**Article:**

Martin, GP, Curzen, N, Goodwin, AT et al. (8 more authors) (2021) Indirect Impact of the COVID-19 Pandemic on Activity and Outcomes of Transcatheter and Surgical Treatment of Aortic Stenosis in England. Circulation: Cardiovascular Interventions, 14 (5). e010413. ISSN 1941-7640

https://doi.org/10.1161/CIRCINTERVENTIONS.120.010413

# Indirect Impact of the COVID-19 Pandemic on Activity and Outcomes of Transcatheter and Surgical Treatment of Aortic Stenosis in England

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**Subject Terms:** Aortic Valve Replacement/ Transcatheter Aortic Valve Implantation

**Running Title:** Indirect Impact of COVID-19 on AVR in England

**Word Count**: 4052

**Funding:** None

**Competing Interest:** None

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## Abstract

### Background

Aortic stenosis requires timely treatment with either surgical aortic valve replacement (SAVR) or transcatheter aortic valve replacement (TAVR). This study aimed to investigate the indirect impact of COVID-19 on national SAVR and TAVR activity and outcomes.

### Methods

The UK TAVR Registry and the National Adult Cardiac Surgery Audit were used to identify all TAVR and SAVR procedures in England, between January 2017 and November 2020. The number of isolated AVR, AVR+coronary artery bypass graft (CABG) surgery, AVR+other surgery and TAVR procedures per month was calculated. Separate negative binomial regression models were fit to monthly procedural counts, with functions of time as covariates, to estimate the expected change in activity during COVID-19.

### Results

We included 15142 TAVR cases, 13357 isolated AVR cases, 8550 AVR+CABG cases, and 6773 AVR+Other cases. Prior to March 2020 (UK lockdown), monthly TAVR activity was rising, with a slight decrease in SAVR activity during 2019. We observed a rapid and significant drop in TAVR and SAVR activity during the COVID-19 pandemic, especially for elective cases. Cumulatively, over the period March to November 2020, we estimated an expected 4989 (95% CI 4020, 5959) cases of aortic stenosis who have not received treatment.

**Conclusion**

This study has demonstrated a significant decrease in TAVR and SAVR activity in England following the COVID-19 outbreak. This situation should be monitored closely, to ensure that monthly activity rapidly returns to expected levels. There is potential for significant backlog in the near-to-medium term, and potential for increased mortality in this population.

**Keywords**

aortic valve replacement; aortic stenosis; COVID-19; outcomes; survival

## Abbreviations

AVR = aortic valve replacement

CABG = coronary artery bypass graft

COVID-19 = coronavirus disease 2019

CPM = Clinical Prediction Model

NACSA = National Adult Cardiac Surgery Audit

NHS = National Health Service

NICOR = National Institute for Cardiovascular Outcomes Research

SAVR = surgical aortic valve replacement

TAVR = transcatheter aortic valve replacement

## What is Known

- The COVID-19 pandemic has resulted in widespread changes in operational activity of health services

- The impact, from a national perspective, of COVID-19 on activity and outcomes of surgical and transcatheter aortic valve replacement is unknown.

## What the Study Adds

- We show that there has been a significant decrease in TAVR and SAVR activity during COVID-19.

- Cumulatively, over the period March to November 2020, we estimated an expected 4989 (95% CI 4020, 5959) cases of severe aortic stenosis who have not received treatment

- There is potential for significant backlog in the near-to-medium term, and potential for increased mortality in this population

## Introduction

The coronavirus disease 2019 (COVID-19) [1] presents a global health crisis and has resulted in significant excess mortality [2, 3]. Many countries have imposed restrictions based on social distancing and movement (i.e. 'lockdowns'), with the aim of mitigating and managing the spread of COVID-19. A UK-wide lockdown was initiated on 23rd March 2020, with a second national lockdown imposed in England at beginning of November 2020.

The lockdown restrictions, and the pandemic, have resulted in widespread changes in operational activity of health services. Many healthcare systems have faced significant pressure on services, particularly within critical care [4,5]. This has necessitated the need for restructuring of resources to meet those needs. Simultaneously, COVID-19 has influenced the ways in which people interact with health services. Previous studies have illustrated that there have been decreases in admissions and diagnosis of health conditions including acute coronary syndromes [6–10], stroke [11,12] and cancer [13]. It is crucial to understand the consequences of this on public health and on future planning, especially for conditions requiring timely healthcare interventions, such as severe symptomatic aortic stenosis.

Aortic stenosis is the most common valvular heart disease where the onset of symptoms is associated with rapid deterioration. Thus, timely treatment by either surgical aortic valve replacement (SAVR) or transcatheter aortic valve replacement (TAVR) is key. SAVR has been the default treatment strategy for symptomatic aortic stenosis, although TAVR has emerged as an effective option across operative-risk strata [14–18]. While the activity and outcomes for aortic valve replacements have been studied in historic cohorts [19], there is a lack of data in contemporary practice, especially surrounding the impact of COVID-19 from a national perspective. A survey of members of the European Association of Percutaneous Coronary Intervention indicated that 51% had reported cessation of TAVR, and 89% reported at least decreased volumes [20]. Furthermore, early in the COVID-19 pandemic, preliminary work characterized patients whose SAVR/TAVR procedures were deferred and their outcomes [21]. The impact of COVID-19 on aortic valve replacement (AVR) activity from a national perspective is unclear.

