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Original Article

The impact of nursing workforce skill-mix on patient outcomes in intensive care units in Victoria, Australia

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ABSTRACT

Objective: This article aims to examine the impact of nursing workforce skill-mix (percentage of critical care registered nurses [CCRN]) in the intensive care unit (ICU) during a patient's stay.
Design: Registry linked cohort study of the Australian and New Zealand Intensive Care Society Adult Patient Database and the Critical Health Resources Information System using real-time nursing workforce data.
Settings: Fifteen public and 5 private hospital ICUs in Victoria, Australia.
Participants: There were 16,618 adult patients admitted between 1 December 2021 and 30 September 2022.
Main outcome measures: Primary outcome: in-hospital mortality. Secondary outcomes: in-ICU mortality, development of delirium, pressure injury, duration of stay in-ICU and hospital, after-hours discharge from ICU and readmission to ICU.
Results: In total, 6563 (39.5%) patients were cared for in ICUs with >75% CCRN, 7695 (46.3%) in ICUs with 50–75% CCRN, and 2360 (14.2%) in ICUs with <50% CCRN. In-hospital mortality was 534 (8.1%) vs. 859 (11.2%) vs. 252 (10.7%) respectively. After adjusting for confounders, patients cared for in ICUs with 50–75% CCRN (adjusted OR 1.21 [95% CI 1.02–1.45]) were more likely to die compared to patients in ICUs with >75% CCRN. A similar but non-significant trend was seen in ICUs with <50% CCRN (adjusted OR 1.21 [95% CI 0.94–1.55]), when compared to patients in ICUs with >75% CCRN. In-ICU mortality, delirium, pressure injuries, after-hours discharge and ICU length of stay were lower in ICUs with CCRN>75%.

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Conclusion: The nursing skill-mix in ICU impacts outcomes and should be routinely monitored. Health system regulators, hospital administrators and ICU leaders should ensure nursing workforce planning and education align with these findings to maximise patient outcomes.

1. Introduction

In Australia, national nursing workforce standards for intensive care provide an evidence-informed framework for staffing, and include nursing skill-mix recommendations.[1] In the intensive care unit (ICU), skill-mix refers to the percentage of registered nurses that hold postgraduate specialist qualification in critical care nursing. These standards recommend a minimum skill-mix of 50% critical care nurses, with the optimal percentage of 75% critical care qualified staff.[2,3] These skill-mix standards have been in place for over 20 years with no real substantial change over this time despite changes to healthcare systems and pandemic events.[4,5] It is recognised Australian ICU patients experience excellent outcomes in comparison to other health systems.[6]

International studies have shown that the education level, and number of nursing staff are associated with patient outcomes, such as mortality and adverse events.[7–9] A single centre Australian ICU study demonstrated an inverse association between the percentage of critical care nurses and the risk of adverse events occurring.[10] There are no published multi-centre studies which examine the impact of nursing workforce skill-mix in Australian ICUs on patient outcomes.

2. Objectives

The aim of this study was to examine the association between nursing skill-mix and ICU patient outcomes. The hypothesis was that outcomes would be better when a patient is cared for in an ICU which has a higher percentage of trained critical care nurses.

3. Methods

3.1. Design and setting

We conducted a registry linked cohort study at fifteen public and five private Victorian hospital adult ICUs between 1 December 2021 and 30 September 2022 (303 days).

3.2. Data sources

Individual patient demographic, diagnostic and outcome data were extracted from the Australia and New Zealand Intensive Care Society (ANZICS) Adult Patient Database. The ANZICS Adult Patient Database is a dataset held by the ANZICS Centre for Outcomes and Resources Evaluation Clinical Quality Registry for purposes of benchmarking ICU outcomes in Australia and New Zealand. All ICUs in Victoria submit individual patient data on a quarterly basis. Illness severity was assessed using the Australian and New Zealand Risk of Death.[11] This is a highly discriminatory and well-calibrated risk model which combines age, acute physiological and biochemical disturbance, chronic comorbidities, treatment limitations, elective surgical status and source of admission with individual predictive equations for each admission diagnosis, into a single mortality risk estimate for each patient. It does not include sex, frailty or a prediction equation for COVID-19.[11] Readmission episodes to ICU, palliative admissions, children (<16 years), patients still in ICU at time of data extraction and those with missing information about mortality outcomes or length of stay in ICU were excluded.

ICU staffing data were extracted from the Critical Health Resources Information System (CHRIS), a real-time dashboard of ICU activity, acuity and resources, developed and implemented nationally in response to the Coronavirus disease 2019 (COVID-19) pandemic by ANZICS, Ambulance Victoria, the Australian Government Department of Health, and Telstra Purple™. ICUs contribute summary 'snapshot' information about ICU resources and activity at least twice daily for the purposes of monitoring provision of critical care services.

In November 2021, all Victorian ICUs were invited to voluntarily contribute additional data about the nursing staff providing direct patient care within each ICU. This study examined a convenience sample of ICUs where more than 60% of admissions could be linked to staffing data. Nursing workforce skill-mix was categorised into four groups as defined by the Safer Care Victoria COVID-19 surge workforce guideline.[12,13]

- Group One: postgraduate qualified critical care registered nurses (CCRN) or general registered nurses with five plus years of current/continuous ICU experience (referred to collectively as CCRN).
- Group Two: early career general registered nursing staff including foundation year/transition to ICU speciality nurses, 2021–2022 postgraduate critical care nursing students, nurses with critical care experience not normally working in ICU pre-pandemic.
- Group Three: redeployed nursing staff with no ICU experience (novice to ICU).
- Group Four: registered undergraduate students of nursing, enrolled nurses and allied health staff providing direct patient care.

3.3. Exposure

Our exposure of interest was the overall mean proportion of CCRNs (group one) throughout the patient's ICU stay. This was calculated as the sum of CCRNs at every site, divided by the total nursing staff providing direct patient care (groups one to four) for that 24-h period. Daily values from ICU admission up until discharge/death, were then summed and divided by the total available days of data. The percentage of CCRN was categorised into three groups (>75%, 50%–75%, <50%) reflecting 'ideal', 'minimum recommended' and 'less than ideal' staffing levels as designated by national critical care organisations (Australian College of Critical Care Nurses and College of Intensive Care Medicine).[2,3]

3.4. Outcomes

The primary outcome was in-hospital mortality. Secondary outcomes were in-ICU mortality, development of delirium, pressure injury in ICU, duration of ICU stay (days), ratio of observed to

predicted length of ICU stay, after-hours discharge from ICU and duration of stay in hospital.

3.5. Subgroups

The primary outcome of in-hospital mortality was also examined in the following subgroups: patients who required one or more critical care therapy (invasive ventilation, renal replacement, extracorporeal membrane oxygenation [ECMO]), patients who did not receive any of these therapies, and only patients in public hospitals.

3.6. Statistical analysis

All data were analysed using Stata version 16.1, College Station, Texas.[14] Results are presented as number (%), median (interquartile range) or mean (standard deviation) as appropriate depending on type and distribution of data. Chi-square, t-test, analysis of variance (ANOVA), Wilcoxon rank-sum and Kruskal–Wallis tests were used to compare groups depending on the type of data, and number of groups examined. Mixed effects hierarchical multivariable logistic regression (with patients clustered by site and site entered as a random effect) was used to determine variables independently associated with the primary outcome (in-hospital mortality). Patients admitted to ICUs with CCRN >75% were the reference category. Potential confounders were identified through univariable comparison of survivors and deaths (Appendix Table 1). The Activity index of the ICU on the day of the patient's admission was included.[15] The Activity index combines overall patient acuity and staffing within the ICU into a single measure where higher values represent increasing levels of strain within the unit. Additional information about the Activity index is provided in Appendix Table 2. Colinear variables were identified using variance inflation factor, with the best model selected using Akaike and Bayesian information criteria. Marginal risk-adjusted probabilities of death are reported for all patients and for subgroups after holding other parameters constant using the margins command in Stata. Sensitivity analyses were undertaken, modelling the exposure (CCRN percentage) with restricted cubic splines. No imputation for missing data was performed. A two-sided p value of <0.05 was considered statistically significant.

3.7. Ethical approval

Ethics was approved by The Alfred Health Human Research and Ethics Committee (HREC 246/22). The study was unfunded research undertaken by the authors.

4. Results

There were 19,598 admissions to the 20 study ICUs, of which 16,618 patients met inclusion criteria (Appendix Figs. 1 and 2). There were 6563 (39.5%) patients cared for in ICUs where the CCRN was >75%, 7695 (46.3%) where this was 50–75% and 2360 (14.2%) with CCRN <50%. Study ICUs were larger public units, with younger patients, more invasive therapies and higher mortality than ICUs in other Victorian hospitals (Appendix Tables 3 and 4).

Patients in the highest CCRN percentage category were older, had lower illness severity scores and less commonly received renal replacement therapy or ECMO. There was no difference in the proportion receiving invasive mechanical ventilation. Although medical patients were the most common diagnostic category overall, a relatively greater proportion of patients in the highest CCRN percentage category were planned admissions to ICU following elective surgery or admitted following cardiac surgery. COVID-19 patients were most common in ICUs in the lowest CCRN percentage category (Table 1).

Patients in the highest CCRN percentage category were cared for in larger ICUs (more baseline ICU beds, more total patients already in ICU needing 1:1 nursing) with lower occupancy. As a proportion of the total number of patients admitted to each hospital type, 2386 (85%) patients in private hospitals were cared for in ICUs where the CCRN percentage was >75%, compared to 3311 (43%) in tertiary ICUs, 676 (17%) in metropolitan ICUs and 190 (9%) in rural/regional ICUs (Table 1). Private hospital ICUs had the greatest proportion of days with skill-mix >75% CCRN, followed by tertiary ICUs, then metropolitan ICUs, with the lowest seen in rural/regional ICUs (Fig. 1).

4.1. Primary outcome – in-hospital mortality

Observed in-hospital mortality was lowest when patients were cared for in ICUs with the highest nursing skill-mix category CCRN >75% (n = 534, 8.1%) vs. CCRN 50–75% (n = 859, 11.2%) vs. CCRN <50% (n = 252, 10.7%) (Table 2). After adjusting for confounders including illness severity, sex, COVID-19, frailty, ICU Activity index, and hospital type, patients in ICUs with CCRN 50–75% were more likely to die (adjusted OR 1.21 [95% Confidence Interval 1.02–1.45]) than those in ICUs with a higher CCRN percentage. Although the point estimate for patients in ICUs with CCRN <50% (adjusted Odds Ratio 1.21 [95% CI 0.94–1.55]) suggested a potential signal for harm, this did not reach statistical significance (Table 3) and (Appendix Table 5). The mortality risk associated with the percentage of CCRN, modelled using cubic splines is shown in Fig. 2.

