Table 1: Spare capacity at the pre-pandemic baseline and under alternative hospital provision intervention scenarios for the observed peak number of 3,100 COVID-19 patients in CC and 15,700 COVID-19 patients in G&A. The percentage change in spare capacity of each resource for each intervention, compared to spare capacity with no interventions at peak COVID-19 patient numbers, is shown in brackets.

Scenario	CC Beds	CC Nurses (FTE)	CC Junior Doctors (FTE)	CC Senior Doctors (FTE)	Ventilators	G&A Beds	G&A Nurses (FTE)	G&A Junior Doctors (FTE)	G&A Senior Doctors (FTE)
No interventions	-2,283	-2,773	-217	403	4,804	-5,931	8,666	1,819	3,871
All implemented interventions	-474 (79%)	-359 (87%)	-22 (90%)	568 (41%)	6,430 (34%)	46,567 (885%)	42,816 (394%)	9,499 (422%)	7,636 (97%)
Individual hospital provision interventions									
Cancellation of elective operations	-1,294 (43%)	-1,784 (36%)	-94 (57%)	469 (16%)	5,230 (9%)	30,887 (621%)	16,029 (85%)	4,273 (135%)	6,326 (63%)
Set up of field hospitals	-1,783 (22%)	-2,773 (0%)	-217 (0%)	403 (0%)	4,804 (0%)	2,069 (135%)	8,666 (0%)	1,819 (0%)	3,871 (0%)
Deployment of newly qualified and final year medicine and nursing students	-2,283 (0%)	-2,773 (0%)	-217 (0%)	403 (0%)	4,804 (0%)	-5,931 (0%)	23,805 (175%)	5,981 (229%)	3,871 (0%)
Use of private hospitals	-1,963 (14%)	-1,891 (32%)	-203 (6%)	424 (5%)	6,004 (25%)	1,749 (129%)	15,879 (83%)	2,041 (12%)	4,144 (7%)
Return of former healthcare staff	-2,283 (0%)	-2,230 (20%)	-161 (26%)	482 (20%)	4,804 (0%)	-5,931 (0%)	13,099 (51%)	2,660 (46%)	4,909 (27%)

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Combining the interventions as parameterised in Table 2 provides an illustration of actual capacity within NHS England during the surge phase. We estimate that these interventions would allow for up to 2,627 and 62,267 COVID-19 patients to be accommodated in CC and G&A on any day, respectively (Figure 2).

The most limiting resources were CC nurses, beds and junior doctors, and G&A beds. The intervention that made the largest contribution to increasing their capacity was cancellation of elective surgery (Table 1, Figure 2). Use of private hospitals and deployment of former staff were also essential to increase capacity of CC nurses. Additionally, under the peak number of COVID-19 patients, setting-up of field hospitals and use of private hospitals each led to large increases of around 130% in spare G&A bed capacity compared with no interventions, and deployment of medical students increased spare capacity of G&A nurses and G&A junior doctors by 175% and 229%, respectively (Table 1).

At the peak of the epidemic, with the combination of interventions in place, there was spare capacity in G&A beds (with a spare 46,500 beds) (Table 1) as well as capacity in staff (42,800 G&A nurses, 17,100 G&A doctors and 570 CC senior doctors) and equipment (6,400 ventilators). While we estimate a small deficit in CC beds, CC nurses and CC junior doctors at the time of the peak number of hospitalised COVID-19 patients, additional interventions which could not be quantified at the national level could have been used. For example, converting 474 G&A beds to CC beds and upskilling 359 G&A nurses to CC nurses would have overcome this deficit.