The aim of this study was to investigate the activity and post-procedural outcomes of all AVRs in contemporary practice, from a national perspective, and to investigate the indirect impact of COVID-19 on activity and outcomes. The intention is to estimate the effect of reduced activity on projected backlog of cases.

## Methods

Because of the sensitive nature of the data collected for this study, requests to access the dataset from qualified researchers trained in human subject confidentiality protocols may be sent to the National Institute for Cardiovascular Outcomes Research. The analytical code used for this study is available upon reasonable request, for the purposes of reproducibility.

**UK TAVR Registry**

The UK TAVR registry collects data for every TAVR procedure undertaken within the UK [22]. Data collection occurs prospectively at each contributing centre and is submitted to the National Institute for Cardiovascular Outcomes Research (NICOR). Data collection is mandated for all centres licensed to undertake TAVR procedures. We extracted data from NICOR on all TAVR procedures undertaken in England between January 2017, and November 2020.

## UK National Adult Cardiac Surgery Audit

The NICOR National Adult Cardiac Surgery Audit (NACSA) contains data on all major heart operations undertaken in the UK [23]. Each centre is responsible for prospective data collection and submission of this to NICOR. We extracted all surgical aortic valve replacements (SAVRs) undertaken in England between January 2017 and November 2020. We defined SAVR to be any procedure recorded as being a valve replacement, where the aortic valve implant type was recorded as being mechanical, biological, homograft or autograft replacement. We further categorised SAVRs into (i) isolated AVR, (ii) AVR with coronary artery bypass graft (AVR+CABG), or (iii) AVR with other surgery (AVR+Other). Here, "other surgery" was any mitral valve procedure, tricuspid valve procedure, pulmonary valve procedure, major aortic surgery, or other cardiothoracic procedures.

## Data Flows during COVID-19

The British Cardiovascular Intervention Society and the Society for Cardiothoracic Surgery have made significant efforts to maintain data flows during COVID-19. NICOR have provided weekly uploads of data throughout the pandemic. Thus, at the time of analysis, we had updated data until end of November 2020. Nonetheless, to reflect the possibility that some individual centres might have stopped submitting data to NICOR during the pandemic or have delays in submitting data, we define a set of "rapid-data-submitting" centres to be those that submitted at least one case (of either TAVR and/or SAVR) in November 2020 (latest month of our analysis). We perform sensitivity analysis (of the analyses described below) on this subset of centres. Similarly, we also considered sensitivity analyses focusing on the subset of centres that submitted at least one case (of either TAVR and/or SAVR) across every month in 2020.

## Outcomes

The primary outcome was presentation and treatment of aortic stenosis with AVR. As secondary outcomes, we considered 30-day mortality and post-procedural length of stay. Mortality information was provided by linking the UK TAVR registry and the NACSA with the office for national statistics civil registration of deaths dataset. Linkage was made based on each patient's NHS number. We defined post-procedural length of stay to be the number of days between the TAVR/SAVR procedure and hospital discharge.

## Statistical Analysis

We excluded any cases in which the age of the patient at the time of the procedure was under 18 years. Additionally, we excluded cases where the NHS number was missing or with missing procedure urgency. Finally, we removed any duplicate cases in either datasets, identified using NHS number, age, sex, admission date, and date/time of the procedure.

In all analyses, we stratified by procedure type (i.e. isolated AVR, AVR+CABG, AVR+Other or TAVR). We made no formal comparisons between these procedural types, since there are several confounding factors surrounding the decision-making between TAVR/SAVR (many of which are not captured in the dataset).

Cases performed between 1st February and 30th November 2020 were defined into a "during COVID-19" group, with any case performed in these same months across the preceding years being defined into a "pre-COVID-19" group. The 1st February 2020 was chosen since the first COVID-19 case reported in England was on 28th January 2020.

We report patient baseline characteristics for each procedure type, as whole cohorts and across the "during COVID-19" and "pre-COVID-19" groups. Continuous variables were reported using the mean with standard deviations. Categorical variables were presented as frequencies of occurrence with relative percentages. Comparisons between continuous variables were made using t-tests/ANOVA, while comparisons between categorical variables were made using the chi-squared test. Predicted procedural risk was quantified using the UK TAVR clinical prediction model (CPM) [24] for all TAVR procedures, and the Logistic EuroSCORE CPM [25] for all SAVR procedures. For the purposes of calculating the risk predictions, missing values in any predictor variables were set to "risk factor absent", representing a plausible missingness process in the registries [19,24,26].

The number of procedures per month was calculated across the full study period, separately for each procedure type. Percentage increase or decrease in monthly activity was calculated for each "during COVID-19" month, against the respective "pre-COVID-19" months. We fitted negative binomial models to the number of TAVR/SAVR procedures performed per month between January 2017 and December 2019, using time as covariates, which was modelled continuously to capture trends in outcome and as a factor variable of month to capture seasonality. This model was used to estimate the expected number of TAVR/SAVR procedures per month in 2020, to compare with the observed activity level.