4.2. Secondary outcomes

In-ICU mortality, delirium, pressure injuries, after-hours discharge, ICU length of stay and ratio of observed to predicted length of ICU stay were all lower amongst patients admitted to ICUs with CCRN >75%, compared to the other skill-mix categories (Table 2).

4.3. Subgroup and sensitivity analyses

Amongst patients who received invasive ventilation, renal replacement or ECMO, observed in-hospital mortality was lowest amongst patients cared for in ICUs with the highest nursing skill-mix category CCRN >75% (n = 352, 12.8%) vs. CCRN 50–75% (n = 602, 18.3%) vs. CCRN <50% (n = 169, 17.8%) (Appendix Table 6). After adjusting for confounders, those admitted to ICUs with a CCRN 50–75% were more likely to die (adjusted OR 1.35 [95% CI 1.11–1.64]) when compared to patients in ICUs with CCRN >75%. A similar but non-significant trend was seen in ICUs with CCRN <50% (adjusted OR 1.28 [95% CI 0.98–1.66]) (Table 3, Appendix Table 5). In-ICU mortality, delirium, pressure injuries, after-hours discharge, and ICU and hospital length of stay were also all lower amongst patients admitted to ICUs with CCRN>75% (Appendix Table 6).

Amongst the subgroup who did not receive invasive ventilation, renal replacement or ECMO, there was no difference in observed or adjusted in-hospital mortality between patients in each of the skill-mix categories (Appendix Tables 5 and 7). However, unadjusted in-ICU mortality, delirium, after-hours discharge, and ICU length of stay were lower amongst patients in ICUs with CCRN >75% (Appendix Table 7).

Amongst the subgroup who were in public hospital ICUs, unadjusted in-ICU mortality, delirium, after-hours discharge, and ICU length of stay were lower amongst patients in ICUs with CCRN >75% (Appendix Table 8). After adjusting for confounders, those

Table 1
Characteristics of patients and intensive care units (ICUs) by category of percentage of critical care registered nurses in each ICU.

	<50 % CCRN	50–75% CCRN	>75% CCRN	p value
Patient characteristics	N = 2360	N = 7695	N = 6563	
Age in years[a]	60.7 (18.0)	61.1 (17.5)	62.1 (17.2)	<0.001
Men	1401 (59.4%)	4482 (58.2%)	3768 (57.4%)	0.24
ICU admission category				<0.001
Medical admission	1594 (67.5%)	4970 (64.6%)	3113 (47.4%)	
Emergency surgical admission	406 (17.2%)	1379 (17.9%)	1065 (16.2%)	
Elective surgery with planned ICU admission	360 (15.3%)	1346 (17.5%)	2385 (36.3%)	
ICU admission diagnosis				<0.001
Cardiac medical diagnoses	305 (12.9%)	960 (12.5%)	611 (9.3%)	
Respiratory medical diagnoses (excl. pneumonia)	212 (9.0%)	660 (8.6%)	334 (5.1%)	
Sepsis and other infections (incl. pneumonia)	424 (18.0%)	1378 (17.9%)	844 (12.9%)	
Other medical diagnoses	361 (15.3%)	1191 (15.5%)	738 (11.2%)	
Cardiothoracic & vascular surgery	140 (5.9%)	540 (7.0%)	568 (8.7%)	
Coronary Artery Bypass Grafting and/or valve surgery	134 (5.7%)	514 (6.7%)	882 (13.4%)	
Gastro-intestinal surgery	204 (8.6%)	733 (9.5%)	799 (12.2%)	
Neurological and neurosurgical diagnoses	118 (5.0%)	502 (6.5%)	529 (8.1%)	
Orthopaedic surgery	44 (1.9%)	183 (2.4%)	392 (6.0%)	
Trauma	271 (11.5%)	565 (7.3%)	363 (5.5%)	
Other surgical diagnoses	147 (6.2%)	469 (6.1%)	503 (7.7%)	
COVID-19 pneumonitis	105 (4.4%)	297 (3.9%)	106 (1.6%)	<0.001
Illness severity scores				
Acute Physiology and Chronic Health Evaluation (APACHE) III/IV score[a]	54.1 (25.7)	56.2 (25.2)	52.0 (23.6)	<0.001
Australian & New Zealand Risk of Death (ANZROD) percent (mean, median [IQR])	10.8, 2.9 (0.7–11.2)	11.5, 3.1 (0.8–12.8)	9.4, 1.8 (0.5–8.3)	<0.001
Therapies provided in ICU				
Invasive ventilation	903 (38.3%)	3101 (40.3%)	2639 (40.2%)	0.19
Renal replacement therapy	163 (7.0%)	562 (7.6%)	291 (5.4%)	<0.001
Extracorporeal membrane oxygenation	32 (1.4%)	44 (0.6%)	13 (0.2%)	<0.001
Inotropes	1034 (44.2%)	3763 (50.9%)	2431 (45.4%)	<0.001
Invasive ventilation, renal replacement or ECMO	952 (40.3%)	3297 (42.8%)	2751 (41.9%)	0.09
Intensive Care Unit Characteristics				
Hospital classification				<0.001
Public rural/regional (4 ICUs)	702 (30%)	1179 (15%)	190 (3%)	
Public metropolitan (6 ICUs)	748 (32%)	2599 (34%)	676 (10%)	
Public tertiary (5 ICUs)	900 (38%)	3496 (45%)	3311 (50%)	
Private (5 ICUs)	10 (0%)	421 (5%)	2386 (36%)	
Characteristics of the ICU and nursing skill-mix profile on the day of patient's admission to ICU (unless otherwise stated)				
Activity index of the ICU	1.3 (0.5–1.7)	1.4 (0.9–1.6)	1.2 (0.7–1.5)	<0.001
Occupancy (%)[b]	88 (67–95)	90 (77–95)	85 (73–93)	<0.001
Number of baseline 'business as usual' ICU beds[b]	10.0 (6.0–46.0)	14.0 (10.0–25.0)	17.0 (11.0–26.0)	<0.001
Number of patients receiving 1:1 nursing in ICU[b]	7.0 (2.0–47.7)	8.5 (4.0–23.3)	10.0 (3.0–21.3)	<0.001
Number of COVID-19 patients in ICU on day of admission[b]	2.0 (0.0–6.7)	1.3 (0.0–3.8)	0.8 (0.0–2.0)	<0.001
Number of Critical Care Registered Nurses[b]	6.0 (3.0–28.0)	9.0 (6.0–20.0)	13.0 (7.0–22.0)	<0.001
Number of early career/in training critical care nurses[b]	5.0 (3.0–26.0)	4.0 (2.0–9.0)	2.0 (1.0–4.0)	<0.001
Number of nurses without ICU experience redeployed into ICU[b]	1.0 (0.0–5.0)	0.0 (0.0–2.0)	0.0 (0.0–0.0)	<0.001
Number of nursing students & 'non-nursing' staff providing ICU bedside care[b]	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	<0.001
Percentage of CCRN as proportion of all staff providing bed-side ICU care[b]	44.1 (36.4–49.3)	62.1 (54.5–70.0)	84.6 (77.8–93.8)	<0.001
Percentage of CCRN throughout patient's ICU admission[b]	44.5 (39.5–47.7)	62.7 (55.6–69.1)	83.3 (78.7–90.4)	<0.001

CCRN, Critical Care Registered Nurses; ICU, Intensive Care Unit. A vacant ICU bed is one that is not occupied by a patient but is available, equipped and can be staffed with 1:1 nursing ratio. A staffed ICU bed is equipped and can be staffed with 1:1 nursing ratio but may or may not be filled by a patient.
[a] Data reported as mean (standard deviation).
[b] Median (interquartile range); all other data reported as number (percentage).

admitted to ICUs with a CCRN 50–75% were more likely to die (adjusted OR 1.27 [95%CI 1.06–1.52]) (Appendix Tables 5 and 8).

5. Discussion

This study of 16,618 patients admitted to 20 ICUs in Victoria, Australia between December 2021 and September 2022, demonstrated that patients cared for in ICUs with 50–75% CCRN were more likely to die in hospital than patients in ICUs with a higher CCRN skill-mix. This effect on mortality was predominantly accounted for by those who required critical care therapies such as invasive mechanical ventilation, renal replacement or ECMO and was consistent when only patients in public hospital ICUs were analysed. In addition, patients admitted to ICUs with CCRN >75% were observed to have lower in-ICU mortality, delirium, pressure injuries, after-hours discharge, and reduced ICU length of stay.

Studies that have examined nurse staffing and level of education on ICU patient outcomes have been limited by the use of static or aggregated data from sources which do not measure daily or shift by shift variation in workforce.[9,16,17] Although the impact of overall staff resources on ICU patient mortality and morbidity has been described, the effect of experience and training level of ICU nurses has limited evidence. A cross-sectional study of 303 acute care hospitals in the USA found that a 10% increase in nurses with a bachelor's degree was associated with a 2% reduction in the odds of 30-day mortality in mechanically ventilated patients.[18] Additionally, fewer nursing resources in ICU contribute to adverse events such as increase healthcare associated infections,[19] poorer quality of care, and reduced adherence to guidelines and protocols.[20,21] Organisational factors, such as appropriate nursing workforce levels directly influence quality of care, with increased missed or omitted nursing care interventions reported.[22,23] Our study suggests that improvements in patient mortality and patient quality

