Device associated complications in the intensive care unit

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ABSTRACT

Invasive devices are routinely used in the care of critically ill patients. Although they are often essential components of patient care, devices such as intravascular catheters, endotracheal tubes, and ventilators are a common source of complications in the intensive care unit. Critical care practitioners who use these devices need to use strategies for risk reduction and understand approaches to management when adverse events occur. This review discusses the identification, prevention, and management of complications of vascular, airway, and mechanical support devices commonly used in the intensive care unit.

Introduction

Although mortality in the intensive care unit (ICU) has declined over time, ICU associated complications remain common, affecting up to a half of critically ill patients and resulting in increased mortality, longer hospital stays, and higher healthcare costs.[1-4] Although both patient related and healthcare associated factors contribute to adverse events, many complications are either direct or indirect consequences of ICU practices and are thus potentially avoidable. Invasive devices used in the ICU, although crucial for the management of critically ill patients, represent a common source of complications. The mainstay of avoiding device related adverse events consists of judicious use of devices and their timely removal. However, complications can occur even with vigilant use. In this narrative review, we focus on identifying, preventing, and managing complications associated with devices frequently used in the ICU.

Sources and selection criteria

We searched PubMed, Medline, and the Cochrane Database of Systematic Reviews for articles published from 2000 to 2023. We used the following search terms: “central venous catheters”, “arterial catheters”, “endotracheal tube”, “endotracheal intubation”, “tracheostomy”, “percutaneous dilatational tracheostomy”, and “extracorporeal membrane oxygenation”. Several keywords were combined with the term “complications” or with terms representing adverse events specific to particular devices. We reviewed relevant titles and abstracts and prioritized meta-analyses, systematic reviews, international guidelines, randomized controlled trials (RCTs), and large observational studies. In some areas, available data were limited to smaller observational studies or articles published before 2000; we included these when relevant. We excluded case reports and articles not in the English language.

Epidemiology

The insertion of vascular catheters, endotracheal airways, and extracorporeal support devices constitutes some of the most common invasive procedures in intensive care. Intravascular catheters, including central venous catheters (CVCs), arterial catheters, hemodialysis catheters, and pulmonary artery catheters, are inserted in up to three quarters of critically ill patients.[5] The use of airway devices is similarly widespread, with more than 1.5 million endotracheal intubations occurring outside of the operating room in the US annually and up to 24% of mechanically ventilated patients going on to receive tracheostomies.[6 7] The use of extracorporeal membrane oxygenation (ECMO) has also grown exponentially over the past decade, with notable rises seen during both the H1N1 influenza outbreak and the covid-19 pandemic.[8] The frequency of device associated complications in their entirety and their impact on morbidity and mortality in the ICU are not well established. Most large epidemiologic studies focus on infectious complications; less is known about mechanical complications. The rates, risk factors, and outcomes for such complications vary according to the type of device.

Complications of vascular devices

Although well defined indications for vascular devices have not been clearly established in clinical practice guidelines, these devices are used for several purposes, including the administration of vasoactive drugs, hemodynamic monitoring, hemodialysis, or introduction of other devices such as transvenous pacemakers. Two of the most used vascular devices—CVCs and arterial catheters—are discussed here.

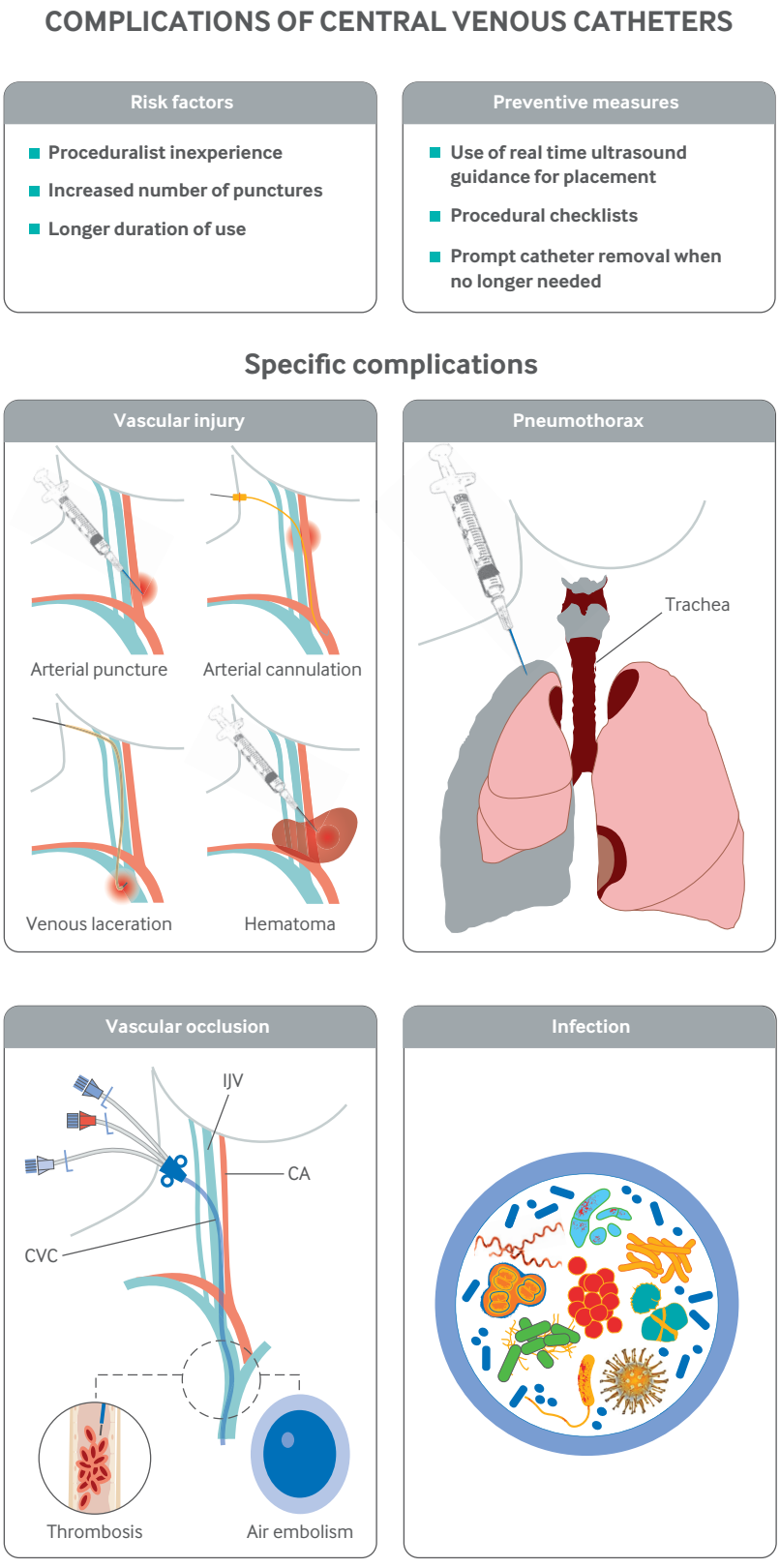

Fig 1 | Complications of central venous catheters (CVCs). CA=carotid artery; IJV=internal jugular vein

Central venous catheters

CVCs are placed in up to two thirds of patients in the ICU, with considerable center and geographic variability in use,[9 10] and are typically inserted in the internal jugular, femoral, or subclavian veins.[9 11 12] Adverse events can occur either during or after insertion. Although data from large epidemiologic studies are lacking, rates reported in RCTs and available observational studies range from 2% to 15%, with the type and frequency of complication varying by site.[12 13] Factors influencing the incidence of insertion related complications include the proceduralist's proficiency, number of punctures needed, cannulation site, and use of ultrasound.[12 14 15] Clinical practice guidelines recommend the use of real time ultrasonic guidance, with meta-analyses showing an associated improvement in first pass success rate, a decrease in the number of insertion attempts, and a reduction in the risk of insertion related complications.[5 15-18] Even with the use of ultrasound, however, limited operator experience (defined as <100 catheterizations) increases the risk of mechanical complications (odds ratio 3.11, 95% confidence interval (CI) 1.64 to 5.77).[19] Insertion related complications include vascular injury with resultant hematoma and/or blood loss, pneumothorax, and air embolism (fig 1).[20] Post-insertion risks include thrombosis and infection, which can be mitigated by prompt removal of the CVC once it is no longer indicated.[9 21] Although several steps can be taken to minimize the risk of individual complications, ultimately the most important risk reduction tactic is avoiding unnecessary CVC insertion. One of the most common uses for CVCs is vasopressor administration, but growing evidence shows that short term peripheral vasopressor infusion may be safe and feasible in select patients.[22-24] This information, as well as an assessment of patient specific risk factors for CVC associated complications, should be factored into decision making before catheter placement. We discuss individual complications of CVCs below. Notably, although many of the principles and complications that pertain to CVCs are also applicable to hemodialysis lines and pulmonary artery catheters, each of these devices has additional specific and nuanced complications that are outside the scope of this review.