For each of the four procedural types, we compared mortality up to 30-days, across the "during COVID-19" and "pre-COVID-19" groups by fitting a Cox proportional hazards model, with the COVID-19 group as a covariate, adjusting for the linear predictor of either the UK TAVR prediction model [24] or the Logistic EuroSCORE [25], as appropriate. Differences in post-procedural length of stay between the "during COVID-19" and "pre-COVID-19" groups were also investigated by fitting a Cox proportional hazards model. The proportional hazards assumption was checked by examining the Schoenfeld residuals.

All analyses were performed using R version 4.0.0 [27], along with the tidyverse suite of packages [28], and the survival package [29,30].

**Ethics Approval**

In the efforts to understand the impact of the COVID-19 pandemic on cardiology services, extraordinary government permission was obtained to evaluate anonymised records from these databases through an agreement with NHS Digital. This work was endorsed by: (A) Scientific Advisory Group for Emergencies (a body responsible for ensuring timely and coordinated scientific advice is made available to decision makers to support UK cross-government decisions in the Cabinet Office Briefing Room), (B) NHS England, a public body of the Department of Health and Social Care and (C) NHS Improvement, responsible for overseeing NHS trusts. NICOR, which houses the British Cardiovascular Intervention Society registry, has support under section 251 of the NHS Act 2006 to use patient information for approved medical research without informed consent. For this rapid NHS evaluation, health data analysis was enabled under Section 254 of the Health and Social Care Act 2012.

## Results

The UK TAVR registry included 15741 procedures across the study period, of which we included 15142. The NACSA registry included 108881 cases over the study period, of which we included 28680 SAVR procedures, comprised of 13357 (46.6%) isolated AVR, 8550 (29.8%) AVR+CABG, and 6773 (23.6%) AVR+Other cases.

**Table 1** shows the baseline characteristics of each procedural group. The mean age of isolated AVR, AVR+CABG, AVR+Other and TAVR was 67.7, 72.2, 62.9 and 81.3, respectively. Across all surgical groups, the majority of cases were male. The mean Logistic EuroSCORE was 7.50%, 10.7% and 14.1% for isolated AVR, AVR+CABG and AVR+Other, respectively, while the mean UK TAVR prediction model was 3.11% ( **Table 1**).

**TAVR and SAVR Activity**

There has been an increase in the number of TAVR procedures performed per month between January 2017 and December 2019, with the majority of procedures being elective ( **Figure 1**). While the number of monthly AVR+CABG and AVR+Other procedures remained relatively stable pre-2020, there was a slight decrease in the number of elective isolated AVR cases per month in 2019. The average number of elective isolated AVR cases per month was 250 in 2017 and 252 in 2018, while the monthly activity in 2019 decreased from 226 cases in January, to 173 cases by December ( **Figure 1**). After 1st March 2020 there was a significant drop in activity across all AVR procedures compared with historic levels ( **Figure 2**). There was a slight recovery in AVR activity in May - August 2020.

Importantly, similar findings were found in the subgroup of “rapid-data-submitting” centres (**Supplementary Figure I**). In particular, in this subset of centres, the observed rapid drop in cases during March and April 2020, persisted. Interestingly, activity in these “rapid-data-submitting” centres has actually returned (at least approximately) to expected levels in September to November 2020 (**Supplementary Figure I**). This indicates that levels of AVR activity have started to recover following the initial rapid drop caused by the first national lockdown.

The number of elective SAVR procedures, was below 150 cases per month between March-June 2020 for each of isolated AVR, AVR+CABG and AVR+Other ( **Figure 1**). In contrast, there remained >100 elective TAVR cases per month after March 2020. The percentage change in monthly activity between 2020 and historic levels was lower for TAVR than SAVR with a maximum percentage difference of 86.5%, 80.7%, 83.4% and 55.7%, for isolated AVR, AVR+CABG, AVR+Other and TAVR, respectively ( **Figure 2, panel B**).

**Figure 3** shows the expected (from the negative binomial model) and actual monthly AVR activity during 2020. For the first few months after lockdown, the estimated difference (95% CI) in the number of TAVR cases per month compared with those expected based on historic trends was -2 (-40, 35) in March 2020, -229 (-264, -193) in April 2020, -191 (-229, -154) in May 2020, and -129 (-166, -92) in June 2020 ( **Figure 3, panel B**). The estimated decrease in Isolated AVR activity was -171 (-201, -140), -231 (-257, -205), -177 (-205, -148) and -96 (-124, -69), across March-June 2020, respectively. Similar observations were made for AVR+CABG and AVR+Other cases ( **Figure 3, panel B**). Cumulatively, over the period March to November 2020, this amounts to an estimated expected drop of 4989 (95% CI 4020, 5959) cases of severe aortic stenosis in England, of which 1683 (95% CI 1429, 1937) were for isolated AVR, 1038 (95% CI 848, 1229) were for AVR+CABG, 703 (95% CI 519, 887) were for AVR+Other, and 1565 (95% CI 1223, 1906) were for TAVR.