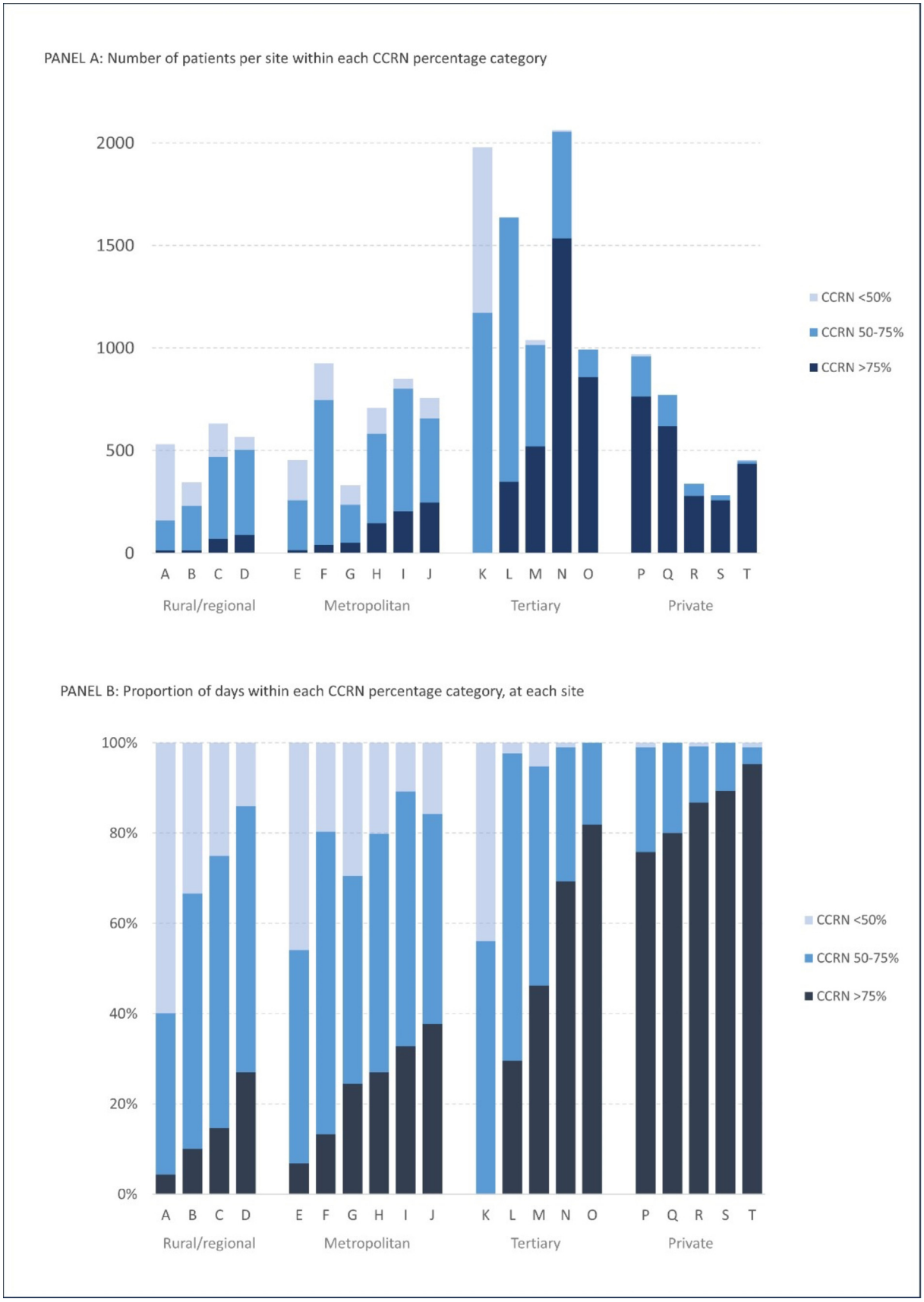

Fig. 1. Number of patients within each critical care registered nurse (CCRN) percentage category (Panel A) and proportion of days within each CCRN percentage category (Panel B) at each site.

Table 2
Unadjusted primary and secondary outcomes of patients by category of critical care registered nurses in each intensive care unit.

	<50% CCRN	50–75% CCRN	>75% CCRN	p value
	N = 2360	N = 7695	N = 6563	
Primary outcome				
In-hospital mortality	252 (10.7%)	859 (11.2%)	534 (8.1%)	<0.001
Secondary outcomes				
In-ICU mortality	180 (7.6%)	594 (7.7%)	351 (5.3%)	<0.001
Delirium in ICU	258 (12.8%)	618 (10.0%)	150 (4.1%)	<0.001
Pressure injury developed in ICU	57 (2.7%)	135 (2.1%)	46 (1.2%)	<0.001
Duration of ICU stay (days)	2.2 (1.1–4.8)	2.1 (1.1–4.2)	1.8 (0.9–3.2)	<0.001
Ratio of observed to predicted length of ICU stay[b]	1.18 (0.66–2.16)	1.11 (0.65–1.93)	1.01 (0.64–1.63)	<0.001
Duration of stay in hospital (days)	7.8 (3.8–14.8)	8.3 (4.3–15.8)	8.0 (4.3–14.6)	<0.001
After-hours discharge from ICU[a]	552 (25.3%)	1576 (22.2%)	831 (13.4%)	<0.001

CCRN, Critical Care Registered Nurse; ICU, Intensive Care Unit.
[a] ICU survivors only.
[b] Predicted length of ICU stay is derived from the ANZICS prediction model to estimate expected ICU length of stay. A ratio >1 represents an ICU stay that is longer than predicted.

Table 3
Mixed effects hierarchical multivariable logistic regression for in-hospital mortality adjusted for sex, illness severity, COVID-19 status, frailty, ICU activity index and hospital type (with site as random effect) in all patients and in subgroups categorised by a. invasive therapies (invasive ventilation, renal replacement or ECMO), b. no invasive therapies and c. patients in public hospital ICUs.

Patient category	CCRN group	No. of patients	Observed mortality	Adjusted Odds Ratio (95% CI)	p value
All patients	CCRN >75%	(n = 6563)	534 (8.1%)	Reference value	
	CCRN 50–75%	(n = 7695)	859 (11.2%)	1.21 (1.02–1.45)	0.032
	CCRN <50%	(n = 2360)	252 (10.7%)	1.21 (0.94–1.55)	0.14
Subgroups					
a. Invasive ventilation, renal replacement or ECMO	CCRN >75%	(n = 2751)	352 (12.8%)	Reference value	
	CCRN 50–75%	(n = 3297)	602 (18.3%)	1.35 (1.11–1.64)	0.003
	CCRN <50%	(n = 952)	169 (17.8%)	1.28 (0.98–1.66)	0.07
b. No invasive ventilation, renal replacement or ECMO	CCRN >75%	(n = 3812)	182 (4.8%)	Reference value	
	CCRN 50–75%	(n = 4398)	257 (5.8%)	1.05 (0.79–1.39)	0.76
	CCRN <50%	(n = 1408)	83 (5.9%)	1.14 (0.76–1.71)	0.52
c. Public hospital ICUs	CCRN >75%	(n = 4177)	425 (10.2%)	Reference value	
	CCRN 50–75%	(n = 7274)	844 (11.6%)	1.27 (1.06–1.52)	0.011
	CCRN <50%	(n = 2350)	251 (10.7%)	1.24 (0.97–1.59)	0.08

For full multivariable models see Appendix Table 5. CCRN, Critical Care Registered Nurse; CI, Confidence interval; ECMO, Extracorporeal membrane oxygenation; ICU, Intensive Care Unit.

care outcomes might be achieved by increasing the percentage of postgraduate qualified critical care nurses within an ICU.

Excluding patients admitted for COVID-19, the all-cause mortality has increased in Australian ICUs for the first time in five years.[24] The COVID-19 pandemic required an adaptable nursing workforce with nursing redeployment, rapid upskilling and changed models of staffing.[13] The COVID-19 pandemic impacted health and healthcare delivery, with workforce shortages, especially in critical care environments continuing to be a global challenge for healthcare systems.[25–27] Pandemic models of care may have influenced healthcare systems and patient outcomes.[28] Our study covered the COVID-19 peak which affected Victoria between the end of 2021 and early 2022, when many hospitals relied on nursing staff without critical care experience redeployed into ICU.[13] While it is likely that this is an important factor in our findings, it is also important to note that without redeployment to increase total ICU staffing levels over the peak pandemic demand, it is possible mortality would have been even higher.

Chronic shortages of postgraduate qualified critical care nurses existed pre-pandemic and continue to challenge health systems' ability to respond to critical care demand through sustainable training, education, recruitment, and retention strategies.[29,30] These were exacerbated during the COVID-19 pandemic. Our study raises the possibility that inadequate numbers of critical care trained nurses may have contributed to excess mortality during the pandemic and also potentially to the ongoing reversal of the annual reduction in mortality presently reported in Australian ICUs.[24,31] The consistency of our findings after adjusting for the ICU Activity index, which is a measure of overall ICU strain combining patient acuity and staffing, suggests that the skill-mix itself is an independent factor influencing patient outcomes which goes beyond the absolute number of nursing staff available and the overall acuity of the ICU. Our finding that CCRN skill-mix was not associated with outcomes in those who did not receive invasive ventilation, renal replacement or ECMO, has important implications to the allocation of nurse staffing. Our study also highlights the need to continue to gather nursing workforce skill-mix data so that changes to ICU models of care and staffing can be properly evaluated. We recommend classifying post-graduate ICU educated nurses as CCRN in future data collection with years of experience as a different construct.

5.1. Strengths

Our study included a large number of patients from 20 hospitals representing a majority of ICU admissions in Victoria, all hospital types and all major diagnostic groups. We controlled for confounding factors, including severity of illness, gender, frailty, COVID-19, Activity index, and hospital type. We have accounted for ICU strain which is recognised as an important factor influencing

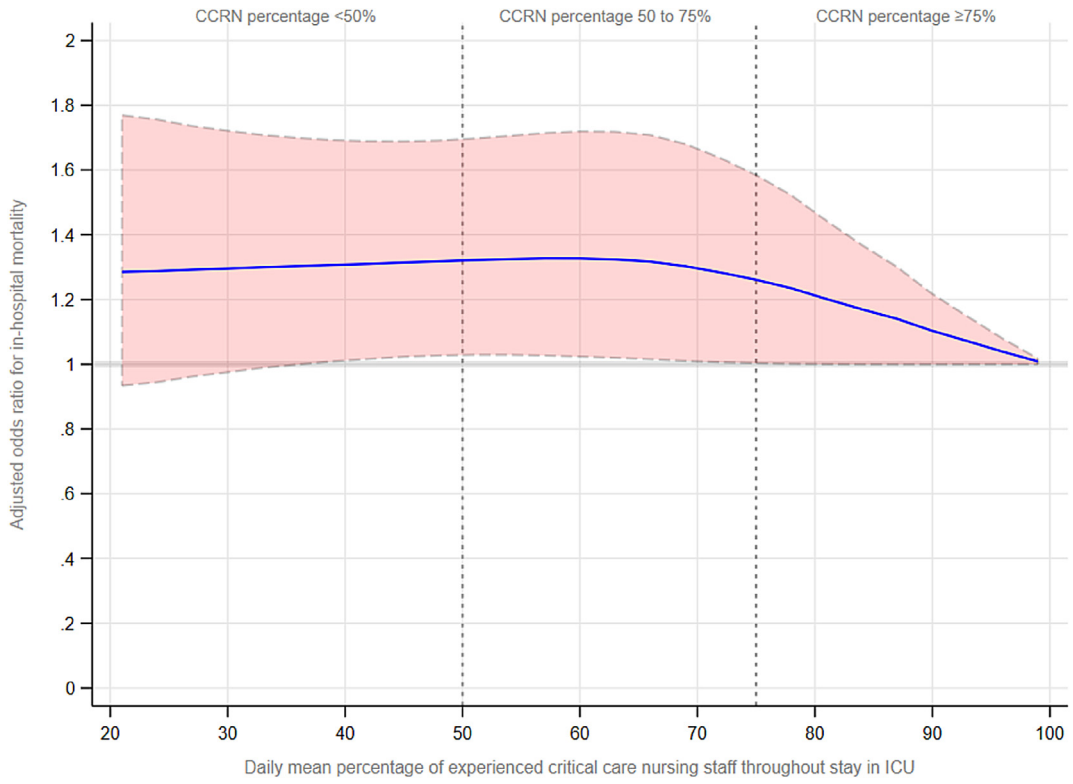

Fig. 2. Adjusted odds of in-hospital mortality plotted across the mean daily percentage of critical care registered nurses (CCRN) over the duration of the patient stay in ICU.

access to ICU and patient outcomes.[31,32] Subgroup and sensitivity analyses showed the relationship between the percentage of CCRN and mortality was predominantly confined to patients requiring invasive ICU therapies in whom critical care expertise is most needed. This supports a causal relationship between nursing skill-mix and patient outcomes.

