as less than 50 mmHg or higher than 110 mmHg; and 5924 had heart rate measurements of which 722 were excluded as being less than 50 beats per minute and higher than 120 beats per minute.

The association between the difference in oxygen saturation using the paired pulse oximetry and arterial oxygen saturation difference measurements with each cardiovascular parameter is presented in Figure 2. Age, sex, ethnicity, smoking and body mass index were all separately added to the model, but these were not confounding factors and therefore omitted from the final statistical model.

In the final analysis, the difference in oxygen saturation using the paired pulse oximetry and arterial oxygen saturation difference measurements was inversely associated with systolic blood pressure, increasing by 0.02% with each mmHg decrease in systolic blood pressure (95% confidence interval; CI: 0.00 to 0.03%); inversely associated with diastolic blood pressure increasing by 0.03% with each mmHg decrease in diastolic blood pressure (95% CI: 0.00 to 0.05%); and inversely associated with heart rate, increasing by 0.04% (95% CI: 0.02 to 0.06%) for each beat per minute decrease in the heart rate.

A sensitivity analysis restricting the univariate analysis to samples with a 10 minute window between pulse oximetry and arterial blood gas measurement (Table 2) shows similar qualitative associations as in the primary analysis that used a 30 minute window between the two measurements of oxygen saturation.

Discussion

This analysis of the association between the accuracy of oxygen saturation as measured by pulse oximetry within the different ranges of systolic and diastolic blood pressure and heart rates commonly observed in clinical practice demonstrates that there is an inverse linear association between the accuracy of pulse oximeters measurements of oxygen saturations and all three cardiovascular exposures of systolic blood pressure, diastolic blood pressure and heart rate. This means that as blood pressure or heart rate fell, the inaccuracy of the oxygen saturations increased.

The strengths of the analysis are that it includes data from a group of patients with a range of severity of respiratory failure with paired oxygen saturation measurements from both pulse oximetry and arterial blood gases, along with corresponding values for blood pressure that extended over a wide range of values. All available eligible data were analysed, thus minimising selection bias. We used demographic data on the study population to exclude the possibility that our analysis was confounded by age, sex, ethnic group [6], body mass index or cigarette smoking status. One limitation of the analysis is that used an opportunistic dataset of patients with available paired oxygen saturations that will have been collected as part of the process of delivering normal clinical care as opposed to a random sampling approach which would represent the ideal study design. The sensitivity analysis demonstrated little qualitative change in the signals observed in the main statistical analysis, suggesting that the timing between the two paired measurements of oxygen saturation does not explain the associations we observed. These data are likely to be generalisable to similar populations and institutions elsewhere.

The size of the associations in measurement error of oxygen saturation by pulse oximetry observed across the range of cardiovascular measurements that are commonly observed in clinical practice is worth consideration. For a systolic blood pressure range of 80 to 180mmHg, a point estimate of -0.02 would lead to a difference of 2% measurement error across this range of blood pressures, while the comparable values for the diastolic blood pressure range we have studied of 50 to 110mmHg would be 1.8%, and over the heart rate range of 50 to 120 beats per minute would be 2.8%. In terms of smaller differences that are observed clinically, each 10-mmHg

fall in systolic blood pressure was associated with an adjusted 0.16% increase in pulse oximetry error, each 10-mmHg fall in diastolic pressure with 0.27% increased error, and each 10 beat per minute fall in heart rate with 0.40% increased error. Therefore, a drop systolic blood pressure from 135 to 110mmHg for the same arterial oxygen saturation (study mean 89.4%) would be associated with a misleading increase in the average measured pulse oximetry level from 92.6% to 93.0%.

The impact of manipulating systolic blood pressure of pulse oximetry measurements of oxygen saturation has been studied in 25 mechanically ventilated patients on an intensive care unit in 2003. Decreasing the arterial flow using a blood pressure cuff while measuring oxygen saturation using both an arterial catheter and pulse oximeter suggested that pulse oximetry was reliable if the systolic blood pressure was greater than 80mmHg, although below that value the pulse oximeter was less reliable giving oxygen saturation measurements higher than reality [7]. It is worth noting that this population is very different to the one in our analysis, having a mean arterial blood gas measurement of oxygehn saturation of 97.8%. A very different study population was also used to explore the impact of a non-invasive blood pressure measurement using a cuff on pulse oximetry. This suggested that oxygen saturation as measured by pulse oximeters increases by a mean value of 2.9% during the process of recording blood pressure [8], and hence highlights the importance of taking pulse oximetry measurements separately to measuring blood pressure.