Vascular injury

Vascular injury can be venous or arterial. Venous damage can involve posterior wall puncture, common in hypovolemic patients and typically of minimal consequence unless adjacent structures are injured, or the more serious complication of venous wall laceration. Laceration can occur as a result of inadvertent trapping of the guide wire against the vessel wall followed by attempts to advance the catheter or dilator; the resulting injury can potentially extend beyond the target vein to include the vena cava, other intrathoracic vessels, or the right atrium.[25] To avoid this complication, the guide wire should not be advanced when resistance is felt. Similarly, arterial injury can consist of either simple arterial puncture or more significant arterial cannulation. Real time ultrasonography has

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decreased the incidence of arterial puncture, with one meta-analysis of 130 studies showing a decrease from 69 events to 14 events per 1000 catheters (risk ratio 0.20, 95% credible interval (CrI) 0.09 to 0.44). Nevertheless, prompt identification of arterial puncture remains crucial for preventing the graver consequences of arterial cannulation.[15] Although identification is usually immediate via visualization of pulsatile blood flow, this may not be a reliable indicator in cases of severe shock. If the location of the needle or wire is unclear even after visualization with real time ultrasonography, a small single lumen catheter can be inserted over the guide wire and connected to a pressure transducer to ensure venous waveform before proceeding with dilation.[25]

When recognized, arterial puncture can typically be managed by removing the needle and applying pressure at the access site, although this may be more difficult at the subclavian position. Clinically significant bleeding (that is, needing blood transfusion or intervention), although rare, may occur, and consequent hematoma formation can potentially compress adjacent structures or lead to hemodynamic compromise, particularly in the femoral location.

If arterial dilation or cannulation occurs, complications can include life threatening bleeding, pseudoaneurysm formation, arterio-venous fistula development, and stroke.[13] Management can consist of device removal with manual compression of the arterial system, endovascular intervention, or open surgical repair. Existing data comparing these approaches are limited, with the largest systematic review limited to 150 cases, but suggest that a strategy of manual external pressure is associated with substantially higher complication rates than is endovascular intervention or surgical repair.[26 27] Thus, leaving the CVC in place until prompt surgical or endovascular management can be obtained may be advisable.

Blood loss

Clinically significant bleeding is rare, with a reported incidence of 0.8% in a large multicenter cohort.[20] Factors increasing the risk include arterial puncture, higher number of needle passes, and pre-procedural coagulopathy.[20 28] The role of prophylactic transfusion in the setting of coagulopathy is uncertain. RCT data on the administration of prophylactic plasma are lacking, and no clear transfusion threshold has been established.[29] With regard to thrombocytopenia, one RCT of 373 CVC placements compared a strategy of prophylactic platelet transfusion with no transfusion in patients with a platelet count of 10-50×10^9/L and found that withholding platelet transfusion resulted in more serious CVC related bleeding events (11.9% *v* 4.8%; risk ratio 2.43, 95% CI 0.75 to 7.93).[30] Nevertheless, the minimal platelet count for safe catheter insertion remains unknown.[28 30]

Pneumothorax

Pneumothorax is an infrequent but serious complication of internal jugular and subclavian vein CVC insertion, occurring in about 1% of cases.[31] Risk factors include subclavian vein placement, presence of underlying lung disease, mechanical ventilation, insertion under emergency circumstances, and multiple attempts at cannulation.[32] A recent meta-analysis found that insertion under ultrasound guidance decreased the incidence of pneumothorax for both the internal jugular sites (0.4 *v* 18 events per 1000 catheters; risk ratio 0.02, 95% CrI 0.001 to 0.28) and subclavian sites (3 *v* 12 events per 1000 catheters; 0.26, 0.04 to 1.60).[15] Although chest radiographs are routinely ordered to rule out pneumothorax and malpositioning, both can also be detected by bedside ultrasonography, which may be more readily available. In one meta-analysis, ultrasonography showed a pooled sensitivity of 0.82 (95% CI 0.77 to 0.86) and specificity of 0.98 (0.97 to 0.99) for catheter malpositioning; the calculated sensitivity and specificity for pneumothorax was 100%, and ultrasonography also decreased the time to confirmation.[32 33] Management of pneumothorax consists of either observation or tube thoracostomy placement, depending on the size of pneumothorax, the stability of the patient, and the need for positive pressure ventilation.

Air embolism

Air embolism is an extremely rare but potentially fatal complication, with an incidence of 0.13% reported in one large observational study.[34] Air can be introduced into the venous system during CVC placement or subsequently when accessing or removing the catheter. Although air is introduced through the venous system, air emboli can pass through a septal defect or patent foramen ovale to the arterial circulation. Hemodynamic instability is common; other symptoms can include dyspnea, chest pain, and neurologic changes.[35] Although evidence based studies are lacking, CVC insertion and removal in the Trendelenburg position is often suggested to decrease the risk of occurrence.[36] Management is largely supportive, although placement of the patient in the left lateral decubitus position with the head down may help by facilitating movement of air into the right atrium and away from the pulmonary circulation. Additionally, the administration of supplemental oxygen (F_iO_2 1.0) may accelerate reabsorption of nitrogen gas from the air embolism into the bloodstream. Finally, on the basis of limited retrospective reports and expert opinion, hyperbaric oxygen has been suggested for patients with neurologic symptoms concerning for cerebral air embolism.[35 37 38] In these cases, prompt initiation of hyperbaric oxygen (that is, within six hours of the event) may confer a higher likelihood of benefit.[39]

Thrombosis

The reported rates of thrombotic complications vary from 0.9% to 14%.[12 40-42] Risk factors may be patient specific (hypercoagulable state, malignancy, previous deep venous thrombosis, critical illness) or catheter related (large relative to vessel size, multilumen catheter, termination proximal to the superior vena cava). In one randomized trial of 3471 catheters comparing the incidence of deep venous thrombosis at different catheter insertion sites, higher rates of symptomatic thrombosis were reported with femoral catheters than with subclavian and internal jugular CVCs (hazard ratio 3.4 (95% CI 1.2 to 9.3) and 2.4 (1.1 to 5.4), respectively); no significant difference was seen between internal jugular and subclavian vein CVCs (hazard ratio 1.8, 0.6 to 4.9).[12] Duplex ultrasonography is the diagnostic modality of choice, and management consists of anticoagulation for three months in patients without contraindications.[43] Clinical practice guidelines suggest leaving CVCs that remain functional and are still needed in place, with close monitoring for worsening symptoms and removal if the catheter is occluded or no longer necessary or if symptoms worsen.[43]

Infection

More than 23 000 central line associated bloodstream infections (CLABSIs) were reported in the US in 2022.[44] Several approaches have been shown to reduce the risk of infection and are recommended by clinical practice guidelines, including the use of checklists, aseptic technique with full barrier precautions during insertion, application of chlorhexidine impregnated dressings, routine dressing changes every seven days, and prompt removal of the CVC when it is no longer needed.[5 9 21 45 46] One study of 4416 CVC insertions found that the use of a checklist decreased the CLABSI rate (3.8 *v* 5.9 CLABSIs per 1000 catheter days; P=0.001).[47] The subclavian vein was associated with a lower rate of bloodstream infections than either the internal jugular or femoral vein in one randomized trial of 3471 catheters (hazard ratio 2.3 (95% CI 0.8 to 6.2) and 3.4 (1.0 to 11.1), respectively).[12] However, subsequent meta-analyses have found comparable CLABSI rates across the three sites.[15 48] Consequently, although clinical practice guidelines suggest the use of the subclavian site when feasible, the risk and benefit of different insertion sites must be considered on an individual basis.[5 21]

With regard to duration of CVC use, data from a multicenter observational study of more than 1900 CVCs show that although the daily incidence of CLABSI does not increase with catheter duration, the cumulative risk does (daily hazard ratio of colonization 1.2% on day 5, 1.6% on day 10, and 1.4% on day 15; cumulative risk for catheter related infection 1.09 per 1000 days).[49] Accordingly, although timely removal of unnecessary CVCs is crucial, routine line replacement (either at a new site or via guide wire exchange) after any specific number of catheter days is not recommended.[5 9 21 50] CLABSI management involves both systemic antimicrobial treatment and CVC removal whenever feasible.[5] Guide wire exchange is not recommended as an alternative to catheter removal. Pooled data from 12 randomized trials suggest higher rates of catheter colonization (risk ratio 1.26, 95% CI 0.87 to 1.84) and catheter related bacteremia (1.72, 0.89 to 3.33) with guide wire exchange alone.[51] Rather, placement at a different site is preferable if central access is still needed.[50]