5.2. Limitations

The Safer Care Victoria COVID-19 ICU Group One staffing classification combined nurses with a specialist postgraduate qualification with general registered nurses who had at least five years of ICU experience.[12] Thus, we cannot determine whether years of experience or formal critical care training with a qualification has a greater effect on patient outcomes. The influence of advanced clinical nursing roles such as nurse practitioners, clinical nurse educator, charge nurse/associate nurse unit manager and clinical coordinator/patient access nurse is unknown as they were not identifiable in our skill-mix calculations. We cannot tell whether the lack of effect seen in the group with the lowest CCRN percentage contains a true effect which we failed to detect in this smaller group, or if there were strategies in place to support patients looked after in these ICUs to mitigate any adverse outcomes. This study has all the limitations of retrospective data, with the potential for residual unmeasured confounding leading to overestimation of the effect of nursing skill-mix in the primary risk-adjusted analysis. Generalisability of our findings to other parts of Australia and healthcare systems in other countries is uncertain. It is possible that Victorian ICUs which were invited to participate but did not provide staffing data, were those with fewer staffing resources and could thus not collect the required information. Our study was limited to reporting ICU-only workforce data and not other components of the hospital system. The primary outcome of in-hospital mortality may also have been impacted by the levels and experience of ward nursing staff. Other potential factors such as organisational culture, impact of the COVID-19 pandemic on healthcare professionals' work practices, well-being, burnout and attrition were unknown. Finally, we did not have data on ICU medical or allied health staffing.

6. Conclusion

The nursing skill-mix in ICU impacts patient outcomes and should be routinely monitored. Addressing CCRN shortages is likely to lead to improved patient outcomes. Health system regulators, hospital administrators and leaders in Australian ICUs should ensure nursing workforce planning and education align with these findings to maximise patient outcomes.

Conflict of interest

Conflicts of interests and relevant funding are also disclosed as part of this statement.

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CRediT authorship contribution statement

Paul Ross: Conceptualisation of the project; Contributed to the development and design of methodology; contributed to the achievement of the project design, objectives, deliverables, and outcomes; Participated in project meetings; Contributed to HREC application, data collection tool, ethics preparation and application, data analysis and interpretation and reports; Contributed to the

validation and formal analysis of results; Contributed in the preparation, review and editing of the manuscript; Contribute to publication and dissemination; No funding relevant to the article; Nil conflict of interests to report. **Rose Jaspers**: Conceptualisation of the project; Contributed to the development and design of methodology; Contributed to the achievement of the project design, objectives, deliverables, and outcomes; Participated in project meetings; Contributed to HREC application, data collection tool, ethics preparation and application, data analysis and interpretation and reports; Contributed to the validation and formal analysis of results; Contributed in the preparation, review and editing of the manuscript; Contribute to publication and dissemination; No funding relevant to the article; Conflict of interests to report: Rose Jaspers represents the Australian College of Critical Care Nurses (ACCCN) for the Victorian ICU Nurse Unit Manager Community of Practice group. **Jason Watterson**: Conceptualisation of the project; 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Appendix

Table A1
Comparison of survivors to those who died in-hospital

Patient characteristics	Alive	Dead	p value
	N = 14,973	N = 1645	
Critical Care Registered Nurse percentage	70.0 (55.2–81.1)	66.7 (54.6–77.7)	<0.001
Critical Care Registered Nurse group			<0.001
CCRN >75%	6029 (40.3%)	534 (32.5%)	
CCRN 50–75%	6836 (45.7%)	859 (52.2%)	
CCRN <50%	2108 (14.1%)	252 (15.3%)	
Age in years	60.8 (17.6)	67.7 (14.7)	<0.001
Men	8587 (57.3%)	1064 (64.7%)	<0.001
Source of admission to ICU			<0.001
Operating theatre	6458 (43.1%)	308 (18.7%)	
Emergency department	5311 (35.5%)	689 (41.9%)	
Hospital ward	1959 (13.1%)	473 (28.8%)	
Other hospital	1196 (8.0%)	174 (10.6%)	
Other/unknown admission source	49 (0.3%)	1 (0.1%)	
Admission category			<0.001
Emergency surgical admission	2590 (17.3%)	260 (15.8%)	
Medical ICU admission	8343 (55.7%)	1334 (81.1%)	
Planned ICU admission after elective surgery	4040 (27.0%)	51 (3.1%)	
ICU admission diagnosis			<0.001
Cardiac medical diagnoses	1454 (9.7%)	422 (25.7%)	
Respiratory medical diagnoses (excl. pneumonia)	1075 (7.2%)	131 (8.0%)	
Sepsis and other infections (incl. pneumonia)	2182 (14.6%)	464 (28.2%)	
Other medical diagnoses (incl. overdose)	2139 (14.3%)	151 (9.2%)	
Cardiothoracic & vascular surgery	1176 (7.9%)	72 (4.4%)	
Coronary artery bypass and/or valve surgery	1511 (10.1%)	19 (1.2%)	
Gastro-intestinal surgery	1641 (11.0%)	95 (5.8%)	
Neurological and neurosurgical diagnoses	1000 (6.7%)	149 (9.1%)	
Orthopaedic surgery	606 (4.0%)	13 (0.8%)	
Trauma	1101 (7.4%)	98 (6.0%)	
COVID-19 pneumonitis	391 (2.6%)	117 (7.1%)	<0.001
Comorbidities and frailty			
Diabetes	3468 (23.2%)	436 (26.5%)	0.002
Chronic - cardiovascular	813 (5.4%)	119 (7.2%)	0.003
Chronic - respiratory	1080 (7.2%)	166 (10.1%)	<0.001
Chronic - dialysis dependent	524 (3.5%)	89 (5.4%)	<0.001
Chronic - liver disease (cirrhosis)	382 (2.6%)	104 (6.3%)	<0.001
Frailty category (clinical frailty scale – CFS)			<0.001
Not frail (CFS <5)	7565 (50.5%)	612 (37.2%)	
Pre-frail (CFS 5 or 6)	3970 (26.5%)	604 (36.7%)	
Frail (CFS >6)	814 (5.4%)	222 (13.5%)	
Frailty score missing	2624 (17.5%)	207 (12.6%)	
Illness severity scores			
APACHE III/IV score	50.8 (21.4)	85.9 (30.0)	<0.001
ANZROD percent (mean, median [IQR])	7.2, 1.9 (0.6–7.3)	41.1, 36.1 (15.4–65.5)	<0.001
Therapies provided in ICU			
Invasive ventilation	5591 (37.3%)	1052 (64.0%)	<0.001
Renal replacement therapy	657 (4.8%)	359 (23.5%)	<0.001
Extracorporeal membrane oxygenation	61 (0.5%)	28 (1.9%)	<0.001
Inotropes	6056 (44.6%)	1172 (77.2%)	<0.001
Invasive ventilation, renal replacement or ECMO	5877 (39.3%)	1123 (68.3%)	<0.001
Daily staffing characteristics of the ICU			
Overall daily percentage of experienced CCRNs throughout admission	70.0 (55.2–81.1)	66.7 (54.5–77.7)	<0.001
Percentage of experienced CCRNs on day of admission	69.7 (54.8–82.5)	66.7 (53.8–78.9)	<0.001
Critical care trained nurses	12.0 (6.0–25.0)	10.0 (5.0–22.0)	<0.001
Early career/in training critical care nurses	3.0 (1.0–7.0)	4.0 (2.0–8.0)	<0.001
Nurses without ICU experience redeployed into ICU	0.0 (0.0–1.0)	0.0 (0.0–2.0)	<0.001
Nursing students & 'non-nursing' staff providing bedside care in ICU	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.71
Hospital classification			<0.001
Public rural/regional (4 ICUs)	1894 (13%)	177 (11%)	
Public metropolitan (6 ICUs)	3555 (24%)	468 (28%)	
Public tertiary (5 ICUs)	6832 (46%)	875 (53%)	
Private (5 ICUs)	2692 (18%)	125 (8%)	
Characteristics of the ICU on day of admission			
Baseline business as usual ICU beds	17.0 (10.0–26.0)	17.0 (10.0–32.0)	<0.001
Number of open available ICU beds	12.0 (7.5–27.0)	14.0 (9.0–32.0)	<0.001
Number of vacant ICU beds	1.9 (0.9–3.3)	1.8 (0.8–3.0)	0.12
Occupancy	87.0 (75.0–94.0)	90.0 (79.0–95.0)	<0.001
Activity Index of the ICU			
Number of patients receiving 1:1 nursing in ICU	8.8 (3.0–23.7)	11.0 (5.0–28.0)	<0.001

(*continued on next page*)

Table A1 (*continued*)

Patient characteristics	Alive	Dead	p value
	N = 14,973	N = 1645	
Number of ventilated patients in ICU	4.0 (1.0–13.3)	6.0 (2.0–15.3)	<0.001
Number of COVID-19 patients in ICU	1.0 (0.0–3.0)	1.6 (0.0–4.5)	<0.001
Number of patients on renal replacement therapy in ICU	1.0 (0.0–2.0)	1.0 (0.0–3.0)	<0.001
Number of 1:2/HDU patients in ICU	3.0 (1.3–5.0)	3.0 (1.0–5.3)	0.064
Outcomes			
In-ICU mortality	0 (0.0%)	1125 (68.4%)	N/A
Delirium in ICU	885 (8.2%)	141 (12.9%)	<0.001
Pressure injury developed in ICU	169 (1.5%)	69 (5.9%)	<0.001
Duration of ICU stay (days)	1.9 (1.0–3.7)	3.3 (1.2–6.9)	<0.001
Ratio of observed to predicted length of ICU stay	1.05 (0.65–1.77)	1.37 (0.64–2.98)	<0.001
Duration of stay in hospital (days)	8.2 (4.4–15.1)	7.0 (2.8–14.8)	<0.001
After-hours discharge from ICU (ICU survivors only)	2838 (19.0%)	121 (23.3%)	0.014

APACHE, Acute Physiology and Chronic Health Evaluation; ANZROD, Australian & New Zealand Risk of Death. CCRN, Critical Care Registered Nurse; HDU, high-dependency unit; ICU, Intensive Care Unit. A vacant ICU bed is one that is not occupied by a patient but is available, equipped and can be staffed with 1:1 nursing ratio. A staffed ICU bed is equipped and can be staffed with 1:1 nursing ratio but may or may not be filled by a patient.