It is important to consider biological plausibility in considering why we observed that lower systolic and diastolic blood pressure and heart rates are associated with higher levels of measurement error from pulse oximeters oxygen saturation measurements in a linear relationship. It has been recognised that patients with sepsis and low blood pressure have poor peripheral perfusion, and that this may impair the signal integrity through the translucent tissue used by the pulse oximeter. A retrospective cohort study of 88 patients with severe sepsis and septic shock reported a mean measurement error of +2.75% for pulse oximetry readings [9], which is of a similar magnitude to the errors we observed in the hypotensive patients in our sample (Figure 2). However, these septic patients tend to have faster pulse rates as a consequence of the autonomic nervous systemic responses, which is not consistent with our analysis. Using routinely collected cardiovascular measurements, our data provide no mechanistic guidance to the interpretation of these issues, and it is possible that there is more than one process contributing to the associations observed in our data.

One possible unifying hypothesis may be the interaction between capillary blood flow and local oxygen demand and extraction; this interaction could be affected by pulse wave velocity through

the nail capillary bed. Pulse wave velocity will be modified by both blood pressure and pulse volumes and rates.

In conclusion, our data demonstrate that the measurement error of pulse oximeters is inversely associated with both systolic and diastolic blood pressure, as well as with heart rate. This may have significant implications in the assessment of patients and affect the interpretation of early warning scores. Clinicians using pulse oximeters need to be mindful of this and consider using arterial blood gas measurements of oxygen saturation when precise measurements are clinically indicated.

Contributors

AF and DS developed the hypothesis. JW, TC, CC, IJ, SB, S H-P, SC developed the database. CC did the statistical analysis. The first draft of the manuscript was written by AF and edited by all authors.

Declaration of interests

The authors have no conflicts of interest.

Data sharing

These data are not available for sharing as a consequence of UK law.

Patient and public involvement

Neither patients nor the public were involved in any aspect of this study.

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Table 1. Study population, with the mean difference in pulse oximetry and arterial blood gas oxygen saturations in a 30 minute window for paired samples

	Number of paired samples	Number of unique patients	Mean O_2 saturation Difference **(pulse oximetry – arterial blood gas)(%)**	Standard deviation
Overall	5927	3420	3.0	13
Age: <60 years	1819	1015	3.3	13
60-80 years	2915	1579	2.7	13
>80 years	1193	826	3.1	14
Male	3334	1929	3.1	13
Female	2593	1491	2.8	13
BMI: missing	172	128	8.6	18
< 21	758	388	3.0	14
21-30	3003	1808	3.2	13
>30	1994	1096	2.3	12
Smoking: not reported	4603	2735	2.7	13
Current Smoker	1324	685	3.9	14
Ethnicity: Asian	269	153	5.3	16
Black	200	124	5.2	15
Other	132	73	4.2	12
White	4330	2487	2.7	13
Not recorded	996	583	2.9	12
	Number of paired samples	Number of unique patients	Mean measurement after extremes excluded	Standard deviation
Systolic Blood Pressure (mmHg)	5546	3260	127	22
Diastolic Blood Pressure (mmHg)	5590	3278	71	13
Heart Rate (beats per minute)	5202	3128	91	16

Figure 1. Flowchart of patients included in the study analyses with paired samples with clinical observations within the study ranges.