**Evolution of Patient Demographics and Procedural Risk**

**Table 2** shows patient baseline characteristics of isolated AVR cases across the pre-COVID-19 and during-COVID-19 groups. For isolated AVR, the mean age was significantly lower in the during-COVID-19 group than the pre-COVID-19 group ($p<0.001$), and there was a significantly higher CCS angina status ($p=0.002$), NYHA class ($p<0.001$) and mean PA systolic pressure ($p<0.001$). For TAVR cases, the mean age, proportion of current/ex-smokers and mean creatinine were significantly lower in the during-COVID-19 group compared with the pre-COVID-19 group (**Table 3**). There was a lower proportion of TAVR cases with previous MI ($p<0.001$), previous cardiac surgery ($p<0.001$), and extracardiac arteriopathy ($p=0.001$) in the during-COVID-19 group. Similar findings were found for AVR+CABG (**Supplementary Table I**) and AVR+Other (**Supplementary Table II**). We also explored differences in baseline characteristics between pre-COVID-19 and during-COVID-19 groups, restricting to just 2019 and 2020 data (to look at changes in most contemporary practice); the findings were quantitively similar (**Supplementary Table III – Supplementary Table VI**).

Overall surgical AVR procedural risk, as estimated by the Logistic EuroSCORE, has remained relatively stable over time (**Supplementary Figure II**). While the mean UK TAVR prediction model was significantly lower in the during-COVID-19 group compared with the pre-COVID-19 group (p<0.001, **Table 3**), this was largely driven by 2017 cases (**Supplementary Figure II**). Indeed, upon comparing cases in February-November 2019 with corresponding months in 2020, we found that there was no significant difference in the UK TAVR CPM between February and November 2020, compared with corresponding months in 2019 (**Supplementary Table VI**).

Between 2017 and December 2019, there has been a steady increase in the monthly TAVR activity in the lowest quantiles of risk strata, while the monthly activity in the highest quantiles of risk strata as remained relatively stable (**Supplementary Figure III**). In contrast, the monthly activity of surgical AVR has been gradually decreasing through time across all quantiles of risk strata (**Supplementary Figure IV, Supplementary Figure V,** and **Supplementary Figure VI**).

**Outcomes**

The overall Kaplan-Meier estimates of 30-day survival were 98.5% for isolated AVR, 95.8% for AVR+CABG, 94.8%, for AVR+Other, and 97.5% for TAVR. For isolated AVR, AVR+Other and TAVR, we found no significant difference in mortality hazards up to 30-days post procedure between the pre-COVID-19 group and the during-COVID-19 group ( **Table 4**). In contrast, mortality hazards up to 30-days post procedure were significantly higher in patients undergoing AVR+CABG during-COVID-19 compared with the pre-COVID-19 group (HR 1.41; 95% CI 1.05, 1.89).

The median length of stay (LOS) following TAVR was 3 days (interquartile range: 2-5 days) in the pre-COVID-19 group, and 2 days (interquartile range: 1-3 days) in the during-COVID-19 group. The median (interquartile range) LOS in the pre-COVID-19 group for isolated AVR, AVR+CABG and AVR+Other was 7 (5-9) days, 8 (6-12) days and 9 (6-15) days, respectively, with these being 6 (5-9) days, 7 (6-11) days and 8 (6-14) days in the during-COVID-19 group. For AVR+CABG procedures performed in the during-COVID-19 period, the adjusted hazard ratios (95% CI) for early discharge was 1.09 (1.02, 1.17), showing significantly shorter LOS ( **Table 5**). TAVR patients in the during-COVID-19 group were also significantly more likely for early discharge, up to 2 days post TAVR (**Table 5**).

## Discussion

This study is the first to investigate activity and outcomes following all aortic valve replacement procedures in contemporary practice, including the potential indirect impacts of the COVID-19 pandemic. We observed a rapid decrease in TAVR and SAVR activity during the COVID-19 pandemic. Over the period March to November 2020, this decline in activity accounts for an estimated 4989 patients with aortic stenosis left untreated by AVR intervention. This will have major implications on this cohort of patients whose untreated mortality is high.

The treatment of severe aortic stenosis has evolved from SAVR being the default treatment modality, to TAVR now being an evidence-based option at all surgical risk categories [14–18]. We observed changes in TAVR and SAVR activity, with steadily increasing TAVR activity and corresponding slight decreases in elective isolated AVR cases, up-to 2019. This supports previous findings in this area [19]. Although TAVR is currently only approved for inoperable or high-risk cases in the UK, the evidence of equivalence in low-risk cases is accumulating [18,31]. This may partially explain our finding of a steadily increasing proportion of TAVR cases within the lowest quantile of risk, prior to 2020. The observed decrease in SAVR activity before COVID-19, also provides evidence that the clinical envelope for TAVR has expanded into lower risk cases within real-world contemporary practice.

Inevitably, the initiation of national lockdown in the UK was associated with a significant reduction in the monthly number of AVR procedures being performed. We found a relatively smaller fall in TAVR than SAVR. One potential explanation is that TAVR has a low probability of requiring stay in an intensive treatment unit, which is important given constraints during the pandemic. Indeed, during the pandemic, patients with severe symptomatic aortic stenosis were recommended to be treated by TAVR where appropriate [32]. However, given that the UK TAVR registry and the NACSA dataset does not contain information on the decision-making behind the SAVR or TAVR choice, we are not able to investigate this directly. Importantly, we observed evidence that monthly activity levels across SAVR and TAVR are returning to expected levels towards the end of the study period (September-November 2020), particularly in centres that rapidly submit data to NICOR. Nonetheless, there will inevitably remain a back-log of cases incurred by the first national lockdown in the UK.