Table A2
Supplementary methods information about the ICU Activity index

A high Activity Index is a marker of ICU strain. The Activity index of the ICU was extracted from The Critical Health Resources Information System (CHRIS).[33] It combines markers of aggregate patient acuity with overall available nursing resources to staff open beds within the ICU. The Activity index was calculated as:

$$Activity\ index\ = \frac{1:1\ Nursing + MV + RRT + ECMO + COVIDs}{Staffed\ ICU\ beds}$$

where 1:1 nursing = number of patients requiring 1:1 nurse to patient ratio; MV = number of ICU patients receiving invasive ventilation; RRT = number of ICU patients receiving renal replacement therapy; ECMO = number of ICU patients receiving extracorporeal membrane oxygenation (ECMO); COVIDs = number of 'active' COVID-19 patients requiring isolation within the ICU; and staffed ICU beds = total number of available, equipped and staffed bed spaces in the ICU, including any open additional surge beds. The number of staffed ICU beds is equal to the total number of nurses available to provide 1:1 care to ICU patients. Activity indices for each day at every site were summed and divided by the total number of values available for that 24-h period, to create a mean daily Activity index on the day of each patient's admission to ICU.

For example, the Activity index of a ten-bed ICU where five beds were occupied by ventilated patients (five points) requiring 1:1 nursing (five points), of whom two were isolated for COVID-19 (two points), one bed was occupied by a non-ventilated patient requiring 1:1 nursing (one point) and there were four non-ventilated patients requiring 1:2 nursing (zero points) including one who had COVID-19 but was no longer in isolation precautions (zero points), had a value of 1.3.

Patients in an ICU with a high Activity Index have an increased risk of death, afterhours discharge, readmission, and transfer to another ICU.[15]

Table A3
Characteristics of study ICUs compared to ICUs in all other Victorian hospitals

	Other Victorian hospitals	Study hospitals	p value
	N = 26	N = 20	
Number of patients per site	438 (303–685)	758 (562–1044)	0.001
Hospital type: n (%)			0.063
Public rural/regional	8 (31%)	4 (20%)	
Public metropolitan	4 (15%)	6 (30%)	
Public tertiary	1 (4%)	5 (25%)	
Private	13 (50%)	5 (25%)	
Demographics			
Age in years	65.4 (61.8–68.4)	61.6 (59.6–64.8)	0.019
Proportion male (%)	55.2 (52.1–57.4)	56.9 (53.5–59.0)	0.44
Proportion elective surgical admissions (%)	30.3 (6.5–67.5)	16.6 (12.4–47.5)	0.56
Proportion medical admissions (%)	57.2 (22.3–81.1)	65.3 (40.4–70.7)	0.86
Proportion cardiac surgery (%)	0 (0–18.2)	0 (0–14.4)	0.75
Therapies (number of patients per site)			
Invasive ventilation	81 (14–211)	235 (107–531)	0.005
Renal replacement therapy	3 (0–17)	37 (9–73)	<0.001
Ventilated, renal replacement or ECMO	89 (16–216)	257 (114–553)	0.005
Illness severity and frailty scores			
Frailty score (clinical frailty scale)	3.4 (3.2–3.8)	3.5 (3.3–3.7)	0.79
APACHE II score	14.1 (12.3–16.1)	15.9 (13.7–16.8)	0.088
APACHE III score	48.1 (43.7–52.6)	52.9 (46.8–57.4)	0.13
Predicted risk of death	5.5 (3.6–9.7)	10.5 (5.1–12.4)	0.076
Outcomes			
In-hospital mortality	5.6 (1.9–8.4)	10.3 (5.3–11.6)	0.012
In-ICU mortality	2.5 (0.7–4.8)	6.4 (2.9–8.3)	0.015
Readmission to ICU	3.0 (1.5–4.4)	3.5 (2.1–4.5)	0.71
ICU length of stay in days	1.8 (1.5–2.1)	2.0 (1.7–2.2)	0.23
Hospital length of stay in days	6.4 (4.4–8.6)	7.6 (5.5–8.6)	0.18

All statistics are median and interquartile value for sites during the study period (Dec 2021 to Sept 2022) unless otherwise stated. APACHE, Acute Physiological and Chronic Health Evaluation; ECMO, Extracorporeal membrane oxygenation.

Table A4
Comparison of patients at participating sites who could be linked to staffing data to those where linkage was not possible (admitted on days went no staffing information was submitted.

	No Staffing Data	Staffing Data Available	p value
	N = 1653	N = 16,618	
Age in years	62.6 (17.5)	61.5 (17.4)	0.012
Men	994 (60.1%)	9651 (58.1%)	0.11
Source of admission to ICU			<0.001
Operating theatre	893 (54.0%)	6766 (40.7%)	
Emergency department	473 (28.6%)	6000 (36.1%)	
Hospital ward	193 (11.7%)	2432 (14.6%)	
Other hospital	83 (5.0%)	1370 (8.2%)	
Other/unknown admission source	11 (0.7%)	50 (0.3%)	
Admission category			<0.001
Emergency surgical admission	264 (16.0%)	2850 (17.2%)	
Medical ICU admission	757 (45.8%)	9677 (58.2%)	
Planned ICU admission after elective surgery	632 (38.2%)	4091 (24.6%)	
ICU admission diagnosis			<0.001
Cardiac medical diagnoses	116 (7.0%)	1876 (11.3%)	
Respiratory medical diagnoses (excl. pneumonia)	108 (6.5%)	1206 (7.3%)	
Sepsis and other infections (incl. pneumonia)	208 (12.6%)	2646 (15.9%)	
Other medical diagnoses (incl. overdose)	181 (10.9%)	2290 (13.8%)	
Cardiothoracic & vascular surgery	136 (8.2%)	1248 (7.5%)	
Coronary artery bypass and/or valve surgery	241 (14.6%)	1530 (9.2%)	
Gastro-intestinal surgery	193 (11.7%)	1736 (10.4%)	
Neurological and neurosurgical diagnoses	128 (7.7%)	1149 (6.9%)	
Orthopaedic surgery	129 (7.8%)	619 (3.7%)	
Trauma	131 (7.9%)	1199 (7.2%)	
Other surgical diagnoses	82 (5.0%)	1119 (6.7%)	
COVID-19 pneumonitis	42 (2.5%)	508 (3.1%)	0.24
Comorbidities and frailty			
Diabetes	342 (20.7%)	3904 (23.5%)	0.010
Chronic - cardiovascular	163 (9.9%)	932 (5.6%)	<0.001
Chronic - respiratory	115 (7.0%)	1246 (7.5%)	0.42
Chronic - dialysis dependent	42 (2.5%)	613 (3.7%)	0.017
Chronic - liver disease (cirrhosis)	21 (1.3%)	486 (2.9%)	<0.001
Frailty category			<0.001
Not frail (CFS1-3)	731 (44.2%)	8177 (49.2%)	
Pre-frail (CFS 4,5)	416 (25.2%)	4574 (27.5%)	
Frail (CFS 6–8)	98 (5.9%)	1036 (6.2%)	
Frailty unknown	408 (24.7%)	2831 (17.0%)	
Illness severity scores			
APACHE III/IV score	52.2 (23.7)	54.2 (24.7)	0.002
ANZROD percent	7.7 (15.7)	10.6 (18.4)	<0.001
Hours in hospital prior to ICU admission	10.1 (5.4–26.9)	9.4 (4.8–24.5)	<0.001
Therapies provided in ICU			
Invasive ventilation	654 (39.6%)	6643 (40.0%)	0.75
Renal replacement therapy	71 (4.7%)	1016 (6.7%)	0.002
ECMO	5 (0.3%)	89 (0.6%)	0.20
Invasive ventilation, renal replacement or ECMO	672 (40.7%)	7000 (42.1%)	0.25
Inotropes	658 (42.8%)	7228 (47.9%)	<0.001
No ventilation, renal replacement or ECMO	981 (59.3%)	9618 (57.9%)	0.25
Hospital classification			<0.001
Public rural/regional (4 ICUs)	180 (11%)	2071 (12%)	
Public metropolitan (6 ICUs)	266 (16%)	4023 (24%)	
Public tertiary (5 ICUs)	420 (25%)	7707 (46%)	
Private (5 ICUs)	787 (48%)	2817 (17%)	
Characteristics of the ICU on day of admission			
Baseline business-as-usual ICU beds	11.0 (7.0–26.0)	17.0 (10.0–26.0)	<0.001
Number of open available ICU beds	10.5 (6.0–17.0)	12.3 (8.0–27.3)	<0.001
Number of vacant ICU beds	2.5 (1.3–4.3)	1.8 (0.9–3.3)	<0.001
Occupancy	80.0 (66.0–91.0)	88.0 (75.0–94.0)	<0.001
Activity Index of the ICU	1.0 (0.5–1.5)	1.3 (0.8–1.6)	<0.001
Number of 'ICU equivalents'	8.0 (3.5–14.0)	10.5 (5.5–25.5)	<0.001
Number of patients receiving 1:1 nursing in ICU	6.0 (1.5–12.5)	9.0 (3.5–24.0)	<0.001
Number of ventilated patients in ICU	2.0 (1.0–6.0)	4.5 (1.3–13.5)	<0.001
Number of COVID-19 patients in ICU	1.0 (0.0–3.5)	1.0 (0.0–3.0)	<0.001
Number of patients on renal replacement therapy in ICU	0.0 (0.0–2.0)	1.0 (0.0–2.0)	<0.001
Number of 1:2/HDU patients in ICU	3.0 (1.7–5.0)	3.0 (1.3–5.0)	0.047
Outcomes			
In-hospital mortality	143 (8.7%)	1645 (9.9%)	0.10
In-ICU mortality	103 (6.2%)	1125 (6.8%)	0.40
Delirium in ICU	117 (8.6%)	1026 (8.6%)	0.94
Pressure injury developed in ICU	30 (2.2%)	238 (1.9%)	0.52
Duration of ICU stay (days)	1.9 (1.0–3.4)	2.0 (1.0–3.9)	0.006

(*continued on next page*)

Table A4 (*continued*)

	No Staffing Data	Staffing Data Available	p value
	N = 1653	N = 16,618	
Ratio of observed to predicted length of ICU stay	1.09 (0.71–1.76)	1.07 (0.65–1.84)	0.36
Duration of stay in hospital (days)	8.5 (4.9–14.4)	8.1 (4.2–15.1)	0.25
After-hours discharge from ICU (ICU survivors only)	228 (14.7%)	2959 (19.1%)	<0.001

APACHE, Acute Physiology and Chronic Health Evaluation; ANZROD, Australian & New Zealand Risk of Death. CCRN, Critical Care Registered Nurse; HDU, high-dependency unit; ICU, Intensive Care Unit. A vacant ICU bed is one that is not occupied by a patient but is available, equipped and can be staffed with 1:1 nursing ratio. A staffed ICU bed is equipped and can be staffed with 1:1 nursing ratio but may or may not be filled by a patient.