Arterial catheters

Arterial catheters are placed in more than a third of all patients in the ICU and more than half of those with shock in the US, totaling eight million catheters placed annually.[10 52-55] Catheterization is most commonly performed in the radial and femoral arteries, although the brachial, axillary, and dorsalis pedis arteries are also used.[56] Similarly to CVCs, additional data from large epidemiologic studies are needed to better understand the rate of complications. Although the reported incidence of serious adverse events resulting in lasting morbidity or harm is less than 1%,[40] many of the existing data have been obtained from surgical and cardiac settings and pertain to use of an arterial line for cardiac catheterization and intraoperative monitoring.[40 56] Current and robust data describing complications from arterial catheter use in the intensive care unit are lacking. As such, many of the complication rates may be underestimated, as less is known about arterial catheter use in the ICU, which is often more prolonged than elsewhere.[40 56]

Complications can include vascular injury, blood loss, neurologic injury, vascular occlusion, and infection (fig 2).[56 57] These events can occur at all sites, although incidence and risk factors for individual complications vary by location.[57] Ultrasound guidance for insertion can improve the first pass success rate (risk ratio 1.39 (95% CI 1.21 to 1.59; P<0.001) in a meta-analysis of 19 RCTs) and reduce the risk of complications (0.51 (0.28 to 0.91) in a meta-analysis of 1422 patients).[58-60] As with CVCs, although means of minimizing complications exist, avoiding unnecessary use of arterial catheters remains of utmost importance. Although the Surviving Sepsis guidelines suggest the use of arterial catheters for patients with septic shock,[61] this is acknowledged to be a weak recommendation based on very low certainty of evidence. Multiple observational studies have found that arterial lines are not associated with improved outcomes.[62-64] The largest of these studies, a propensity matched cohort study of more than 60 000 patients, found no association between use of an arterial line and in-hospital mortality (odds ratio 0.98, 95% CI 0.93 to 1.03; P=0.40).[64] The use of arterial catheters should hence be judicious, with careful consideration of their necessity in each case.

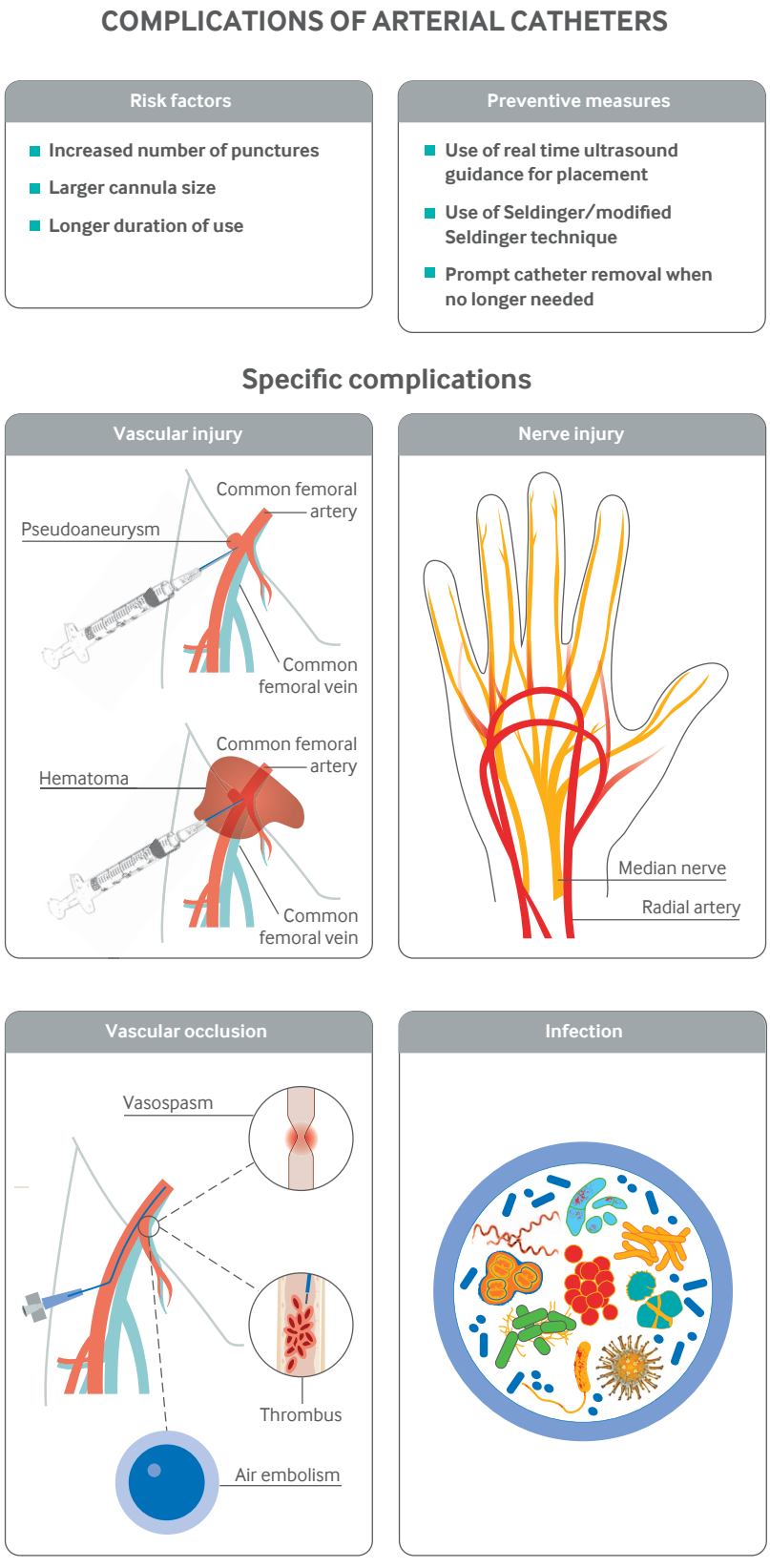

Fig 2 | Complications of arterial catheters

Vascular injury

Vascular injury can occur with any arterial puncture and typically takes one of two forms: hematoma or pseudoaneurysm formation. Hematomas are usually small but can increase the risk of vascular occlusion.[56] Pseudoaneurysm is more common at the femoral site (0.3%) than at the radial site (<0.1%).[56] The use of a Seldinger technique or modified Seldinger technique rather than direct puncture can reduce the risk of vascular injury.[65] Although the use of ultrasound guidance can decrease the number of punctures needed to access the vessel, data are inconclusive about its effect on risk of pseudoaneurysm or arteriovenous fistula formation.[66-70]

Blood loss

Blood loss occurs most commonly and significantly at the femoral site. A misguided femoral artery puncture can result in retroperitoneal hematoma and potentially life threatening blood loss.[56] Insertion of femoral arterial catheters in the common femoral artery distal to the inguinal ligament can help to ensure that the puncture site remains compressible should blood loss occur.[69] Additionally, puncture of the superficial femoral artery or the femoral vein can result in hemorrhage or pseudoaneurysm formation.[69] Real time visualization with ultrasonography may mitigate these risks,[60 66 69 71] with one meta-analysis of 19 RCTs showing that its use decreased risk of hematoma formation (risk ratio 0.40, 95% CI 0.22 to 0.72; P=0.03).[60] However, its effect on pseudoaneurysm formation is uncertain.[71]

Peripheral nerve injury

Peripheral nerve injury can result in significant functional impairment and leave lasting paresthesias and weakness. This is most often reported with radial artery placement and consequent damage to the median nerve, through direct puncture, pressure from hematoma formation, or prolonged wrist hyperextension.[72 73] Although arterial line related median nerve injury has been reported in 3.1% of patients in the intraoperative setting,[74] data on its incidence at other sites are lacking. Moreover, additional studies are needed to better understand the rates and sequelae of nerve injury with the more prolonged arterial catheter use typically seen in critically ill patients.