The observed reduction in AVR activity was largely driven by elective cases. A possible explanation is that the UK governments response to the pandemic was to recommend cancellation of elective procedures [33]. This was made to allow a re-structuring of hospital services, thereby allowing more staff and resource to deal with the increased admissions due to COVID-19. Another hypothesis for this observed reduction in elective cases could be secondary to patients being less active during the COVID-19, and hence less AS-related symptoms resulting in non-diagnosis of AS or lack of urgent need for intervention. Interestingly, we observed that monthly activity for TAVR and SAVR had a slight recovery in May and June 2020. We were unable to investigate the reasons for this, but previous studies have made similar observations [6]. Again, one could speculate that this relates to decreasing demands on healthcare systems as the pandemic evolved, with an aim to resume elective activity once the peak of the pandemic had passed. Given that England has entered a second national lockdown in November 2020, it will remain to be seen if there is another drop in elective AVR activity. Elective cases were being encouraged to continue through the second lockdown.

Nevertheless, despite restructure of healthcare services nationally during COVID-19, overall procedural risk has maintained relatively constant. In many ways, some individual baseline characteristics of those undergoing SAVR during COVID-19 were lower risk than pre-COVID patients. There was inevitably an element of careful selection in patients eligible for SAVR during the initial lockdown, particularly for elective cases that were advised to be cancelled. This might partially explain these findings, due to the complex (multivariable) interactions between procedural risk and individual baseline characteristics. Nonetheless, it is important to note that overall procedural risk for SAVR (quantified by the EuroScore) and TAVR (quantified by UK TAVR CPM) was not significantly different between pre- (2019 months) and during-COVID-19 groups.

While the observed temporal changes in activity are perhaps unsurprising, these findings raise important implications for healthcare resource planning in the near-to-medium term. Namely, the results suggest that there will likely be significant increased future demand for TAVR and SAVR. This will lead to an inevitable increase in waiting times [34] and associated adverse impacts on outcomes [35]. Recommendations for how to manage this challenge are emerging [34,36]. It was not possible for us to forecast future demand for AVR since we do not have information on patients who are candidates for AVR, but who have not currently undergone the procedure. However, based on the available data, we estimated that, cumulatively, between March and November 2020, there were 4989 (95% CI 4020, 5959) cases of severe aortic stenosis who have not received treatment in England. Previous studies have shown that, under normal circumstances, the median wait-time for TAVR is 80 days [37]. Thus, assuming these figures apply to AVR generally, we postulate that approximately 2495 patients will remain untreated by 80 days (3742 if procedures are made at 50% capacity), even without considering the additional cases over this period. While such figures are an approximation, they do suggest that, on a national-level, strategies will be required to mitigate this large backlog of cases, to reduce avoidable deaths in patients with severe symptomatic aortic stenosis.

Indeed, it remains unclear what effect the reduction in the number of procedures per month has had on outcomes for patients with aortic stenosis who would otherwise have been treated with AVR during the initial lockdown period (March - June 2020). Previous studies have estimated that the risk of death whilst waiting for intervention for severe aortic stenosis in routine clinical practice is between 2% and 14% [38]. This means that of the estimated 4989 currently delayed cases, there will be between 99 and 698 deaths while waiting for intervention. Any additional delays due to the backlog will lead to increased mortality. Of course, these are approximate figures and does not account for excess mortality due to COVID-19 [39]. Similarly, they are dependent on the estimated mortality proportion while waiting for AVR, and we note that this estimate varies across the literature. For example, other studies have reported mortality proportions while waiting for AVR in the high-risk TAVR era of 3.7%, 8.0%,and 9.6%, at 1-, 6-, and 12-months respectively, with SAVR, and 3.8%, 23.3%,and 27.5%, respectively, with TAVR [40]. In the intermediate-risk TAVR era, waiting-time mortality proportions have been estimated at 2% at 80 days [37]. Such figures can give further indications of the expected deaths while waiting for intervention.

Several limitations should be noted. Firstly, we make no statistical comparisons between isolated AVR, AVR+CABG, AVR+Other or TAVR groups. Any such comparisons would be subject to confounding by indication. This means that we were not able to investigate changes in patient-level propensity to undergo SAVR vs. TAVR through the COVID-19 period. Secondly, while we used the Logistic EuroSCORE to summarise overall SAVR procedural risk, this model is known to overpredict mortality risk. However, this model is commonly used for benchmarking in national cardiovascular registries, and we use the model in the same capacity here. Thirdly, this analysis is limited to procedures in England; however, given that COVID-19 has caused changes in healthcare utilisation globally, one might expect similar findings in other healthcare settings. Finally, some delays in data reporting during the pandemic might contribute to some of the results; however, significant efforts have been made to maintain data flows with weekly uploads of data. Additionally, we undertook a sensitivity analysis of "rapid-data-submitting" centres, which indicated quantitively similar results to the main analysis, particularly regarding the drastic decrease in activity following the first UK lockdown. Further work should explore if activity is returning in later months, as suggested by this sensitivity analysis.