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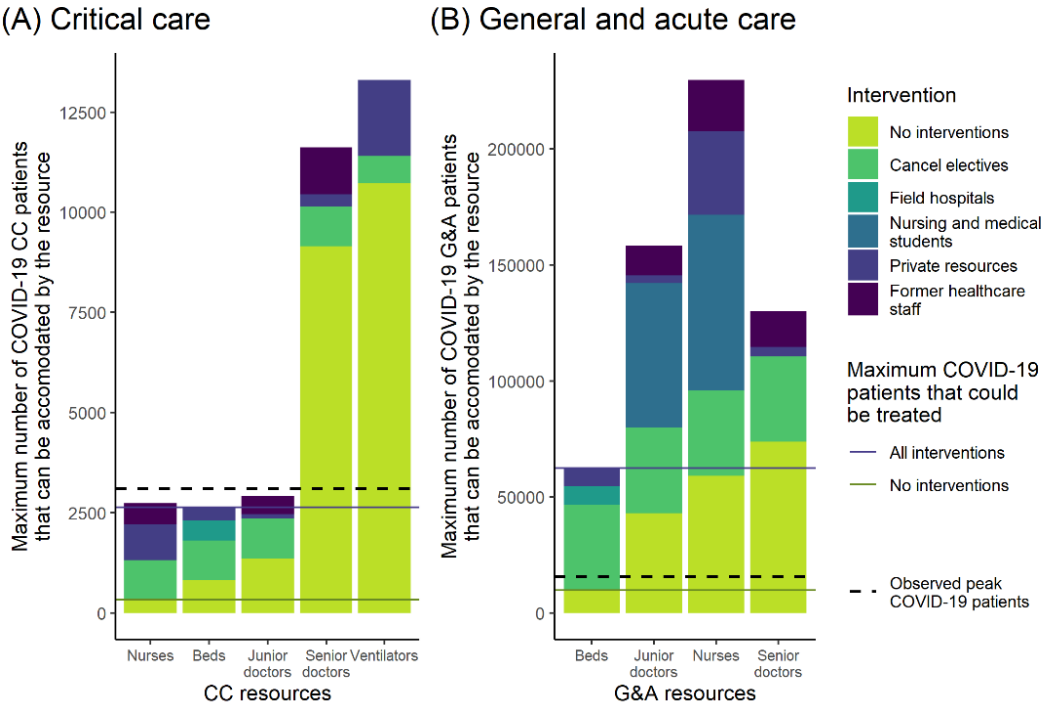

Figure 2: Maximum daily number of COVID-19 patients that could be accommodated by different CC (A) and G&A (B) resources with and without hospital provision interventions. Note**:** Bars show the threshold of COVID-19 patients at which capacity of different resources would have been exceeded in the absence of interventions in yellow, and any additional patients under individual interventions stacked on top, so that the height of the bar represents the COVID-19 patients that can be accommodated by the combination of all interventions. Solid lines show the maximum number of COVID-19 CC (A) and G&A (B) patients that could be accommodated on any day, which is determined by the limiting resource. The dashed line highlights the observed peak number of COVID-19 patients in CC and G&A during the first pandemic wave (12th April). Note that (A) and (B) have very different vertical scales.

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Table 2: Overview of hospital provision interventions implemented in England. Although further interventions involving reallocation of resources, such as conversion of operating theatres and G&A resources into CC wards and changes in staffing ratios, were also approved on a national level, these are implemented at a hospital level. As a result, their effect could not be quantified nationally and thus were not included in the analysis.

Intervention	Description	Effect on CC resources	Effect on G&A resources	Source
Interventions managing admissions				
Cancellation of elective surgery	Cancelling elective surgery reduces the number of beds occupied, and thereby also reduces the number of staff and ventilators required on a daily basis.	• Beds: Reduce occupancy by 30%	• Beds: Reduce occupancy by 41%	NHS Hospital Episode Statistics; Redaniel and Savovic [21,22]
Interventions increasing supply				
Set up of field hospitals*+	Non-hospital sites are temporarily turned into hospitals. This increases bed numbers, but with no additional staff. In England, no details were provided about any increases in ventilator numbers solely through this intervention.	• Beds: Increase total by 500 (12%)	• Beds: Increase total by 8,000 (8%)	NHS England news (03/04/20) [23], Health systems response monitor [20]
Deployment of newly qualified/final year medicine and nursing students*+	Final-year medical and nursing students have their qualification process accelerated to enable them to start working immediately. They are allocated as G&A nurses and G&A junior doctors respectively.	-	• Nurses: Increase FTEs by 16,456 (51%) • Junior Doctors: Increase FTEs by 4,840 (47%)	BBC news (24/03/20) [24]