Table A5
Mixed effects hierarchical multivariable logistic regression for in-hospital mortality adjusted for sex, illness severity, COVID-19 status, frailty, ICU activity index and hospital type (with site as random effect) in all patients and in subgroups categorised by a. invasive therapies (invasive ventilation, renal replacement or ECMO), b. no invasive therapies and c. patients in public hospital ICUs.

	Whole study cohort		Subgroups					
	All patients		a. Invasive ventilation, renal replacement, ECMO		b. No invasive ventilation, renal replacement, ECMO		c. Public Hospital ICUs	
	OR (95% CI)	p value	OR (95% CI)	p value	OR (95% CI)	p value	OR (95% CI)	p value
CCRN >75%	Reference value		Reference value		Reference value		Reference value	
CCRN 50–75%	1.21 (1.02–1.45)	0.032	1.35 (1.11–1.64)	0.003	1.05 (0.79–1.39)	0.76	1.27 (1.06–1.52)	0.011
CCRN <50%	1.21 (0.94–1.55)	0.14	1.28 (0.98–1.66)	0.07	1.14 (0.76–1.71)	0.52	1.24 (0.97–1.59)	0.08
Male	1.29 (1.13–1.46)	<0.001	1.07 (.91–1.26)	0.41	1.51 (1.22–1.87)	<0.001	1.28 (1.12–1.47)	<0.001
Australian & New Zealand Risk of Death (%)	1.06 (1.06–1.07)	<0.001	1.06 (1.05–1.06)	<0.001	1.07 (1.07–1.08)	<0.001	1.06 (1.06–1.06)	<0.001
COVID-19 patient	2.61 (2.11–3.21)	<0.001	2.92 (2.21–3.86)	<0.001	2.48 (1.77–3.46)	<0.001	2.59 (2.10–3.20)	<0.001
Frailty category (clinical frailty scale – CFS)								
Not frail (CFS <5)	Reference value		Reference value		Reference value		Reference value	
Pre-frail (CFS 5 or 6)	1.67 (1.44–1.94)	<0.001	1.54 (1.29–1.85)	<0.001	2.62 (1.96–3.49)	<0.001	1.62 (1.40–1.89)	<0.001
Frail (CFS >6)	2.89 (2.34–3.57)	<0.001	1.99 (1.44–2.75)	<0.001	6.10 (4.39–8.48)	<0.001	2.60 (2.10–3.23)	<0.001
Frailty score missing	1.49 (1.08–2.03)	0.014	0.86 (0.64–1.14)	0.29	3.18 (1.98–5.11)	<0.001	1.09 (0.77–1.55)	0.62
ICU activity index	1.03 (0.86–1.24)	0.72	0.95 (0.76–1.19)	0.65	1.01 (0.76–1.34)	0.96	1.01 (0.84–1.22)	0.91
Hospital classification								
Tertiary (5 ICUs)	Reference value		Reference value		Reference value		Reference value	
Metropolitan (6 ICUs)	1.09 (0.83–1.44)	0.54	1.06 (0.85–1.33)	0.59	1.38 (0.90–2.12)	0.14	1.02 (0.80–1.29)	0.89
Rural/regional (4 ICUs)	1.03 (0.71–1.49)	0.89	1.18 (0.81–1.73)	0.39	1.25 (0.72–2.17)	0.43	0.94 (0.67–1.32)	0.73
Private (5 ICUs)	0.94 (0.64–1.38)	0.75	1.16 (0.76–1.76)	0.48	1.04 (0.60–1.82)	0.88	Not applicable	
AUROC	0.892		0.878		0.892		0.886	
Brier score	0.063		0.093		0.040		0.070	

Each column represents a separate multivariable hierarchical logistic regression model. The Australian and New Zealand Risk of Death (ANZROD) model includes age, acute physiological and biochemical disturbance, chronic comorbidities, treatment limitations, elective surgical status and source of admission with individual predictive equations for each ICU admission diagnosis. Sex, frailty and COVID-19 status were entered separately into each model because these are not included in ANZROD.
AUROC, Area under receiver operating characteristic curve; CCRN, Critical Care Registered Nurse; ECMO, Extra-corporeal Membrane Oxygenation, ICU, Intensive Care Unit: OR (95% CI), Adjusted odds ratio and 95% confidence interval.

Table A6
Subgroup of 7000 patients who received invasive critical care therapies (invasive ventilation, renal replacement, or extracorporeal membrane oxygenation) – baseline characteristics by category of percentage of critical care registered nurses (CCRN) in each ICU.

	<50 % CCRN	50–75% CCRN	>75% CCRN	p value
	N = 952	N = 3297	N = 2751	
Age in years[a]	57.5 (17.3)	58.8 (16.9)	60.3 (16.9)	<0.001
Men	616 (64.7%)	2138 (64.8%)	1818 (66.1%)	0.55
Source of admission to ICU				<0.001
Operating theatre	377 (39.6%)	1290 (39.1%)	1465 (53.3%)	
Emergency department	366 (38.4%)	1234 (37.4%)	777 (28.2%)	
Hospital ward	85 (8.9%)	398 (12.1%)	235 (8.5%)	
Other hospital	121 (12.7%)	362 (11.0%)	265 (9.6%)	
Other/unknown admission source	3 (0.3%)	13 (0.4%)	9 (0.3%)	
Admission category				<0.001
Emergency surgical admission	216 (22.7%)	742 (22.5%)	513 (18.6%)	
Medical ICU admission	572 (60.1%)	1984 (60.2%)	1239 (45.0%)	
Planned ICU admission after elective surgery	164 (17.2%)	571 (17.3%)	999 (36.3%)	
ICU admission diagnosis				<0.001
Cardiac medical diagnoses	122 (12.8%)	422 (12.8%)	252 (9.2%)	
Respiratory medical diagnoses (excl. pneumonia)	63 (6.6%)	189 (5.7%)	95 (3.5%)	
Sepsis and other infections (incl. pneumonia)	145 (15.2%)	503 (15.3%)	269 (9.8%)	
Other medical diagnoses (incl. overdose)	125 (13.1%)	475 (14.4%)	273 (9.9%)	
Cardiothoracic & vascular surgery	68 (7.1%)	232 (7.0%)	206 (7.5%)	
Coronary artery bypass and/or valve surgery	134 (14.1%)	509 (15.4%)	871 (31.7%)	
Gastro-intestinal surgery	67 (7.0%)	247 (7.5%)	168 (6.1%)	
Neurological and neurosurgical diagnoses	56 (5.9%)	299 (9.1%)	277 (10.1%)	
Orthopaedic surgery	5 (0.5%)	20 (0.6%)	39 (1.4%)	
Trauma	135 (14.2%)	268 (8.1%)	222 (8.1%)	
Other surgical diagnoses	32 (3.4%)	133 (4.0%)	79 (2.9%)	
COVID-19 pneumonitis	53 (5.6%)	145 (4.4%)	31 (1.1%)	<0.001
Comorbidities and frailty				
Diabetes	202 (21.2%)	805 (24.4%)	563 (20.5%)	<0.001
Chronic - cardiovascular	34 (3.6%)	120 (3.6%)	81 (2.9%)	0.30
Chronic - respiratory	61 (6.4%)	258 (7.8%)	93 (3.4%)	<0.001
Chronic - dialysis dependent	29 (3.0%)	170 (5.2%)	89 (3.2%)	<0.001
Chronic - liver disease (cirrhosis)	18 (1.9%)	174 (5.3%)	79 (2.9%)	<0.001
Frailty category				<0.001
Not frail (CFS1-3)	573 (60.2%)	1952 (59.2%)	1058 (38.5%)	
Pre-frail (CFS 4,5)	323 (33.9%)	934 (28.3%)	597 (21.7%)	
Frail (CFS 6–8)	37 (3.9%)	188 (5.7%)	77 (2.8%)	
Frailty unknown	19 (2.0%)	223 (6.8%)	1019 (37.0%)	
Illness Severity Scores				
APACHE II score[a]	19.3 (8.4)	19.5 (8.2)	16.4 (8.3)	<0.001
APACHE III score[a]	64.3 (29.1)	65.2 (27.9)	60.2 (26.5)	<0.001
ANZROD percent (median IQR)[b]	16.6 (23.6)	17.0 (23.4)	14.4 (22.9)	<0.001
ANZROD percent (mean, SD)[a]	5.2 (1.1–21.1)	5.6 (1.2–23.3)	3.0 (0.8–17.5)	<0.001
Therapies provided in ICU				
Invasive ventilation	903 (94.9%)	3101 (94.1%)	2639 (95.9%)	0.004
Renal replacement therapy	163 (17.3%)	562 (17.6%)	291 (13.4%)	<0.001
Extracorporeal membrane oxygenation	32 (3.4%)	44 (1.4%)	13 (0.6%)	<0.001
Inotropes	697 (73.8%)	2481 (77.8%)	1669 (78.3%)	0.015
Hospital Classification				<0.001
Public rural/regional (4 ICUs)	108 (11%)	292 (9%)	45 (2%)	
Public metropolitan (6 ICUs)	287 (30%)	960 (29%)	207 (8%)	
Public tertiary (5 ICUs)	554 (58%)	1941 (59%)	1905 (69%)	
Private (5 ICUs)	3 (0%)	104 (3%)	594 (22%)	
Primary outcome				
In-hospital mortality	169 (17.8%)	602 (18.3%)	352 (12.8%)	<0.001
Secondary outcomes				
In-ICU mortality	137 (14.4%)	462 (14.0%)	284 (10.3%)	<0.001
Delirium in ICU	166 (21.3%)	407 (15.9%)	63 (5.4%)	<0.001
Pressure injury developed in ICU	52 (6.1%)	121 (4.6%)	39 (3.2%)	0.007
Duration of ICU stay (days)	3.9 (1.8–8.1)	3.4 (1.8–7.1)	2.8 (1.7–5.0)	<0.001
Ratio of observed to predicted length of ICU stay	1.37 (0.69–2.58)	1.24 (0.68–2.34)	1.11 (0.65–1.87)	<0.001
Duration of stay in hospital (days)	11.1 (5.4–20.3)	10.9 (5.8–20.8)	9.8 (5.9–16.9)	<0.001
After-hours discharge from ICU[a]	348 (25.5%)	960 (22.5%)	461 (12.3%)	<0.001

APACHE, Acute Physiology and Chronic Health Evaluation; ANZROD, Australian & New Zealand Risk of Death. ICU, Intensive Care Unit. A vacant ICU bed is one that is not occupied by a patient but is available, equipped and can be staffed with 1:1 nursing ratio. A staffed ICU bed is equipped and can be staffed with 1:1 nursing ratio but may or may not be filled by a patient.
[a]Data reported as mean (standard deviation).
[b]median (interquartile range); all other data reported as number (percentage).