In conclusion, this study has demonstrated a significant drop in TAVR and SAVR activity following the COVID-19 outbreak in the UK. The case-mix of patients who have undergone AVR during the COVID-19 period was similar to the case-mix seen in the pre-COVID-19 period. There was evidence that activity is starting to return to expected levels by the end of study follow-up. Nonetheless, there will be a back-log of cases caused by the initial lockdown period, suggesting that there will be a sharp rise in demand for AVR intervention in the near-to-medium term, with the potential for an upturn in mortality in patients waiting to be treated.

## Acknowledgments

The authors acknowledge Chris Roebuck, Tom Denwood, Tony Burton and Courtney Stephenson and data support staff at NHS digital for providing and creating the secure environment for data hosting and analytical support. We also acknowledge Anil Gunesh and Julian Hains from the National Institute of Cardiovascular Outcomes Research for data transfer into the secure environment.

## Contributorship Statement

Authors GPM and MAM conceived and designed the study. GPM performed the analysis, and wrote the first draft of the manuscript in collaboration with MAM. All authors (GPM, NC, ATG, JN, LB, PL, EK, JW, CG, MAB, MAM) contributed to reviewing and revising the manuscript critically for scientific content, helped interpret the results, and approved the final version of the paper.

## Supplementary Materials

Supplementary Figures I-VI and Supplementary Tables I-VI

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## Tables

*Table 1: Baseline characteristics of the SAVR and TAVR cases included in this analysis. TAVR: Transcatheter Aortic Valve Replacement; SAVR: Surgical Aortic Valve Replacement. Note: the numbers in some categories might not sum to the total due to missing data.*

| | Isolated AVR | AVR+CABG | AVR+Other | TAVR |
|---|---|---|---|---|
| n | 13357 | 8550 | 6773 | 15142 |
| Age, years (mean (SD)) | 67.66 (11.64) | 72.23 (8.26) | 62.89 (14.06) | 81.25 (7.24) |
| Female (%) | 5073 (38.0) | 1905 (22.3) | 2269 (33.5) | 6727 (44.5) |
| CCS Angina status (%) | | | | |
| No angina | 7648 (57.4) | 2548 (29.9) | 4497 (66.6) | 10624 (75.2) |
| Class I | 1628 (12.2) | 881 (10.3) | 730 (10.8) | 1045 ( 7.4) |
| Class II | 2818 (21.2) | 2978 (35.0) | 973 (14.4) | 1732 (12.3) |
| Class III or IV | 1222 ( 9.2) | 2109 (24.8) | 557 ( 8.2) | 726 ( 5.1) |
| NYHA (%) | | | | |
| Class I | 1389 (10.5) | 885 (10.5) | 1085 (16.3) | 1032 ( 7.4) |
| Class II | 5226 (39.6) | 3490 (41.4) | 2272 (34.1) | 3246 (23.1) |
| Class III or IV | 6598 (49.9) | 4052 (48.1) | 3298 (49.6) | 9756 (69.5) |
| Previous MI (%) | 785 ( 5.9) | 2182 (25.6) | 332 ( 4.9) | 2099 (14.6) |
| Previous PCI (%) | 674 ( 5.1) | 969 (11.5) | 231 ( 3.5) | 2389 (16.8) |
| Previous Cardiac Surgery (%) | 929 ( 7.5) | 211 ( 2.7) | 949 (15.2) | 2404 (17.5) |
| Diabetic (%) | 2554 (19.2) | 2477 (29.1) | 799 (11.8) | 3464 (24.3) |
| Current/Ex Smoker (%) | 6995 (52.8) | 5233 (61.6) | 3352 (49.9) | 6466 (49.8) |
| Creatinine, umol/L (mean (SD)) | 89.58 (45.91) | 95.90 (54.14) | 96.07 (58.07) | 104.97 (62.54) |
| History of neurological disease (%) | 1142 ( 8.6) | 872 (10.3) | 686 (10.2) | 2229 (15.5) |
| Extracardiac Arteriopathy (%) | 675 ( 5.1) | 1132 (13.3) | 484 ( 7.2) | 1867 (13.2) |

| | | | | |
|---|---|---|---|---|
| Atrial Fibrillation or Flutter (%) | 1175 ( 8.9) | 1147 (13.5) | 1602 (23.9) | 3850 (28.6) |
| One or more vessel with >50% diameter stenosis (%) | 620 ( 5.3) | 7464 (96.8) | 265 ( 5.0) | 4082 (31.8) |
| PA Systolic (mean (SD)) | 27.09 (19.81) | 29.09 (22.61) | 38.59 (22.15) | 37.98 (15.13) |
| LV Function (%) | | | | |
| Good (LVEF > 50%) | 10554 (79.7) | 6018 (70.9) | 4750 (70.7) | 10116 (72.5) |
| Moderate (LVEF 31 - 50%) | 2080 (15.7) | 1968 (23.2) | 1568 (23.4) | 2559 (18.3) |
| Poor (LVEF < 30%) | 614 ( 4.6) | 504 ( 5.9) | 397 ( 5.9) | 1282 ( 9.2) |
| Height, m (mean (SD)) | 1.68 (0.10) | 1.70 (0.10) | 1.71 (0.11) | 1.65 (0.10) |
| Weight, kg (mean (SD)) | 82.85 (18.38) | 83.65 (16.80) | 82.45 (19.08) | 76.00 (17.32) |
| Non-Elective (%) | 3038 (22.7) | 2735 (32.0) | 2307 (34.1) | 2977 (19.7) |
| Logistic EuroSCORE (mean (SD)) | 7.50 (8.54) | 10.68 (11.08) | 14.05 (14.47) | NA |
| UK TAVR CPM (mean (SD)) | NA | NA | NA | 3.11 (2.39) |