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Intervention	Description	Effect on CC resources	Effect on G&A resources	Source
Return of former healthcare staff*	Individuals who recently worked in the health system are asked to return. This is predominantly staff who retired within the previous 3 years, but also includes individuals who left for other professions. In order to account for this fact, and also the fact that some senior staff may not wish to take on clinical decision-making responsibilities, staff are allocated across all six categories. The figures here are only for those estimated to have returned as opposed to all eligible.	• Nurses: Increase FTEs by 587 (15%) • Junior Doctors: Increase FTEs by 64 (10%) • Senior Doctors: Increase FTEs by 92 (10%)	• Nurses: Increase FTEs by 4,822 (15%) • Junior Doctors: Increase FTEs by 979 (10%) • Senior Doctors: Increase FTEs by 1,206 (10%)	BBC news (24/03/20) [24]
Use of private hospitals*	National health systems temporarily use private healthcare resources to provide public care. This increases the number of beds, ventilators and all staff categories.	• Beds: Increase total by 317 (8%) • Nurses: Increase FTEs by 955 (24%) • Junior Doctors: Increase FTEs by 17 (3%) • Senior Doctors: Increase FTEs by 24 (3%) • Ventilators: Increase by 1,200 (15%)	• Beds: Increase total by 7,683 (8%) • Nurses: Increase FTEs by 7,845 (24%) • Junior Doctors: Increase FTEs by 258 (3%) • Senior Doctors: Increase FTEs by 317 (3%)	NHS England news (21/03/20) [25]

*Full supply-side intervention package [4].

⁺Supply-side interventions deemed most sustainable in medium run [4].

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3.3 Reintroduction of elective patients in the post-surge phase

As we enter the post-surge phase (Figure 1A), attention has now turned to reintroducing elective surgery [3,4]. We estimate that there were 989 elective patients requiring CC beds and 36,818 requiring G&A beds on an average day before the pandemic.

At the peak of the pandemic, even with the full supply-side package of interventions (Table 2), there was no capacity to treat elective patients in CC. This full supply-side package of interventions would allow 10% of elective patients requiring CC to be accommodated when COVID-19 CC patients have fallen to 2,530. If no interventions were applied, then the baseline capacity would only allow accommodation of 10% of CC electives with at most 1,210 COVID-19 patients in CC. To accommodate all elective patients requiring CC at average pre-pandemic levels with the full supply-side intervention package in place, the number of COVID-19 patients in CC must fall below 1,550 (Figure 3A). This is a substantial improvement upon the no-interventions scenario, in which COVID-19 patients in CC must fall below 320 for all elective patients requiring CC to be accommodated. The deficit in CC capacity is primarily being driven by nurses, which is why field hospitals, and deployment of medical and nursing students, provide no improvement over the no-interventions scenario.

However, there is greater national capacity to treat G&A patients. Without interventions, the estimated baseline capacity in NHS England could accommodate nearly 10,000 COVID-19 patients, and still treat all of the average number of elective surgery patients requiring overnight admission to G&A (Figure 3B). The full supply-side intervention package substantially increases this capacity, allowing for demand from all G&A patients to be comfortably met even at the observed peak number of COVID-19 patients in G&A, and for more than the daily pre-pandemic number of elective patients to be accommodated (Figure 3B). When implementing the full supply-side interventions, as above for CC, the number of COVID-19 patients that could be accommodated with all G&A elective patients rises to over 25,000.

As long as field hospitals remain operational, capacity is sufficient to meet pre-pandemic demand from all G&A patients regardless of the number of COVID-19 patients (Figure 3B). The full supply-side intervention package could accommodate up to 46,500 elective G&A patients requiring hospital care on a daily basis, and once G&A COVID-19 patients drop to below 7,500 the increase in capacity from the set-up of field hospitals is equivalent to the full supply-side intervention package. However, it is important to note that even under this intervention and with the additional deployment of students, spare capacity in G&A for COVID-19 patients was limited at the peak of the epidemic.