Table A7
Subgroup of 9618 patients who did not receive invasive critical care therapies (i.e. no invasive ventilation, renal replacement or extracorporeal membrane oxygenation) – baseline characteristics by category of percentage of critical care registered nurses (CCRN) in each ICU.

	<50 % CCRN	50–75% CCRN	>75% CCRN	p value
	N = 1408	N = 4398	N = 3812	
Age in years	63.0 (18.1)	62.9 (17.7)	63.4 (17.3)	0.39
Men	785 (55.8%)	2344 (53.3%)	1950 (51.2%)	0.01
Source of admission to ICU				<0.001
Operating theatre	380 (27.0%)	1385 (31.5%)	1869 (49.0%)	
Emergency department	699 (49.6%)	1924 (43.7%)	1000 (26.2%)	
Hospital ward	250 (17.8%)	816 (18.6%)	648 (17.0%)	
Other hospital	75 (5.3%)	265 (6.0%)	282 (7.4%)	
Other/unknown admission source	4 (0.3%)	8 (0.2%)	13 (0.3%)	
Admission category				<0.001
Emergency surgical admission	190 (13.5%)	637 (14.5%)	552 (14.5%)	
Medical ICU admission	1022 (72.6%)	2986 (67.9%)	1874 (49.2%)	
Planned ICU admission after elective surgery	196 (13.9%)	775 (17.6%)	1386 (36.4%)	
ICU admission diagnosis				<0.001
Cardiac medical diagnoses	183 (13.0%)	538 (12.2%)	359 (9.4%)	
Respiratory medical diagnoses (excl. pneumonia)	149 (10.6%)	471 (10.7%)	239 (6.3%)	
Sepsis and other infections (incl. pneumonia)	279 (19.8%)	875 (19.9%)	575 (15.1%)	
Other medical diagnoses (incl. overdose)	236 (16.8%)	716 (16.3%)	465 (12.2%)	
Cardiothoracic & vascular surgery	72 (5.1%)	308 (7.0%)	362 (9.5%)	
Coronary artery bypass and/or valve surgery	0 (0.0%)	5 (0.1%)	11 (0.3%)	
Gastro-intestinal surgery	137 (9.7%)	486 (11.1%)	631 (16.6%)	
Neurological and neurosurgical diagnoses	62 (4.4%)	203 (4.6%)	252 (6.6%)	
Orthopaedic surgery	39 (2.8%)	163 (3.7%)	353 (9.3%)	
Trauma	136 (9.7%)	297 (6.8%)	141 (3.7%)	
Other surgical diagnoses	115 (8.2%)	336 (7.6%)	424 (11.1%)	
COVID-19 pneumonitis	52 (3.7%)	152 (3.5%)	75 (2.0%)	<0.001
Comorbidities and frailty				
Diabetes	349 (24.8%)	1171 (26.6%)	814 (21.4%)	<0.001
Chronic - cardiovascular	115 (8.2%)	292 (6.6%)	290 (7.6%)	0.09
Chronic - respiratory	137 (9.7%)	467 (10.6%)	230 (6.0%)	<0.001
Chronic - dialysis dependent	34 (2.4%)	187 (4.3%)	104 (2.7%)	<0.001
Chronic - liver disease (cirrhosis)	32 (2.3%)	116 (2.6%)	67 (1.8%)	0.03
Frailty category				<0.001
Not frail (CFS1-3)	824 (58.5%)	2316 (52.7%)	1454 (38.1%)	
Pre-frail (CFS 4,5)	420 (29.8%)	1342 (30.5%)	958 (25.1%)	
Frail (CFS 6–8)	131 (9.3%)	389 (8.8%)	214 (5.6%)	
Frailty unknown	33 (2.3%)	351 (8.0%)	1186 (31.1%)	
Illness severity scores				
APACHE II score[a]	14.4 (6.4)	14.6 (6.4)	13.0 (6.2)	<0.001
APACHE III score[a]	47.1 (20.5)	49.4 (20.6)	46.1 (19.2)	<0.001
ANZROD percent (median IQR)[b]	6.9 (12.5)	7.4 (13.1)	5.8 (11.8)	<0.001
ANZROD percent (mean, SD)[a]	2.1 (0.5–7.2)	2.2 (0.6–7.4)	1.3 (0.4–5.1)	<0.001
Therapies provided in ICU				
Invasive ventilation	0 (0.0%)	0 (0.0%)	0 (0.0%)	
Renal replacement therapy	0 (0.0%)	0 (0.0%)	0 (0.0%)	
Extracorporeal membrane oxygenation	0 (0.0%)	0 (0.0%)	0 (0.0%)	
Inotropes	337 (24.2%)	1282 (30.4%)	762 (23.6%)	<0.001
Hospital Classification				<0.001
Public rural/regional (4 ICUs)	594 (42%)	887 (20%)	145 (4%)	
Public metropolitan (6 ICUs)	461 (33%)	1639 (37%)	469 (12%)	
Public tertiary (5 ICUs)	346 (25%)	1555 (35%)	1406 (37%)	
Private (5 ICUs)	7 (0%)	317 (7%)	1792 (47%)	
Primary outcome				
In-hospital mortality	83 (5.9%)	257 (5.8%)	182 (4.8%)	0.07
Secondary outcomes				
In-ICU mortality	43 (3.1%)	132 (3.0%)	67 (1.8%)	<0.001
Delirium in ICU	92 (7.5%)	211 (5.8%)	87 (3.4%)	<0.001
Pressure injury developed in ICU	5 (0.4%)	14 (0.4%)	7 (0.3%)	0.75
Duration of ICU stay (days)	1.7 (0.9–3.1)	1.7 (0.9–2.9)	1.2 (0.8–2.2)	<0.001
Ratio of observed to predicted length of ICU stay	1.10 (0.64–1.91)	1.02 (0.63–1.71)	0.95 (0.64–1.50)	<0.001
Duration of stay in hospital (days)	6.3 (3.2–11.3)	7.0 (3.9–12.7)	7.0 (3.7–12.7)	<0.001
After-hours discharge from ICU[a]	348 (25.5%)	960 (22.5%)	461 (12.3%)	<0.001

APACHE, Acute Physiology and Chronic Health Evaluation; ANZROD, Australian & New Zealand Risk of Death; ICU, Intensive Care Unit. A vacant ICU bed is one that is not occupied by a patient but is available, equipped and can be staffed with 1:1 nursing ratio. A staffed ICU bed is equipped and can be staffed with 1:1 nursing ratio but may or may not be filled by a patient.
[a]Data reported as mean (standard deviation).
[b]Median (interquartile range); all other data reported as number (percentage).

Table A8
Subgroup of 13,801 patients who were treated in public hospital ICUs – baseline characteristics by category of percentage of critical care registered nurses (CCRN) in each ICU.

	<50 % CCRN	50–75% CCRN	>75% CCRN	p value
	N = 2350	N = 7274	N = 4177	
Age in years	60.7 (18.0)	60.8 (17.5)	59.1 (17.6)	<0.001
Men	1395 (59.4%)	4245 (58.4%)	2520 (60.3%)	0.11
Source of admission to ICU				<0.001
Operating theatre	749 (31.9%)	2361 (32.5%)	1521 (36.4%)	
Emergency department	1064 (45.3%)	3115 (42.8%)	1577 (37.8%)	
Hospital ward	334 (14.2%)	1164 (16.0%)	594 (14.2%)	
Other hospital	196 (8.3%)	613 (8.4%)	467 (11.2%)	
Other/unknown admission source	7 (0.3%)	21 (0.3%)	18 (0.4%)	
Admission category				<0.001
Emergency surgical admission	406 (17.3%)	1320 (18.1%)	780 (18.7%)	
Medical ICU admission	1592 (67.7%)	4864 (66.9%)	2548 (61.0%)	
Planned ICU admission after elective surgery	352 (15.0%)	1090 (15.0%)	849 (20.3%)	
ICU admission diagnosis				<0.001
Cardiac medical diagnoses	305 (13.0%)	934 (12.8%)	456 (10.9%)	
Respiratory medical diagnoses (excl. pneumonia)	212 (9.0%)	648 (8.9%)	263 (6.3%)	
Sepsis and other infections (incl. pneumonia)	423 (18.0%)	1350 (18.6%)	696 (16.7%)	
Other medical diagnoses (incl. overdose)	360 (15.3%)	1160 (15.9%)	578 (13.8%)	
Cardiothoracic & vascular surgery	139 (5.9%)	484 (6.7%)	312 (7.5%)	
Coronary artery bypass and/or valve surgery	131 (5.6%)	457 (6.3%)	501 (12.0%)	
Gastro-intestinal surgery	201 (8.6%)	656 (9.0%)	356 (8.5%)	
Neurological and neurosurgical diagnoses	118 (5.0%)	471 (6.5%)	404 (9.7%)	
Orthopaedic surgery	44 (1.9%)	108 (1.5%)	55 (1.3%)	
Trauma	271 (11.5%)	561 (7.7%)	339 (8.1%)	
Other surgical diagnoses	146 (6.2%)	445 (6.1%)	217 (5.2%)	
COVID-19 pneumonitis	105 (4.5%)	291 (4.0%)	97 (2.3%)	<0.001
Comorbidities and frailty				
Diabetes	549 (23.4%)	1918 (26.4%)	1058 (25.3%)	0.014
Chronic - cardiovascular	149 (6.3%)	389 (5.3%)	117 (2.8%)	<0.001
Chronic - respiratory	198 (8.4%)	707 (9.7%)	211 (5.1%)	<0.001
Chronic - dialysis dependent	63 (2.7%)	346 (4.8%)	138 (3.3%)	<0.001
Chronic - liver disease (cirrhosis)	50 (2.1%)	288 (4.0%)	141 (3.4%)	<0.001
Frailty category				<0.001
Not frail (CFS1-3)	1394 (59.3%)	4208 (57.8%)	1976 (47.3%)	
Pre-frail (CFS 4,5)	742 (31.6%)	2233 (30.7%)	1099 (26.3%)	
Frail (CFS 6–8)	168 (7.1%)	567 (7.8%)	214 (5.1%)	
Frailty unknown	46 (2.0%)	266 (3.7%)	888 (21.3%)	
Illness severity scores				
APACHE II score	16.4 (7.7)	16.9 (7.6)	14.8 (8.1)	<0.001
APACHE III score	54.1 (25.8)	56.8 (25.4)	54.7 (25.5)	<0.001
ANZROD percent	10.9 (18.5)	12.0 (19.1)	12.6 (20.5)	0.002
ANZROD percent	2.9 (0.7–11.2)	3.4 (0.9–13.7)	3.3 (0.9–13.7)	<0.001
Therapies provided in ICU				
Invasive ventilation	900 (38.3%)	3002 (41.3%)	2065 (49.4%)	<0.001
Renal replacement therapy	163 (7.0%)	553 (7.8%)	259 (7.7%)	0.46
ECMO	32 (1.4%)	44 (0.6%)	12 (0.4%)	<0.001
Inotropes	1030 (44.2%)	3668 (51.8%)	1823 (55.2%)	<0.001
Hospital Classification				<0.001
Rural/regional (4 ICUs)	702 (30%)	1179 (16%)	190 (5%)	
Metropolitan (6 ICUs)	748 (32%)	2599 (36%)	676 (16%)	
Tertiary (5 ICUs)	900 (38%)	3496 (48%)	3311 (79%)	
Primary outcome				
In-hospital mortality	251 (10.7%)	844 (11.6%)	425 (10.2%)	0.054
Secondary outcomes				
In-ICU mortality	179 (7.6%)	586 (8.1%)	314 (7.5%)	0.54
Delirium in ICU	258 (12.9%)	611 (10.4%)	93 (5.6%)	<0.001
Pressure injury developed in ICU	57 (2.7%)	135 (2.3%)	44 (2.6%)	0.46
Duration of ICU stay (days)	2.2 (1.1–4.8)	2.2 (1.1–4.4)	2.0 (1.0–3.7)	<0.001
Ratio of observed to predicted length of ICU stay	1.18 (0.66–2.16)	1.12 (0.65–1.97)	0.95 (0.56–1.62)	<0.001
Duration of stay in hospital (days)	7.8 (3.8–14.8)	8.3 (4.3–15.9)	8.3 (4.3–15.5)	<0.001
After-hours discharge from ICU[a]	552 (25.4%)	1555 (23.3%)	725 (18.8%)	<0.001