Vascular occlusion

Vascular occlusion, an often temporary event that resolves with catheter removal, occurs in 12% of cases.[56] Permanent ischemic damage is much more rare, with an incidence of 0.1%.[56] The radial artery, although smaller in caliber than the femoral artery, has the benefit of being part of redundant collateral circulation to the hand through the ulnar and interosseous arteries via the palmar arches.[75 76] Although occlusion occurs more frequently in the radial artery than in the femoral artery (19.7% *v* 1.5%), distal perfusion is not as often compromised, and rates of permanent ischemic damage are lower (0.09% *v* 0.18%).[56] Proposed methods for confirming collateral hand circulation include pulse oximetry of the thumb, along with the modified Allen's test, whereby the operator occludes both

the radial and ulnar arteries until the distal hand blanches, followed by release of the ulnar artery to ensure blood return within five to seven seconds.[75-77] However, studies suggest that these measures do not accurately predict the risk of distal hand ischemia with placement of radial arterial lines.[75 76 78] A prospective study of 203 patients undergoing radial arterial coronary angiography found that thumb lactate concentrations did not differ between patients with a normal, intermediate, or abnormal Allen's test (mean 1.85 (standard deviation 0.93) mmol/L *v* 1.85 (0.66) mmol/L *v* 1.97 (0.71) mmol/L; P=0.59).[79] As measures for mitigating the risk of digit ischemia are limited, placement of radial arterial lines in the non-dominant hand may be prudent when feasible.

Mechanisms of vascular occlusion include vasospasm, air embolism, and thrombus formation. Vasospasm is most often seen during initial catheter insertion, whereas air embolism can occur during line flushing and in rare cases can cause life threatening cerebral air embolism.[80] Thrombus formation around the catheter is the most common cause of vascular occlusion and is related to the size of the catheter relative to the diameter of the vessel.[56 57 81 82] A retrospective review of 62 626 arterial lines in the operative setting showed that the risk of complications, although low overall, increased as catheter size increased from 20 gauge to 18 gauge and 5 French (2.7 (95% CI 1.5 to 4.4) per 10 000 versus 17.2 (4.7 to 43.9) per 10 000 versus 9.4 (1.1 to 34.1) per 10 000).[57] Recent data in ICU populations are lacking, although older studies have had similar findings.[81 82] Other risk factors for vascular occlusion include female sex, history of vasculitis or connective tissue disease, low cardiac output, use of high dose vasopressor therapy, multiple arterial punctures, and hematoma formation.[37 56 76] Risk of occlusion also increases after 72 hours of placement, so catheters should be discontinued as soon as clinically feasible.[56] Continuous flush running through the arterial line may prevent thrombus formation, but data comparing heparinized solutions and continuous saline flushes are inconclusive.[76 83 84] Some studies suggest that use of papaverine infusion through an arterial catheter may prevent or relieve temporary obstruction from vasospasm in pediatric and neonatal populations, adults undergoing cardiac catheterization, and intraoperative cardiac surgical patients.[85-89] However, data are lacking to support its use in critically ill adults. Should distal ischemia occur, early recognition and timely vascular surgical consultation are crucial for mitigating the risk of permanent ischemic damage to the digits or limb.[76]

Infection

Infections of arterial catheters are infrequent, with reported rates of 0.25-0.72% for radial sites and 0.4-1.92% for femoral sites.[55 56 76 90 91] As with CVCs, recommended risk reduction measures include the use of sterile technique with full barrier precautions for catheter insertion, skin sterilization with an aseptic solution (most often a chlorhexidine based preparation, although povidone iodine or 70% alcohol may be used as alternatives when necessary), and prompt removal of the catheter when it is no longer needed.[5 55 56 92] Although the application of chlorhexidine impregnated dressings is recommended for prevention of infection in central venous catheters, data are less robust for their use in arterial catheters.[5 90 93 94] A systematic review and meta-analysis found two studies that reported specific infection rates associated with arterial catheters, with pooled data showing a relative risk of 0.35 (95% CI 0.13 to 0.91) in favor of the use of chlorhexidine dressings.[55] Another meta-analysis of nine RCTs showed that the use of chlorhexidine impregnated dressings was associated with a relative risk of catheter associated bloodstream infection of 0.60 (95% CI 0.41 to 0.88; P=0.009) compared with other line dressings, and this finding held true for the three studies that included arterial lines.[93] However, this study did not specifically quantify the rate of catheter associated bloodstream infection due to arterial lines alone.

Complications of airway devices

Airway devices, including endotracheal tubes and tracheostomies, are frequently used for patients with respiratory failure. Complications of these two devices are detailed below.

Endotracheal tubes

Complications of endotracheal tubes occur in nearly half of critically ill patients and can be anatomic or physiologic in nature.[95 96] Although most endotracheal tube related adverse events occur during initial endotracheal intubation, complications may arise at any point during their use, with prolonged intubation increasing the risk. In general, complications can be divided into insertion related events (table 1) and post-procedural events (fig 3).

Insertion related complications

The most common adverse events during endotracheal intubation are physiologic complications. In one international, multicenter observational study of almost 3000 critically ill patients undergoing intubation, cardiovascular instability was seen in 43% of cases, severe hypoxemia in 9%, and cardiac arrest in 3%. Other complications included esophageal intubation (5.6%), aspiration of gastric contents (3.9%), dental injury (1%), pneumothorax (0.7%), and airway injury (0.7%); reported airway injuries included tracheal, bronchial, and laryngeal laceration.[95]

A higher first pass success rate reduces the likelihood of complications.[95] Operator experience is associated with first pass success and successful intubation.[97 98] One study comparing intubation by training level found that postgraduate year 5 residents and emergency medicine specialists had an increased likelihood of successful intubation compared with postgraduate year 2 residents (n=1154; odds ratio

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Table 1 | Periprocedural complications of airway procedures

Complication	Preventive measures
Endotracheal intubation	
Severe hypoxia	Preoxygenation with HFNO or NIV
	Use of bag-mask ventilation after induction
Hemodynamic instability/ cardiac arrest	Use of hemodynamically neutral induction agents
	Ensuring immediate availability of vasoactive drugs during endotracheal intubation
Aspiration of gastric content	Use of rapid sequence intubation
	Nasogastric decompression before endotracheal intubation
Dental injury	Assessment of dentition before intubation
Airway injury	Avoidance of excessive force when passing the endotracheal tube
	Minimizing the number of intubation attempts
Pneumothorax	Avoiding excessive use of positive pressure during bag-mask ventilation
All	First pass success reduces the likelihood of all complications. Methods for improving first pass success rate include use of video laryngoscopy, intubation by an experienced operator, and pre-intubation checklists (less certain benefit)
Tracheostomy placement	
Bleeding	Periprocedural planning with ultrasonography
Pneumothorax	Avoiding excessive use of positive pressure
	Ensuring tracheostomy tube is appropriately positioned and not placed in a false lumen
Tracheal wall injury	Avoidance of forceful or repetitive dilation
	Direct or bronchoscopic visualization of insertion site
Airway compromise	Ensuring immediate availability of emergency airway equipment during tracheostomy insertion

HFNO=high flow nasal oxygen, NIV=non-invasive ventilation.

3.80 (95% CI 1.62 to 5.26) for postgraduate year 5 versus postgraduate year 2; 5.71 (2.07 to 18.67) for emergency medicine specialists versus postgraduate year 2).[98] In addition to operator experience, a recent multicenter trial including 1417 critically ill adults suggests that the use of videolaryngoscopy compared with direct laryngoscopy results in a higher first pass success rate (85.1% *v* 70.8%; absolute risk difference 14.3%, 95% CI 9.9% to 18.7%)[6]; these findings are consistent with those of a previous meta-analysis.[99]

Other strategies for decreasing complications of intubation recommended by current clinical practice guidelines and detailed further below include protocolized approaches to intubation, administration of high flow nasal oxygen (HFNO) or non-invasive ventilation (NIV) for pre-oxygenation, bag-mask ventilation (as opposed to no ventilation) following induction, and the use of hemodynamically neutral induction agents.[100-104] Of these, data on the benefit of checklists and protocolized approaches to intubation are particularly mixed: whereas one prospective controlled study suggested a decrease in life threatening complications with versus without the use of a 10 bundle management protocol (n=144; 21% *v* 34%; P=0.03),[96] another study did not show benefit.[105] By contrast, data for HFNO are more consistent: on the basis of pooled evidence from 13 studies, HFNO seems to decrease the rate and degree of desaturation compared with pre-oxygenation with a face mask.[100] Data comparing HFNO and NIV are less clear but may suggest a benefit of NIV in patients with more severe baseline hypoxemia (PaO_2/FiO_2 ≤200) (n=242; severe hypoxemia in 24% of the non-invasive ventilation group versus 35% in the high flow group; adjusted odds ratio 0.56, 95% CI 0.32 to 0.99).[106] Data supporting bag-mask ventilation compared with no ventilation come from a randomized trial of 401 patients, in which bag-mask ventilation decreased the risk of severe hypoxemia (n=401; 10.9% *v* 22.8%; risk ratio 0.48, 95% CI 0.30 to 0.70) compared with no ventilation, without increasing the risk of aspiration.[104] Finally, recent studies suggest that propofol may increase the likelihood of hemodynamic collapse (n=2760; odds ratio 1.28, 95% CI 1.04 to 1.57), and preferential use of ketamine over etomidate may be associated with decreased mortality (25% *v* 27%; risk ratio 0.93, CrI 0.79 to 1.08).[107 108]