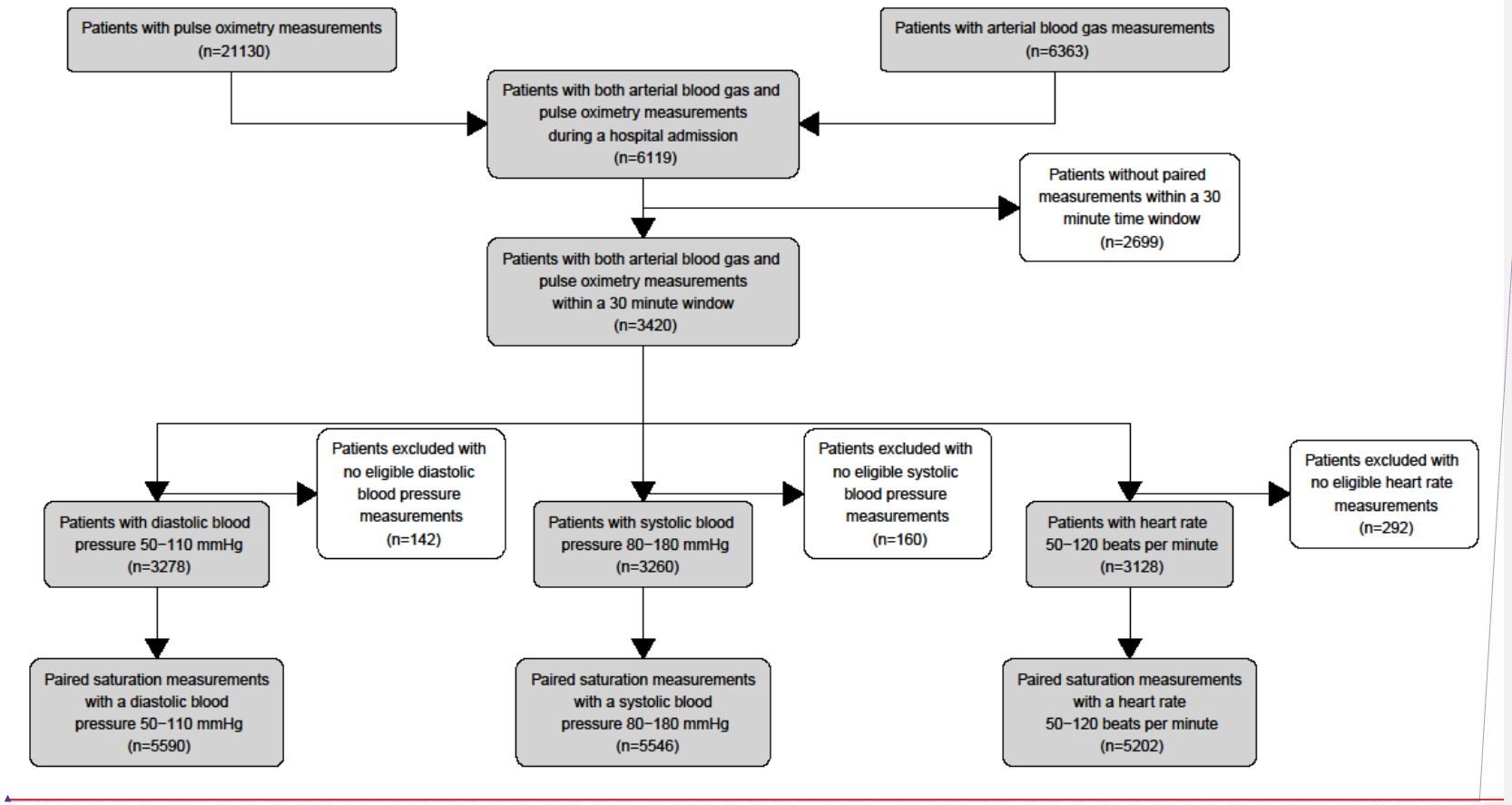

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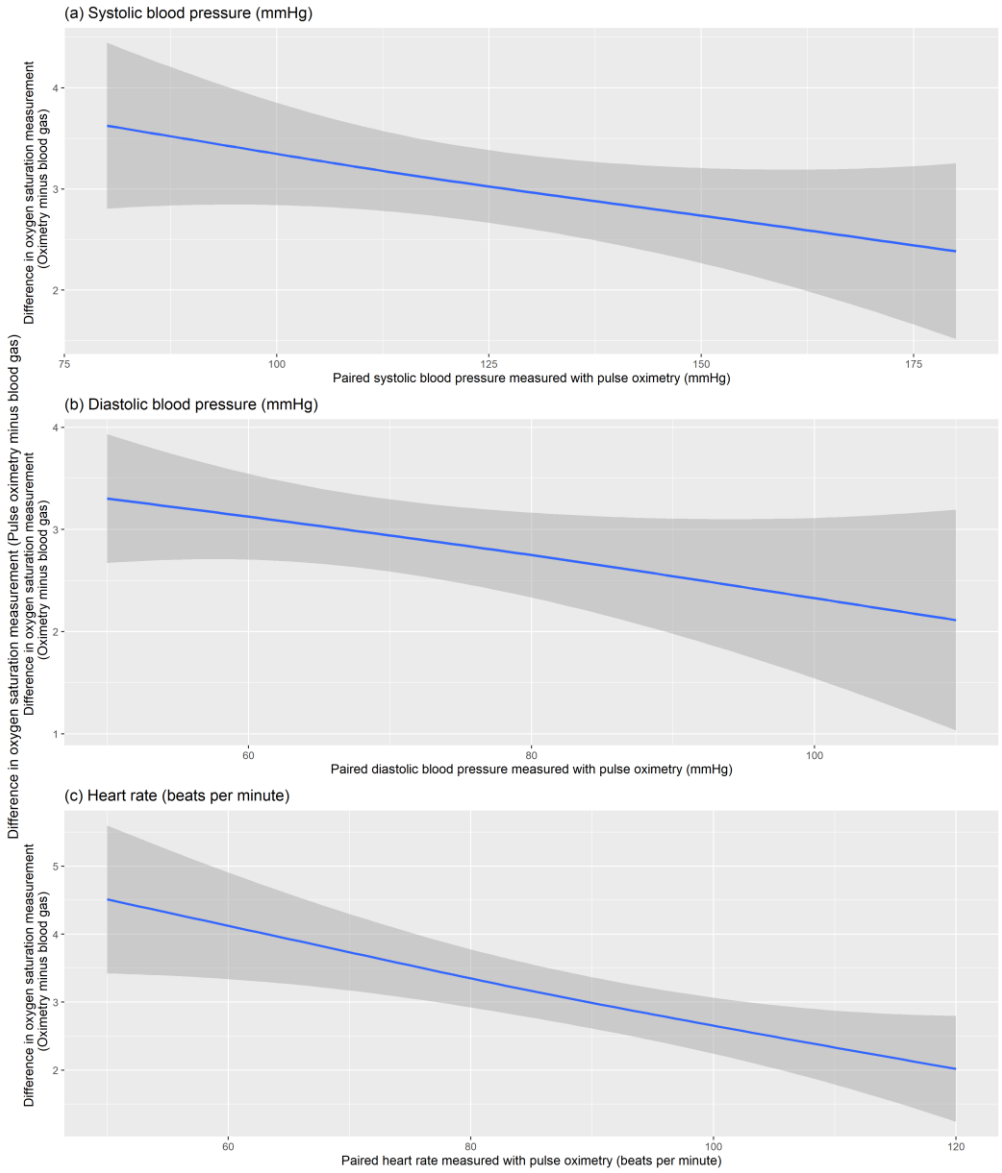
Figure 2. Paired pulse oximetry and arterial oxygen saturation differences versus cardiovascular parameters (a) systolic blood pressure (mmHg), (b) diastolic blood pressure (mmHg), (c) heart rate (beats per minute)



Grey band indicates 95% confidence interval of the estimated smooth mean

Table 2. Three mixed effects linear models of the difference in oxygen saturations as measured by paired pulse oximetry and arterial blood gas and their association with systolic blood pressure, diastolic blood pressure and heart rate

3 univariate models (30 minute window)			Pulse oximetry - Arterial O2 saturation difference	
	Number of patients	Number of observations	Estimate (95% CI)	p value
Systolic Blood Pressure (mmHg)	3260	5546	-0.02 (-0.03 to-0.00)	0.043
Diastolic Blood Pressure (mmHg)	3278	5590	-0.03 (-0.05 to -0.00)	0.047
Heart Rate (Beats per minute)	3128	5202	-0.04 (-0.06 to -0.02)	<0.001
3 univariate models (10 minute window for sensitivity analysis)				
		Number of observations	Estimates (95% CI)	p value
Systolic Blood Pressure (mmHg)	1629	2157	-0.03 (-0.06 to -0.00)	0.028
Diastolic Blood Pressure (mmHg)	1652	2186	-0.03 (-0.08 to +0.01)	0.168
Heart Rate (Beats per minute)	1542	2015	-0.04 (-0.07 to 0.00)	0.058

95% CI = 95% confidence intervals