APACHE, Acute Physiology and Chronic Health Evaluation; ANZROD, Australian & New Zealand Risk of Death; ICU, Intensive Care Unit. A vacant ICU bed is one that is not occupied by a patient but is available, equipped and can be staffed with 1:1 nursing ratio. A staffed ICU bed is equipped and can be staffed with 1:1 nursing ratio but may or may not be filled by a patient.
[a]Data reported as mean (standard deviation).
[b]Median (interquartile range); all other data reported as number (percentage).

Table A9
List of participating hospitals in the study.

Alfred Hospital ICU
Angliss Hospital ICU
Austin Hospital ICU
Bendigo Health Care Group ICU
Dandenong Hospital ICU
Epworth Freemasons Hospital ICU
Epworth Geelong ICU
Epworth Hospital (Richmond) ICU
Footscray Hospital ICU
Frankston Hospital ICU
Latrobe Regional Hospital ICU
Mildura Base Public Hospital ICU
Northeast Health Wangaratta ICU
Peninsula Private Hospital ICU
Royal Melbourne Hospital ICU
St John of God Hospital (Bendigo) ICU
St Vincent's Hospital (Melbourne) ICU
Sunshine Hospital ICU
The Northern Hospital ICU
University Hospital Geelong ICU

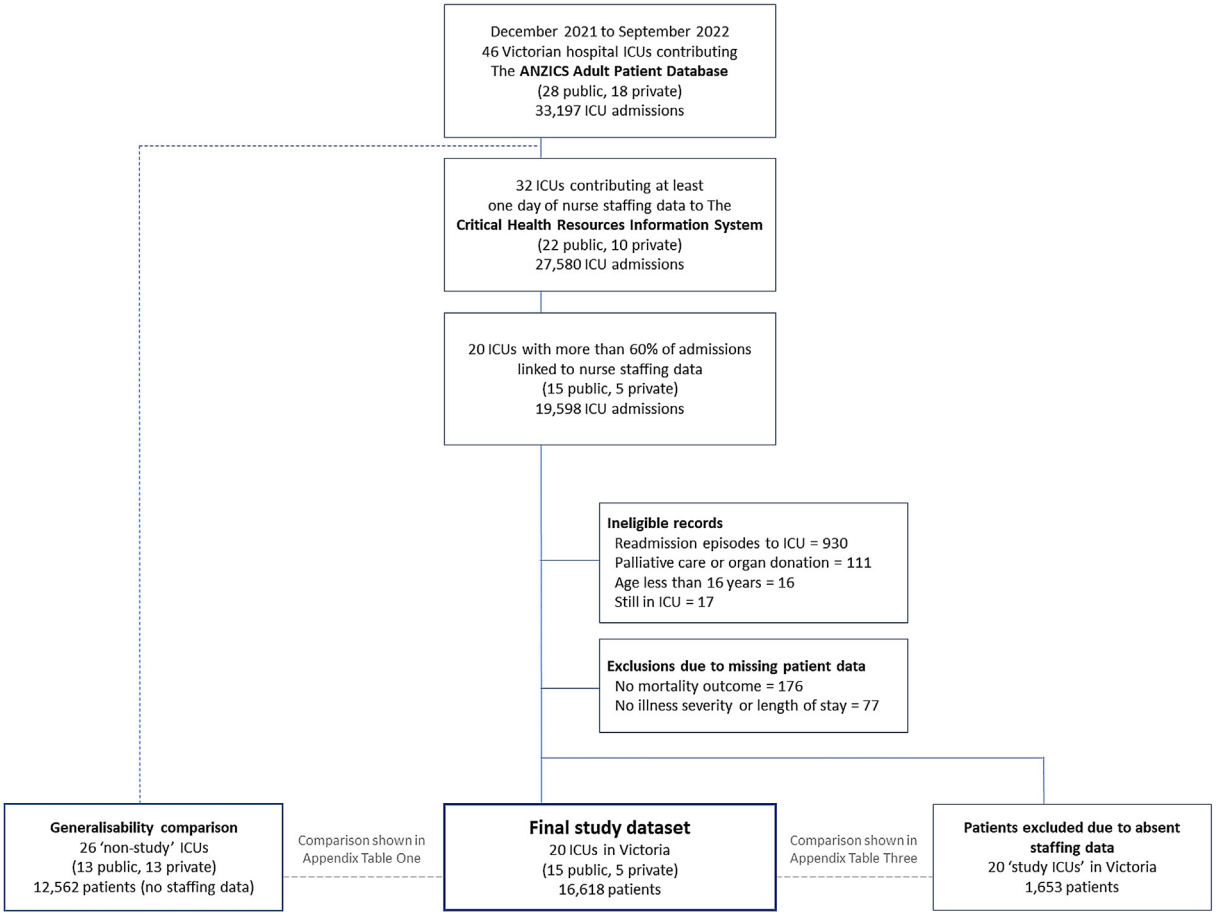

Fig. A1. Inclusions & exclusions.

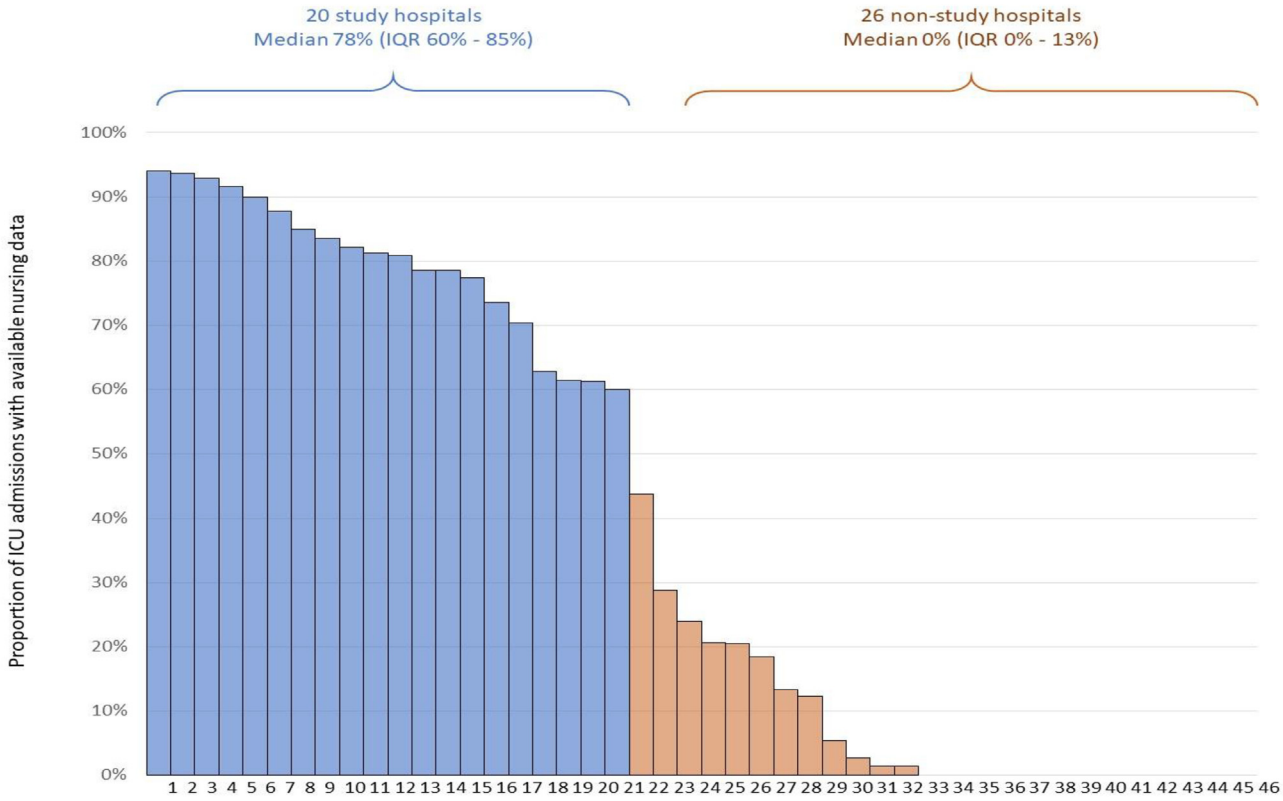

Fig. A2. Proportion of nursing data per site.

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