Intubation strategies that have not been shown to increase first pass success rates include the use of a tracheal tube introducer (or bougie) compared with the traditional endotracheal tube with stylet (n=1106; 80% *v* 83% first pass success rate; absolute risk difference −2.6%, 95% CI −7.3 to 2.2)[109] and the use of a traditional sniffing position compared with a ramped position (n=513; pooled risk ratio 0.97, 95% CI 0.86 to 1.09).[110]

Post-insertion complications

Post-intubation complications include laryngeal injury, vocal cord dysfunction, and tracheal complications. Although laryngeal injury is rarely observed during intubation, a systematic review including nine studies and 775 patients noted a prevalence of 83% in endotracheally intubated critically ill adults,[111] suggesting that it may be under-diagnosed during intubation or develop afterward. Although most of these were self-limiting grade 1 injuries (for example, laryngeal edema or erythema), grade 2 injuries (for example, ulceration or granulation tissue) and grade 3 injuries (for example, vocal fold paresis or glottic or subglottic stenosis) occurred in 31% and 13% of intubated patients, respectively.[111] These injuries are typically

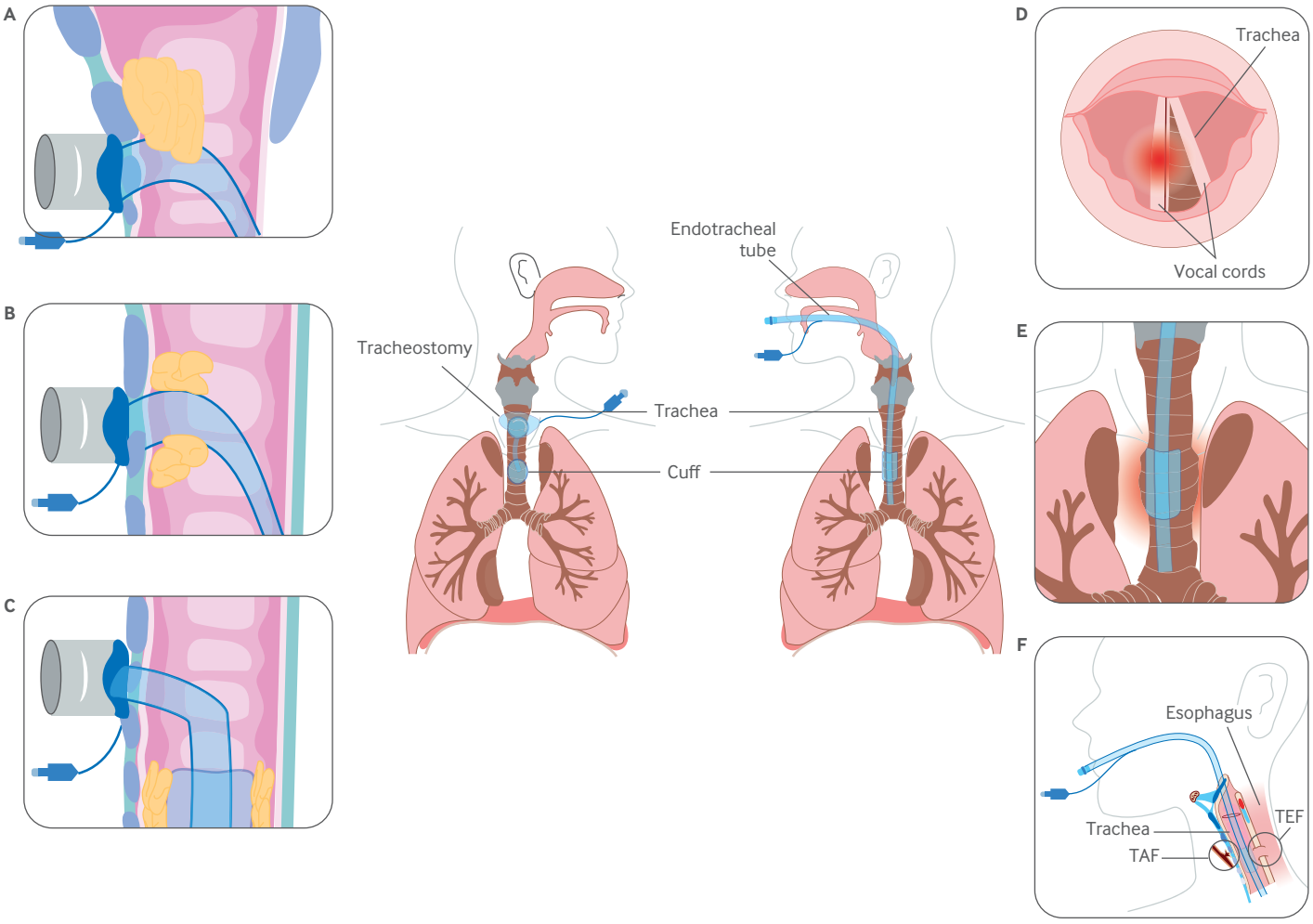

Fig 3 | Post-procedural complications of endotracheal tubes and tracheostomies. A: suprastomal tracheal stenosis. B: tracheal stenosis at site of stoma. C: infrastomal tracheal stenosis. D: vocal cord paralysis. E: tracheomalacia. F: tracheoarterial fistula (TAF) and tracheoesophageal fistula (TEF)

diagnosed via laryngoscopy and can result in ongoing dyspnea and dysphonia. Risk factors include longer duration of intubation and larger sized endotracheal tubes.[112 113] Vocal cord paralysis is less common, occurring in 7% of patients intubated for respiratory failure in one cohort,[114] but can result in impaired phonation and increased risk of aspiration. Paralysis is typically unilateral and is thought to be caused by compression of the recurrent laryngeal nerve by the cuff rather than direct injury to the vocal cords.[114]

Laryngotracheal stenosis is thought to be caused by excessive endotracheal tube cuff pressures resulting in ischemic injury and ulceration with consequent formation of granulation tissue and resulting stenosis. It can be progressive, and prolonged intubation is a risk factor for its development. Its frequency is unclear, with reported rates ranging from 1% to 21% in single center series; location may be supraglottic, glottic, or subglottic.[115] Symptoms include dyspnea or stridor following extubation, with diagnosis made through direct bronchoscopic visualization. Most patients have no symptoms, with interventions needed in only 3-12% of cases.[116] Management strategies can involve surgical or bronchoscopic interventions, and the preferred treatment depends on the location and extent of stenosis.

Other tracheal complications can include tracheomalacia and tracheal fistulization. The incidence of tracheomalacia following endotracheal intubation is unclear, with rates of 0.7-5% reported in single center studies.[117 118] Tracheomalacia is thought to be caused by weakening of the tracheal wall from repetitive ischemic injury, typically due to persistent cuff overinflation, especially in cases of prolonged intubation or tracheostomy use. Loss of tissue integrity can also potentially lead to tracheomegaly, resulting in difficulty with maintaining a seal with the cuff and often leading to further cuff overinflation. Symptoms can include dyspnea, cough, or failure to wean from mechanical ventilation, and diagnosis involves bronchoscopic visualization of dynamic airway collapse. Tracheomalacia can be temporarily managed with positive pressure ventilation or by positioning the tube to bypass the area of tracheomalacia; long term management may involve stenting or surgical resection.[119]

Fistulization of the trachea with either the esophagus or innominate artery is rare, with potentially life threatening complications occurring in <1% of patients.[115 120] Excessive cuff pressure and prolonged intubation are risk factors for both tracheoesophageal fistula and tracheoarterial fistula, which are typically caused by pressure exerted by the tube or cuff, resulting in erosion into the tracheal wall and fistula formation. Tracheoesophageal fistula is caused by erosion into the posterior tracheal wall and can result in respiratory distress, entry of enteric contents into the airway, and gastric distension. Esophogram or computed tomography scanning can be used for diagnosis. Initial management includes elevation of the head of the bed, gastric acid suppression, limitation of oral intake, nasogastric tube removal, and repositioning the cuff distal to the fistula; surgical repair is needed for definitive management.[121] Tracheoarterial fistula, although more commonly seen after tracheostomies, can also be a complication of endotracheal tubes. It is caused by erosion through the anterior tracheal wall, typically with fistulization to the innominate artery. Tracheoarterial fistula manifests as severe bleeding from the stoma or endotracheal tube, sometimes preceded by a brief, self-limited "sentinel bleed," and can result in asphyxiation. Management involves cuff overinflation and, for patients with tracheostomy, endotracheal intubation and application of manual pressure to the anterior tracheal wall through the stoma, followed by emergency surgical repair for definitive treatment.[121]

Despite the adverse effects of tracheal tube cuff overinflation, no clear guidelines on optimal cuff pressure exist.[122 123] Cuff pressures targets of 20-30 cm H_2O are commonly reported by clinicians,[122] but the frequency of cuff pressure monitoring varies considerably in clinical practice.[122-124] Further research to define a safe range is much needed to reduce the risks of complication in mechanically ventilated patients.