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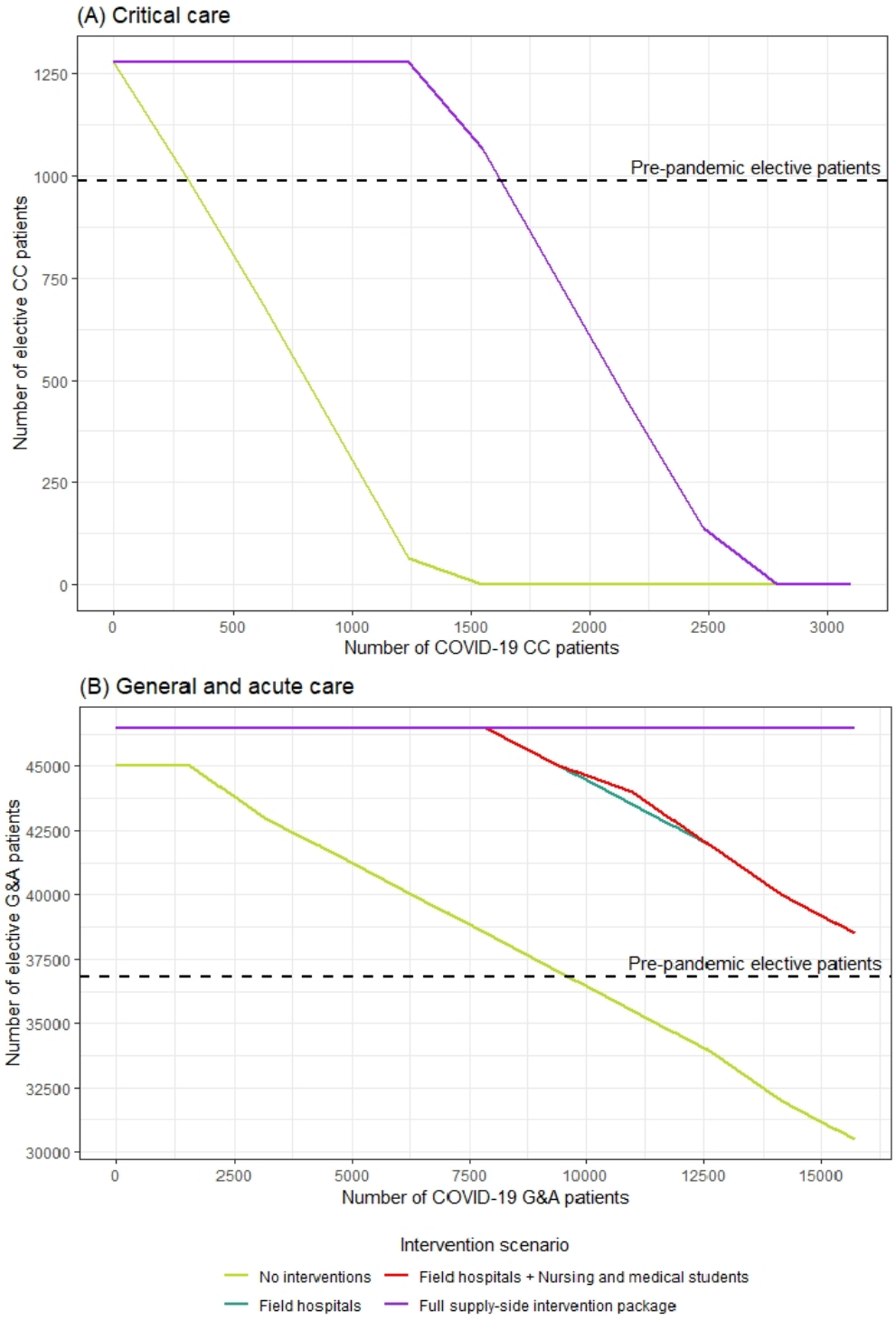

Figure 3: Bed availability for elective surgery considering hospital provision interventions and COVID-19 patients. Note: The relationship between the daily bed occupancy of hospitalised COVID-19 patients and beds available for hospitalised elective patients on an average day under different combinations of hospital provision interventions for (A) critical care beds and (B) general & acute beds. The deficit in capacity in (A) is driven by CC nurses, the capacity of which remains unchanged under all interventions except from the full supply-side package, hence field hospitals and deployment of students do not increase CC capacity above the baseline. Axis ranges cover the observed peak number of hospitalised COVID-19 patients (horizontal) and maximum average open bed numbers (vertical).