*Table 2: Baseline characteristics of the Isolated AVR cases included in the pre-COVID-19 and during-COVID-19 groups, as defined in the methods section. AVR: Aortic Valve Replacement. Note: this only included cases in February-November each year, and the numbers in some categories might not sum to the total due to missing data.*

| | Pre-Covid-19 | During-Covid-19 | p-value |
|---|---|---|---|
| n | 9803 | 1549 | |
| Age, years (mean (SD)) | 67.95 (11.74) | 66.05 (11.22) | <0.001 |
| Female (%) | 3791 (38.7) | 539 (34.8) | 0.004 |
| CCS Angina status (%) | | | 0.002 |
| No angina | 5616 (57.5) | 895 (57.9) | |
| Class I | 1198 (12.3) | 175 (11.3) | |
| Class II | 2095 (21.4) | 299 (19.3) | |
| Class III or IV | 860 ( 8.8) | 178 (11.5) | |
| NYHA (%) | | | <0.001 |
| Class I | 1016 (10.5) | 138 ( 9.0) | |
| Class II | 3908 (40.3) | 512 (33.5) | |
| Class III or IV | 4782 (49.3) | 878 (57.5) | |
| Previous MI (%) | 572 ( 5.9) | 77 ( 5.0) | 0.190 |
| Previous PCI (%) | 479 ( 4.9) | 80 ( 5.2) | 0.721 |
| Previous Cardiac Surgery (%) | 676 ( 7.4) | 116 ( 8.1) | 0.401 |
| Diabetic (%) | 1835 (18.8) | 334 (21.6) | 0.010 |
| Current/Ex-Smoker (%) | 5146 (52.9) | 800 (52.2) | 0.625 |
| Creatinine, umol/L (mean (SD)) | 89.81 (46.49) | 89.12 (47.34) | 0.597 |
| History of neurological disease (%) | 849 ( 8.7) | 123 ( 8.0) | 0.380 |
| Extracardiac Arteriopathy (%) | 510 ( 5.2) | 72 ( 4.7) | 0.391 |
| Atrial Fibrillation or Flutter (%) | 898 ( 9.2) | 100 ( 6.6) | 0.001 |
| One or more vessel with >50% diameter stenosis (%) | 448 ( 5.2) | 78 ( 5.9) | 0.296 |
| PA Systolic (mean (SD)) | 26.79 (18.67) | 32.75 (26.93) | <0.001 |
| LV Function (%) | | | 0.398 |
| Good (LVEF > 50%) | 7760 (79.8) | 1206 (78.3) | |
| Moderate (LVEF 31 - 50%) | 1524 (15.7) | 259 (16.8) | |

| | | | |
|---|---|---|---|
| Poor (LVEF < 30%) | 439 ( 4.5) | 75 ( 4.9) | |
| Height, m (mean (SD)) | 1.68 (0.10) | 1.70 (0.11) | <0.001 |
| Weight, kg (mean (SD)) | 82.60 (18.08) | 84.53 (19.60) | <0.001 |
| Non-Elective (%) | 2109 (21.5) | 462 (29.8) | <0.001 |
| Logistic EuroSCORE (mean (SD)) | 7.55 (8.35) | 6.98 (8.73) | 0.013 |

*Table 3: Baseline characteristics of the TAVR cases included in pre-COVID-19 and during-COVID-19 groups, as defined in the methods section. TAVR: Transcatheter Aortic Valve Replacement. Note: this only included cases in February-November each year, and the numbers in some categories might not sum to the total due to missing data.*