Tracheostomy

Complications are reported to occur in 3-5% of tracheostomies, with a meta-analysis showing similar rates of mortality and serious adverse events with both percutaneous dilatational tracheostomies and those placed using open surgical technique (odds ratio 0.52 (95% CI 0.10 to 2.60; P=0.42) and risk ratio 0.93 (0.57 to 1.53; P=0.78), respectively).[125 126] Higher complication rates have been noted in patients with obesity.[127] Similarly to those with endotracheal tubes, adverse events can be divided into insertion related and post-procedural complications.

Insertion related complications

Complications occurring during tracheostomy placement include bleeding, pneumothorax, and tracheal wall injury. Because these complications have the potential to compromise the airway, emergency airway equipment allowing for endotracheal intubation should always be immediately available during tracheostomy insertion. Bleeding, typically arising from injury of superficial blood vessels, is the most common early complication of tracheostomy placement, with a reported incidence of 2.4-8.7% in meta-analyses[126 128 129]; clinical practice guidelines recommend procedural planning with ultrasound guidance to help to mitigate this risk.[125] Although application of pressure to the bleeding site is usually sufficient for achieving hemostasis, surgical exploration and revision may be needed in some cases. Pneumothorax, a rare complication occurring in <1% of patients,[126 128 129] can have several causes, including perforation of the posterior tracheal wall, creation of a false tract anterior to the trachea, malpositioning of the tracheostomy tube, or excessive positive pressure.[121] Although management is ultimately dictated by cause, the position of the tracheostomy tube should always be verified to ensure that it is not positioned in a false lumen. If the tracheostomy tube is in a false lumen, it should be removed and ventilation should be performed via an endotracheal tube.

Tracheal injury, more common during difficult insertions, can consist of tracheal ring fracture or posterior tracheal wall laceration (reported incidence 3-36% *v* 0.2-12.5%).[116 119] Although the first rarely requires intervention, the second may result in airway bleeding or pneumomediastinum, potentially necessitating surgical intervention or stent placement depending on the extent of injury.[119]

Post-insertion complications

Post-procedural complications include tracheomalacia, tracheal fistulization, tracheal stenosis, and reduced phonation (fig 3). Tracheomalacia and fistulization present similarly in patients with tracheostomy as in patients with endotracheal tubes and were discussed above. Tracheal stenosis is more common in patients with tracheostomies, potentially owing to their prolonged mechanical ventilatory status[130]; the location of stenoses also differs and can be suprastomal, stomal, or infrastomal. Suprastomal and stomal stenoses can be caused by irritation and damage to the trachea from the tube and exacerbated by excessive friction; securing the tube to minimize unnecessary movement may help. Stomal stenosis can develop because of tracheal ring fracture at the time of tracheostomy placement or as a result of repeated stomal infections. Infrastomal stenosis can be caused by sustained, excessive tracheostomy cuff pressures or by trauma from the distal portion of the tracheostomy tube itself.[116] Diagnosis and management strategies are similar to those in endotracheal tube related stenoses.

Finally, loss of phonation has been identified as being among the most negative hospital experiences for patients, resulting in profound communication challenges as well as long term post-traumatic stress disorder.[131 132] Although voice loss is usually temporary, with reported time to phonating 12-18 days after tracheostomy insertion, it can sometimes persist, with 30% of patients unable to vocalize at

hospital discharge in one cohort.[132 133] In a small RCT of 30 mechanically ventilated patients, a targeted early communication intervention conducted by speech pathologists and using inline Passy-Muir valves substantially decreased time to voice restoration (median difference 11 days; hazard ratio 3.66, 95% CI 1.54 to 8.68) without any increase in adverse events.[132] Larger studies are needed to confirm these findings.

Complications of extracorporeal membrane oxygenation

Despite the increasing use of ECMO, mortality remains high. Although this is largely due to patient related factors and severity of illness, ECMO related complications, which can be hematologic, neurologic, infectious, vascular, or mechanical in nature, can also contribute (table 2).

Hematologic complications, encompassing both bleeding and thrombotic events, are the most common adverse events reported in the Extracorporeal Life Support Organization registry, occurring in 40% of patients with venovenous ECMO and 44% of those with venoarterial ECMO.[134 135] Exposure of patients' blood to the ECMO circuit leads to the activation of prothrombotic pathways, with the most common thrombotic events including mechanical thromboses (in the circuit, pump, or oxygenator), hemolysis, and ischemic stroke.[134-136] Bleeding events likely relate to platelet dysfunction, altered fibrinolysis, hemolysis, and use of systemic anticoagulation.[136] The most common bleeding events include cannulation and surgical site bleeding, gastrointestinal bleeding, pulmonary bleeding, intracranial hemorrhage, and cardiac tamponade.[134 135]

Neurologic complications, although rare, represent perhaps the most feared complication of ECMO, primarily in patients receiving venoarterial ECMO support. Ischemic and hemorrhagic stroke are most often reported, and other complications include seizures and hypoxic-ischemic brain injury. Hypoxic-ischemic brain injury warrants special attention, with brain autopsy studies suggesting significant under-diagnosis in the venoarterial ECMO population.[137] Although some injury may be attributable to non-modifiable factors such as precedent cardiac arrest, some may be related to differential hypoxia or "north-south syndrome." This phenomenon occurs in patients with femorally inserted venoarterial ECMO who have both cardiac and respiratory failure. As the cardiac function recovers, the native heart preferentially circulates blood that has not been properly oxygenated through diseased lung to the brain and upper body, while the ECMO circuit preferentially supplies the lower body with blood that has been well oxygenated through the ECMO circuit.

Infectious complications affect about a third to a half of ECMO runs.[138] A high level of clinical suspicion is needed, as patients on ECMO rarely have fever owing to temperature regulation from the ECMO circuit.[139] The treatment of these infections is often additionally complicated by challenges in achieving source control, as changing the ECMO circuit is not always feasible.[138]

Although rare, complications related to the vascular access procedure can be significant; cannulation should thus be performed by skilled operators under ultrasound guidance, following similar precautions to central venous and arterial cannulation.[138] Thereafter, vascular complications most frequently occur in patients with peripheral venoarterial ECMO, with limb ischemia being most common.[140] This can lead to serious downstream complications, including amputation or fasciotomy in cases of compartment syndrome. Clinical practice guidelines recommend distal perfusion cannulas as a strategy for mitigating this risk.[141]

Mechanical complications include circuit, pump, and oxygenator related complications; as these can be immediately life threatening, a pre-primed circuit should be maintained and readily available at all times.[142] ECMO's prothrombotic milieu underlies most of these malfunctions, but air embolism can also cause immediate circuit, pump, or oxygenator failure. Finally, cannula malposition can occur and lead to reduced flows, and cannula dislodgement presents more dramatically and typically requires immediate resuscitative measures, including massive transfusion.

Importantly, the aftermath of ECMO and its associated complications endure long after the patient has been discharged from the ICU. Studies suggest worsened health related quality of life scores in ECMO survivors compared with survivors of mechanical ventilation, with a meta-analysis of 245 patients showing a 5.4 (95% CI 4.11 to 6.68) decrement in SF36 scores among ECMO survivors.[143] Given high rates of post-intensive care syndrome in ICU survivors, further investigation is needed to evaluate the degree and impact of physical,

Table 2 | Complications of extracorporeal membrane oxygenation (ECMO)[8]

Complication	VV-ECMO (%)	VA-ECMO (%)	E-CPR (%)
Mechanical:			
Pump failure	1.5	0.5	0.3
Circuit failure	12.1	3.1	2.2
Oxygenator failure	20.3	3.6	3.1
Neurologic:			
CNS infarction	1.4	3.3	4.2
CNS hemorrhage	3	1.6	1.9
Seizures	0.5	0.7	1.3
Hypoxic-ischemic injury	0.6	1.3	5.7
Brain death	1	1.1	4.7
Hematologic:			
Hemolysis	6.4	3.9	3.3
Gastrointestinal hemorrhage	6.1	4.5	4.4
Pulmonary hemorrhage	3.4	1.4	1.7
Tamponade	0.9	3.6	2.1
Vascular/access:			
Surgical site bleeding	6.8	14.2	7.2
Cannulation site bleeding	4.5	7.2	8.8
Limb ischemia	0.8	3.7	4.4

Data include all adult ECMO runs from 2018 to 2022 reported in the Extracorporeal Life Support Organization Registry (n=74 105).
CNS=central nervous system; E-CPR=extracorporeal cardiopulmonary resuscitation; VA=venoarterial; VV=venovenous.

cognitive, psychological, and financial impairments in the more specific post-ECMO population.