4. Discussion

We developed a model to quantify hospital capacity for general and acute and critical care considering three crucial resources: staff, beds and ventilators. We used this to estimate the individual and combined impact of five interventions that were implemented in England to increase capacity to meet demand for COVID-19 care during the surge phase: cancellation of elective surgery, setting up field hospitals, deployment of newly qualified and final year medicine and nursing students, use of private hospitals, and return of former healthcare staff. We examined potential approaches to enabling resumption of elective surgery in the post-surge phase. If no hospital provision interventions had been implemented, then capacity would have been insufficient to safely care for the peak number of 3,100 hospitalised critical care COVID-19 patients that was reached on 12th April in England. The most severe constraints in critical care were numbers of CC nurses, followed by beds and junior doctors. The estimated CC capacity under the surge phase fell slightly short of the peak number of CC patients, but demand is likely to have been met using additional interventions that could not be quantified at the national level. Peak demand for G&A beds by COVID-19 patients exceeded baseline capacity, but interventions increased capacity well beyond what was eventually needed. In summary, the implementation of hospital provision interventions to manage admissions, reallocate and increase supply of resources, led to a substantial increase in capacity and has clearly contributed to ensuring access to life-supporting treatment during the pandemic surge.

Cancellation of elective surgery made the largest contribution to increasing available capacity and is an intervention that has also been implemented elsewhere in Europe [20,26–28]. However, this may come at a substantial cost to patients whose treatments were cancelled (e.g. [29–31]). We found that elective surgery could be re-introduced at pre-pandemic levels if the other interventions are sustained (field hospitals, deployment of final year students, return of former healthcare staff and use of private hospitals) and there are no more than 1,550 COVID-19 patients in CC beds on a given day (about 50% compared with peak demand). If this combination of interventions is not sustained then this would only be possible for less than 320 COVID-19 patients in CC. National capacity to accommodate G&A patients is higher, with re-introduction of elective G&A patients at pre-pandemic levels being possible even without sustaining hospital provision interventions once there are less than 10,000 COVID-19 patients requiring a G&A bed. However, reducing the backlog caused by surgery cancellations requires accommodating larger numbers of elective G&A patients than pre-pandemic levels, meaning that interventions are likely to need to be maintained for some time. Furthermore, it is likely that delays will have increased the complexity of treating some categories of patient, which may mean they now require CC beds rather than G&A beds.

Several tools have been developed to estimate demand for hospital care by COVID-19 patients [5–8] including the number requiring ventilation [6,7], the different types of beds required [5,8], or expected dates of shortfall and staff needs [5]. Our work has a different complementary objective, as it assesses how to meet demand for COVID-19 care more broadly. A strength of our study is that we evaluated the quantitative impact of interventions during March and April 2020 over baseline capacity and occupancy, by combining a review of the English response to COVID-19 surges in healthcare demand with a detailed analysis of NHS data. We then used these insights to evaluate the feasibility, in terms of capacity, of re-introducing elective surgery. Our study is one of the first to consider key human resources during the COVID-19 pandemic, including COVID-19 related staff absence. Additionally, we

have made the model used in this analysis available as a user-friendly planning tool, which can assist decision makers in the adaptation of hospitals for the pandemic in different settings [19].

Our analysis is conducted at the national level and thus does not consider the geographic distribution of hospital capacity and COVID-19 admissions. Reorganisation of care within individual hospitals occurred during the surge in April, including upskilling of staff and converting operating theatres to CC wards [4], and it may be the case that recommended staff-to-beds ratios were not always able to be maintained. Furthermore, hospital infection control typically involves cohorting patients according to COVID-19 status as well as quarantining elective patients before surgery, which create local capacity challenges. As there are no consistently collected national data available on these practices they cannot be included in the analysis.

Recent modelling predicted that temperate global regions will likely see recurrent wintertime outbreaks of COVID-19 [32] and the authors recommend increasing critical care capacity as an urgent priority. Decisions will need to be made regarding which of the interventions can be sustained and for how long, to accommodate COVID-19 and other emergency patients, address the backlog of elective patients, and meet nascent demand for elective procedures. Additionally, the drop in emergency admissions may have contributed to the NHS's ability to cope with the increase in demand [33,34], but this may exacerbate the backlog of patients in the future.

The most severe constraint in English NHS hospitals is the number of CC nurses. This suggests that two interventions must be sustained: the deployment of former healthcare staff and the use of private healthcare provision. It will be necessary to increase the desirability of nursing to keep former healthcare staff in the profession over the course of both the pandemic and post-pandemic period. An essential intervention would be recruiting and training more CC nurses. It is possible that experienced G&A staff could be upskilled to work in CC, and their usual duties could be filled by the newly qualified and final year medical and nursing students. However, this group may require close supervision from more experienced clinical staff initially. Ongoing arrangements with private hospital providers will need to be considered. Field hospitals do not address the key constraint of CC nurse capacity but could provide overspill facilities for less severe COVID-19 patients that do not require critical nursing care, or for those requiring palliative care.