| | Pre-Covid-19 | During-Covid-19 | p-value |
|---|---|---|---|
| n | 9999 | 2922 | |
| Age, years (mean (SD)) | 81.30 (7.33) | 80.78 (7.06) | 0.001 |
| Female (%) | 4468 (44.7) | 1278 (43.7) | 0.353 |
| CCS Angina status (%) | | | 0.300 |
| No angina | 7066 (75.2) | 2043 (76.5) | |
| Class I | 713 ( 7.6) | 182 ( 6.8) | |
| Class II | 1127 (12.0) | 323 (12.1) | |
| Class III or IV | 486 ( 5.2) | 122 ( 4.6) | |
| NYHA (%) | | | <0.001 |
| Class I | 651 ( 7.0) | 246 ( 9.1) | |
| Class II | 2215 (23.8) | 532 (19.7) | |
| Class III or IV | 6426 (69.2) | 1925 (71.2) | |
| Previous MI (%) | 1483 (15.5) | 314 (11.6) | <0.001 |
| Previous PCI (%) | 1615 (17.1) | 401 (14.9) | 0.008 |
| Previous Cardiac Surgery (%) | 1677 (18.7) | 403 (14.8) | <0.001 |
| Diabetic (%) | 2285 (24.1) | 663 (24.6) | 0.602 |
| Current/Ex-Smoker (%) | 4424 (50.6) | 1079 (45.0) | <0.001 |
| Creatinine, umol/L (mean (SD)) | 105.62 (64.18) | 103.09 (61.96) | 0.076 |
| History of neurological disease (%) | 1490 (15.5) | 405 (14.9) | 0.438 |
| Extracardiac Arteriopathy (%) | 1286 (13.7) | 302 (11.3) | 0.001 |
| Atrial Fibrillation or Flutter (%) | 2552 (28.6) | 760 (29.6) | 0.319 |
| One or more vessel with >50% diameter stenosis (%) | 2788 (32.5) | 679 (28.1) | <0.001 |
| PA Systolic (mean (SD)) | 38.09 (15.18) | 37.46 (14.89) | 0.238 |
| LV Function (%) | | | 0.016 |
| Good (LVEF > 50%) | 6720 (72.3) | 1915 (72.7) | |
| Moderate (LVEF 31 - 50%) | 1759 (18.9) | 451 (17.1) | |
| Poor (LVEF < 30%) | 813 ( 8.7) | 268 (10.2) | |
| Height, m (mean (SD)) | 1.65 (0.10) | 1.66 (0.10) | 0.001 |

| | | | |
|---|---|---|---|
| Weight, kg (mean (SD)) | 75.68 (17.33) | 77.11 (17.47) | <0.001 |
| Non-Elective (%) | 1796 (18.0) | 758 (25.9) | <0.001 |
| UK TAVR CPM (mean (SD)) | 3.16 (2.53) | 2.96 (1.95) | <0.001 |

*Table 4: Multivariable adjusted mortality hazard ratios (95% confidence interval) of COVID-19 period (during- vs. pre-) for up-to 30-day mortality. All values are adjusted for overall procedural risk (Logistic EuroSCORE for SAVR and UK TAVR prediction model for TAVR cases). TAVR: Transcatheter Aortic Valve Replacement; SAVR: Surgical Aortic Valve Replacement.*

| Surgical Group | Hazard Ratio (95% CI) | p-value |
|---|---|---|
| Isolated AVR | 1.02 (0.65, 1.6) | 0.927 |
| AVR+CABG | 1.41 (1.05, 1.89) | 0.023 |
| AVR+Other | 0.94 (0.69, 1.27) | 0.671 |
| TAVR | 0.86 (0.65, 1.14) | 0.296 |

*Table 5: Multivariable adjusted hazard ratios (95% confidence interval) for discharge across COVID-19 period (during- vs. pre-). The event is discharge, so a hazard ratio greater than one implies shorter length of stay. All values are adjusted for overall procedural risk (Logistic EuroSCORE for SAVR and UK TAVR prediction model for TAVR cases). TAVR: Transcatheter Aortic Valve Replacement; SAVR: Surgical Aortic Valve Replacement.*

| Surgical Group (period, where applicable) | Hazard Ratio (95% CI) | p-value |
|---|---|---|
| Isolated AVR | 1.01 (0.95, 1.07) | 0.769 |
| AVR+CABG | 1.09 (1.02, 1.17) | 0.015 |
| AVR+Other | 1.07 (1, 1.15) | 0.061 |
| TAVR | | |
| 0-1 Days | 2.56 (2.36, 2.79) | p<0.001 |
| 1-2 Days | 1.43 (1.32, 1.55) | p<0.001 |
| 2+ Days | 1.02 (0.95, 1.1) | 0.581 |

## Figures Legend

*Figure 1: Temporal plot of the number of TAVR and SAVR procedures per month, stratified according to procedure urgency. The vertical dotted line denotes 23rd March 2020 (date of UK lockdown) with 1st March denoted by the vertical dashed line. TAVR: Transcatheter Aortic Valve Replacement; SAVR: Surgical Aortic Valve Replacement.*

*Figure 2: Panel A: Temporal plot of the number of TAVR and SAVR procedures per month during 2020, compared with monthly averages (minimum and maximum shown by shaded region) across all other years in the dataset. Panel B: Percentage change between the mean monthly activity in 2017-2019 and the monthly activity in 2020; negative percentage change denotes increase in 2020 over historic levels. TAVR: Transcatheter Aortic Valve Replacement; SAVR: Surgical Aortic Valve Replacement.*

*Figure 3: Panel A: Temporal plot of the observed and expected number of TAVR/SAVR procedures per month. Panel B: The difference between the observed and expected number of TAVR/SAVR procedures per month. In both plots the expected monthly count is estimated from a negative binomial model fitted to the 2017-2019 data. The vertical dotted line denotes 23rd March 2020 (date of UK lockdown) with 1st March denoted by the vertical dashed line. TAVR: Transcatheter Aortic Valve Replacement; SAVR: Surgical Aortic Valve Replacement.*