Emerging treatments

Several emerging technologies are being explored, with evolving research focused on enhancing the operator's performance and improving the patient's experience. The incorporation of virtual reality and augmented reality may have potential applications for these purposes.[144 145] From the practitioner standpoint, augmented reality and virtual reality have been used to teach, practice, and perform various ICU procedures. In a prospective RCT examining the feasibility and efficacy of using augmented reality glasses for central line simulation compared with traditional simulation in 32 novice operators, significantly higher adherence to procedural steps was seen with augmented reality simulation. However, no difference was seen between total procedure time or time to venous cannulation.[146] Results of studies on augmented reality and virtual reality for training and support for other ICU procedures, including ECMO cannulation, bronchoscopy, and percutaneous tracheostomy placement, have similarly been mixed.[144 147 148] Nevertheless, these results should be interpreted with caution, as existing data are limited to small studies, and specific approaches for using augmented reality and virtual reality vary considerably. With regard to the patient's experience, virtual reality has been explored as a means for managing procedural pain, with a significant reduction in pain scores seen with the use of virtual reality across a variety of medical procedures in a meta-analysis of 92 RCTs.[149] However, studies assessing the efficacy of virtual reality in critically ill patients is limited, and similarly to the use of augmented reality for procedural training, specific methods of using virtual reality differ among studies; additional data are needed before its use can be adopted outside of the context of clinical trials.

Finally, the development of technology obviating the need for invasive hemodynamic monitoring may serve as the best method for reducing device associated complications. Currently available non-invasive monitoring devices typically use photoplethysmography, bioimpedance, arterial tonometry, ultrasound based technology, or a combination of these modalities.[150 151] Each technology has limitations, with existing data showing that commercially available non-invasive monitoring devices are not yet interchangeable with invasive methods in critically ill patients.[151] Further refinement is needed, along with data validation in diverse cohorts of critically ill patients.

Guidelines

Guidelines relating to ICU devices exist,[5 18 21 103 125 128 141 152 153] but most primarily cover infection control and methods for device insertion. Guidance is lacking in several areas. Firstly, and most importantly, clearly defined indications have yet to be established for many devices. Administration of vasoactive support and hemodynamic monitoring, common uses for CVC and arterial line insertion, are often done without these devices, with an increasing amount of data showing its feasibility.[22 23] However, whether safe thresholds exist with regard to severity of shock, dosing of vasopressor, or duration of infusion above which CVCs and arterial lines should be used is unclear. Similarly, no consensus indications exist for endotracheal intubation or tracheostomy, with substantial practice variation noted in epidemiologic studies.[154 155] Secondly, guidance on reducing the incidence and managing the consequences of several non-infectious complications is limited. For example, regarding bleeding, although procedural methods such as the use of ultrasound can minimize risk for many procedures, best practices for managing coagulopathy are unclear. Finally, appropriate conditions for discontinuation are also poorly defined for some devices, potentially leading to unnecessarily prolonged use. Given the widespread use of these devices, closing these knowledge gaps and generating practical clinical guidance are imperative.

Future directions

Future work should focus not just on improving technology and guidance for clinicians but also on better understanding patients' perspectives and ascertaining outcomes important to patients. Characterizing these concerns is crucial for ensuring that ongoing research and quality improvement efforts are impactful. Patients who contributed to this review identified several areas of concern relating to invasive ICU devices—long term sequelae, inadequate communication by clinicians during their use, and the concurrent usage of restraints (box 1). Little is known about long term consequences of device related complications, particularly as they relate to morbidity, disability, and health related quality of life. Post-intensive care syndrome, a collection of physical, psychological, and cognitive impairments afflicting survivors of critical illness, is being increasingly recognized, but much remains uncertain about the role that invasive procedures may play in its development.[143 156] Long term outcome studies are needed in this patient population to close these knowledge gaps.

The use of physical restraints and communication lapses in the ICU also warrant further investigation. Although often applied as a safety measure to prevent inadvertent device removal, use of physical restraints in the ICU can lead to musculoskeletal and vascular injury, as well as depression, anxiety, and post-traumatic stress disorder in ICU survivors.[157] Despite these adverse effects, physical restraints are used in up to 76% of patients in ICU, although substantial variability exists.[158 159] One factor associated with decreased restraint use is concordance in patient-clinician language,[160] suggesting that strategies for improving communication warrant further exploration. Messaging boards, apps, and voice enabling devices have been explored as options for

Box 1: Patients' experiences with devices used in intensive care unit

Long term symptoms

- My right ventricle was punctured on the first attempt to cannulate me [for ECMO]. I ended up having three sternotomies and still experience a great deal of sternum and rib pain, as well as peripheral neuropathy in my legs. All of this neuromuscular pain makes sleeping extremely difficult… My trach scar is also still painful, seven years out.
- I had central lines in my jugular veins on both sides of my neck. They're gone, but now I cannot sleep with anything touching my neck. Blankets/sheets can touch my cheek/jaw or shoulder, but not my neck.
- One thing many of us have experienced is [ongoing] difficulty swallowing and choking while eating. I don't know what in the ICU causes this, possibly being vented.
- I kept feeling something very uncomfortable at the right side of my neck. I had no idea what it was as I hadn't seen myself in a mirror and had no family there, so I grabbed hold of it and pulled it out. It was a port… I still have moments of pain and stiffness in that area of my neck years later.

Communication

- I remember feeling like I wasn't a person when the decision was made to initiate the ventilator… Imagine lying in a hospital bed, feeling like you are suffocating and fearing that you are dying… The patient doesn't really get much explanation and what is explained is in medical terms and doesn't really make sense. It's confusing and terrifying… To this day, my parents are still experiencing PTSD symptoms.
- There is a lot of anxiety and stress from the staff that fills the room… I became even more anxious and feeling out of control, scared, helpless as everyone runs around grabbing things, poking and prodding me and everyone talks about me, but not to me. Minutes felt like hours.
- I found the insertion of my PICC line to be very rough. A sterile sheet was placed over my face so it was even harder to breathe. I was terrified I would cough and my heart would be punctured. I feel like this could have been accomplished with more care and understanding about how hard and scary it was.

Restraints

- Mechanical and chemical restraints—this is an area that should be considered a device complication and can result in long term issues. A lot of us experienced PTSD symptoms and physical injuries related to their use.
- While I was restrained in the ICU, I managed to damage many of the tendons in both arms, including severing both of my bicep tendons and a few tendons in each forearm. I did so much damage while resisting the restraints that I pretty much destroyed both of my shoulders. This cost me my career.

[1] Selected quotes from patients reflecting their experiences with ICU devices. Some quotes were lightly edited for clarity.
[2] ECMO=extracorporeal membrane oxygenation; ICU=intensive care unit; PICC=peripherally inserted central catheter; PTSD=post-traumatic stress disorder.

aiding communication with critically ill patients with artificial airways. Although evidence for their benefit is uncertain, additional studies are needed to better understand their impact and ensure that the interventions are being optimally designed, tested, and implemented.[161] As research is ongoing, continued efforts should be made to use available resources to facilitate clear, direct communication between clinicians and patients as much as possible.

Conclusion

Invasive procedures are a common source of complications in the ICU. Although the foundation of avoiding device related complications consists of avoiding unnecessary device use, with careful assessment of their need and prompt removal when no longer necessary, understanding modifiable risk factors for complications is essential for critical care practitioners. Additional research is needed to close gaps in available clinical guidelines and better understand long term consequences of ICU devices.

QUESTIONS FOR FUTURE RESEARCH

- What are the most appropriate indications for the insertion of intravascular catheters and airway devices in critically ill patients?
- What are the best methods for managing non-infectious complications of devices and reducing their incidence?
- Which device associated complications are most important to patients?
- What are the long term consequences of invasive devices commonly used in the intensive care unit?

HOW PATIENTS WERE INVOLVED IN THE CREATION OF THIS MANUSCRIPT

We consulted two patients who are survivors of critical illness—Judy Eloed, MSW, LCSW, and Dennis K Gonzales, RN—in the development of this review. Both JE and DKG provided initial input on the planned content. JE then engaged members of a critical illness survivorship support group to elicit additional feedback on the planned content, specifically focusing on identifying matters of particular importance from a patient's perspective, as well as the post-hospital admission impact of device associated complications. Seven additional patients provided written input, which was then incorporated into the manuscript. We subsequently shared the full manuscript with JE and DKG for their review and approval before submission.