The future trajectory of demand for COVID-19 care is uncertain, making it necessary to reassess the planning of elective procedures frequently; this is facilitated with our planning tool [31]. Our study demonstrates that English hospitals were successful in increasing capacity to deal with the surge in COVID-19 patients. These interventions now need to be sustained, and capacity closely monitored, to provide urgently needed care to elective patients who have waited many months for their treatments.

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6. Supplement

Supplementary Material S1: Glossary

Baseline capacity	The average number of beds, staff and ventilators in the non-pandemic phase in the absence of interventions.
Baseline occupancy	The average number of beds, staff and ventilators occupied in the non-pandemic phase in the absence of COVID-19 patients.
CC	Critical care
Elective patients	Elective patients requiring hospital care on any average day pre-COVID-19 for non-urgent treatment, i.e. non-emergency, non-maternity and non-cancer.
FTE	Full-time equivalents, unit that equates to employees working full time
Full supply-side intervention package	Combination of all supply-side interventions: set up of field hospitals, deployment of newly qualified and final year medical and nursing students, return of former healthcare staff, and use of private healthcare resources
G&A	General and acute
Hospital provision intervention	A public health intervention aimed at either: managing admissions to hospitals; or re-allocating or increasing the supply of capacity in hospitals
Post-surge phase	The period after the pandemic peak when the number of COVID patients gradually declined, i.e. after May 2020 in England
Pre-pandemic phase	The period before the pandemic, i.e. before February 2020 in England
Resources	Beds, staff and ventilators
Surge phase	The period during which the pandemic peak, i.e. between March and April 2020 in England
Trust	A trust is an organisational unit, which may consist of one or more hospitals and other healthcare service facilities

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Supplementary Table S1

Table 1: Overview of model inputs, assumptions and how this was quantified for the analysis.

Input	Disaggregation	Description	Value	Source
Capacity Variables				
Total number of beds	G&A; CC	The average daily number of beds that existed at baseline (before the pandemic). It is the sum of beds that are occupied by patients and beds that could be occupied but are not (referred to as open overnight beds in the dataset).	• CC: 4,114 • G&A: 99,569	NHS England [9,10]
Average bed occupancy for non-COVID-19 patients*	G&A; CC	The average daily number of beds that were occupied at baseline (before the pandemic). This comprises of patients recovering from elective operations, as well as emergency cases.	• CC: 3,297 (approx. 989 elective) • G&A: 89,800 (approx. 36,818 elective)	NHS England [9,10]
Observed maximum number of beds occupied by COVID-19 patients*	G&A; CC	The maximum number of COVID-19 hospitalised in English trusts on any day as of 29th May 2020 (occurring on 12th April 2020). Hospitalised case numbers are not split into adults and children, and so this number may slightly overestimate the true observed maximum of adult patients.	• CC: 3,100 • G&A: 15,700	NHS England [4]
Number of ventilators	Only applies to CC	The daily number of ventilators that exist at baseline (before the pandemic). It is the sum of currently used ventilators and ventilators that could be used on the day but are not.	• 8,175	The Financial Times [35]
Total staff (FTE)	G&A; CC; nurses; junior and senior doctors	The average daily full-time equivalent numbers of staff at baseline (before the pandemic).	• CC nurses: 3939 • G&A nurses: 32,354 • CC junior doctors: 677 • CC senior doctors: 965 • G&A junior doctors: 10,293 • G&A senior doctors: 12,680	NHS England [11]
Model Parameters				
Percentage of CC patients requiring a ventilator	COVID-19; non-COVID-19	The proportion of patients in CC expected to require a ventilator on any given day.	• COVID-19: 63% • Non-COVID-19: 43%	ICNARC, Shahin et al 2014 [36–38]

Input	Disaggregation	Description	Value	Source
Staff-to-beds ratios	G&A; CC; nurses; junior and senior doctors	The ratio of the maximum number of beds that a single staff member could safely look after.	• CC nurse: 1:1 • G&A nurse: 1:5 • CC junior doctor: 1:8 • CC senior doctor: 1:15 • G&A junior doctor: 1:15 • G&A senior doctor: 1:15	Royal College of Nursing, Royal College of Physicians, Faculty of Intensive Care Medicine [14–16]
Rate of COVID-19 related staff sickness or absence**	Nurses; doctors	The percentage of staff absent from work for reasons related to the COVID-19 pandemic (estimates from the beginning of April).	• Nurses: 8% • Doctors: 14%	The Guardian [18]
Headcount to FTE multiplier	-	Multiplier to convert staff headcounts into staff FTEs, as official announcements of additional staff numbers are often given in headcounts.	• 0.88	NHS Digital [39]

*These patient numbers were both varied as part of the analysis to open elective surgery (Figure 3).

**The rate of COVID-19 related staff absence was set to 0 during the pre-pandemic phase and held constant at the reported values during the pandemic.

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Supplementary Material S2

Model equations

The calculations underpinning the model are provided below. Calculations are analogous for G&A and CC, and also for nurses, junior doctors and senior doctors.

$$Beds\ needed_i = Number\ of\ non\text{-}COVID\text{-}19\ patients_i + Number\ of\ COVID\text{-}19\ patients_i$$
$$for\ i \in \{G\&A, CC\}$$

$$Staff\ needed_{ij} = \frac{Beds\ needed_i}{Staff\text{-}to\text{-}beds\ ratio_{ij}}$$
$$for\ i \in \{G\&A,\ CC\}$$
$$for\ j \in \{nurse,\ junior\ doctor,\ senior\ doctor\}$$

$$Ventilators\ needed = \sum_k (proportion\ requiring\ ventilation_k \times number\ of\ patients_k)$$
$$for\ k \in \{COVID\text{-}19,\ non\text{-}COVID\text{-}19\}$$

$$Total\ staff_j = 1 - COVID\text{-}19\ sickness\ rate_k \times Staff\ FTE_j$$
$$for\ j \in \{nurse, junior\ doctor, senior\ doctor\}$$
$$for\ k \in \{nurse, doctor\}$$

$$Increase\ to\ capacity_{m,n}(\%) = \frac{Additional\ resource_{m,n}}{Existing\ resource_m} \times 100$$
$$for\ m \in \{beds,\ staff,\ ventilators\}$$
$$for\ intervention\ scenario\ n$$

$$Spare\ capacity_{m,n} = Resource\ available_{m,n} - Resource\ needed_{m,n}$$
$$for\ m \in \{beds, staff, ventilators\}$$
$$for\ intervention\ scenario\ n$$

$$Spare\ capacity_{n,baseline}(\%) = \frac{Space\ capacity_{m,n} - Spare\ capacity_{m,baseline}}{\left|Spare\ capacity_{m,baseline}\right|}$$
$$for\ m \in \{beds, staff, ventilators\}$$
$$for\ intervention\ scenario\ n$$

Further methods and assumptions

Parameterisation of interventions

For any intervention for which the distribution of added hospital resources across CC and G&A or senior and junior doctor strata was not reported, we applied the same distribution as derived from the data on pre-pandemic existing capacity. For example, 4% of NHS beds are CC and so 312 (4% of 8000) of private hospital resource beds were attributed to CC and the rest (7,688) to G&A.

Similarly, interventions presenting staff numbers as headcounts were multiplied by a conversion factor of 0.88 to convert to FTEs. This was determined from the ratio of headcounts to FTEs of total NHS staff in the latest available NHS workforce dataset [39].

Analysis: The relationship between CC and G&A elective patients

We assumed that the number of CC and G&A patients in hospital on a daily basis follows a linear relationship. Using NHS datasets, we estimated a daily average of 89,800 G&A and 3,297 CC hospitalised patients. Furthermore, using an analysis of HES data, we estimated that excluding elective patients frees-up 52,982 G&A and 2,308 CC beds. Using these two points, the relationship could be quantified. This resulted in the following equation:

$$CC\ hospitalised\ elective\ patients = 0.03 \times G\&A\ hospitalised\ elective\ patients + 603$$

In the post-surge analysis numbers of G&A patients were varied between 52,982 and 99,482 in intervals of 500 and then numbers of CC patients were derived using this equation.

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