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1 Ahmed AH, Giri J, Kashyap R, et al. Outcome of adverse events and medical errors in the intensive care unit: a systematic review and meta-analysis. *Am J Med Qual* 2015;30:23-30. doi:10.1177/1062860613514770
2 Sauro KM, Soo A, Quan H, Stelfox HT. Adverse Events Among Hospitalized Critically Ill Patients: A Retrospective Cohort Study. *Med Care* 2020;58:38-44. doi:10.1097/MLR.0000000000001238
3 Cantor N, Durr KM, McNeill K, et al. Increased Mortality and Costs Associated with Adverse Events in Intensive Care Unit Patients. *J Intensive Care Med* 2022;37:1075-81. doi:10.1177/08850666221084908
4 Duke GJ, Shann F, Knott CI, et al. Hospital-acquired complications in critically ill patients. *Crit Care Resusc* 2023;23:285-91. doi:10.51893/2021.3.OA5
5 Timsit JF, Baleine J, Bernard L, et al. Expert consensus-based clinical practice guidelines management of intravascular catheters in the intensive care unit. *Ann Intensive Care* 2020;10:118. doi:10.1186/s13613-020-00713-4
6 Prekker ME, Driver BE, Trent SA, et al. DEVICE Investigators and the Pragmatic Critical Care Research Group. Video versus Direct Laryngoscopy for Tracheal Intubation of Critically Ill Adults. *N Engl J Med* 2023;389:418-29. doi:10.1056/NEJMoa2301601
7 Whitmore KA, Townsend SC, Laupland KB. Management of tracheostomies in the intensive care unit: a scoping review. *BMJ Open Respir Res* 2020;7:e000651. doi:10.1136/bmjresp-2020-000651
8 Extracorporeal Life Support Organization (ELSO). ECLS International Summary of Statistics – October 2023. 2023. https://www.elso.org/registry/internationalsummaryandreports/internationalsummary.aspx.
9 Timsit JF, Rupp M, Bouza E, et al. A state of the art review on optimal practices to prevent, recognize, and manage complications associated with intravascular devices in the critically ill. *Intensive Care Med* 2018;44:742-59. doi:10.1007/s00134-018-5212-y
10 Gershengorn HB, Garland A, Kramer A, Scales DC, Rubenfeld G, Wunsch H. Variation of arterial and central venous catheter use in United States intensive care units. *Anesthesiology* 2014;120:650-64. doi:10.1097/ALN.0000000000000008
11 Czarnik T, Czuczwar M, Borys M, et al. Ultrasound-Guided Infraclavicular Axillary Vein Versus Internal Jugular Vein Cannulation in Critically Ill Mechanically Ventilated Patients: A Randomized Trial. *Crit Care Med* 2023;51:e37-44. doi:10.1097/CCM.0000000000005740
12 Parienti JJ, du Cheyron D, Mermel LA,3SITES Study Group. Complications of Central Venous Catheterization. *N Engl J Med* 2016;374:1491-2.
13 McGee DC, Gould MK. Preventing complications of central venous catheterization. *N Engl J Med* 2003;348:1123-33. doi:10.1056/NEJMra011883
14 Eisen LA, Narasimhan M, Berger JS, Mayo PH, Rosen MJ, Schneider RF. Mechanical complications of central venous catheters. *J Intensive Care Med* 2006;21:40-6. doi:10.1177/0885066605280884
15 Teja B, Bosch NA, Diep C, et al. Complication Rates of Central Venous Catheters: A Systematic Review and Meta-Analysis. *JAMA Intern Med* 2024;184:474-82. doi:10.1001/jamainternmed.2023.8232
16 Brass P, Hellmich M, Kolodziej L, Schick G, Smith AF. Ultrasound guidance versus anatomical landmarks for internal jugular vein catheterization. *Cochrane Database Syst Rev* 2015;1:CD006962. doi:10.1002/14651858.CD006962.pub2
17 Brass P, Hellmich M, Kolodziej L, Schick G, Smith AF. Ultrasound guidance versus anatomical landmarks for subclavian or femoral vein catheterization. *Cochrane Database Syst Rev* 2015;1:CD011447. doi:10.1002/14651858.CD011447
18 Practice Guidelines for Central Venous Access. Practice Guidelines for Central Venous Access 2020: An Updated Report by the American Society of Anesthesiologists Task Force on Central Venous Access. *Anesthesiology* 2020;132:8-43. doi:10.1097/ALN.0000000000002864
19 Adrian M, Borgquist O, Kröger T, et al. Mechanical complications after central venous catheterisation in the ultrasound-guided era: a prospective multicentre cohort study. *Br J Anaesth* 2022;129:843-50. doi:10.1016/j.bja.2022.08.036
20 Björkander M, Bentzer P, Schött U, Broman ME, Kander T. Mechanical complications of central venous catheter insertions: A retrospective multicenter study of incidence and risks. *Acta Anaesthesiol Scand* 2019;63:61-8. doi:10.1111/aas.13214
21 Buetti N, Marschall J, Drees M, et al. Strategies to prevent central line-associated bloodstream infections in acute-care hospitals: 2022 Update. *Infect Control Hosp Epidemiol* 2022;43:553-69. doi:10.1017/ice.2022.87
22 Munroe ES, Heath ME, Eteer M, et al. Use and Outcomes of Peripheral Vasopressors in Early Sepsis-Induced Hypotension Across Michigan Hospitals: A Retrospective Cohort Study. *Chest* 2024;165:847-57. doi:10.1016/j.chest.2023.10.027
23 Tian DH, Smyth C, Keijzers G, et al. Safety of peripheral administration of vasopressor medications: A systematic review. *Emerg Med Australas* 2020;32:220-7. doi:10.1111/1742-6723.13406
24 Yerke JR, Mireles-Cabodevila E, Chen AY, et al. Peripheral Administration of Norepinephrine: A Prospective Observational Study. *Chest* 2024;165:348-55. doi:10.1016/j.chest.2023.08.019
25 Kornbau C, Lee KC, Hughes GD, Firstenberg MS. Central line complications. *Int J Crit Illn Inj Sci* 2015;5:170-8. doi:10.4103/2229-5151.164940
26 Dixon OG, Smith GE, Carradice D, Chetter IC. A systematic review of management of inadvertent arterial injury during central venous catheterisation. *J Vasc Access* 2017;18:97-102. doi:10.5301/jva.5000611
27 Dornbos DL3rd, Nimjee SM, Smith TP. Inadvertent Arterial Placement of Central Venous Catheters: Systematic Review and Guidelines for Treatment. *J Vasc Interv Radiol* 2019;30:1785-94. doi:10.1016/j.jvir.2019.05.017
28 van de Weerdt EK, Biemond BJ, Baake B, et al. Central venous catheter placement in coagulopathic patients: risk factors and incidence of bleeding complications. *Transfusion* 2017;57:2512-25. doi:10.1111/trf.14248
29 Hall DP, Estcourt LJ, Doree C, Hopewell S, Trivella M, Walsh TS. Plasma transfusions prior to insertion of central lines for people with abnormal coagulation. *Cochrane Database Syst Rev* 2016;9:CD011756. doi:10.1002/14651858.CD011756.pub2
30 van Baarle FLF, van de Weerdt EK, van der Velden WJFM, et al. Platelet Transfusion before CVC Placement in Patients with Thrombocytopenia. *N Engl J Med* 2023;388:1956-65. doi:10.1056/NEJMoa2214322
31 Smit JM, Raadsen R, Blans MJ, Petjak M, Van de Ven PM, Tuinman PR. Bedside ultrasound to detect central venous catheter misplacement and associated iatrogenic complications: a systematic review and meta-analysis. *Crit Care* 2018;22:65. doi:10.1186/s13054-018-1989-x
32 Tsotsolis N, Tsirgogianni K, Kioumis I, et al. Pneumothorax as a complication of central venous catheter insertion. *Ann Transl Med* 2015;3:40.
33 Ablordeppey EA, Drewry AM, Beyer AB, et al. Diagnostic Accuracy of Central Venous Catheter Confirmation by Bedside Ultrasound Versus Chest Radiography in Critically Ill Patients: A Systematic Review and Meta-Analysis. *Crit Care Med* 2017;45:715-24. doi:10.1097/CCM.0000000000002188
34 Vesely TM. Air embolism during insertion of central venous catheters. *J Vasc Interv Radiol* 2001;12:1291-5. doi:10.1016/S1051-0443(07)61554-1
35 Alzghoul H, Obeidat O, Abughazaleh S, et al. Venous Air Embolism: A Systematic Review. *Chest Critical Care* 2024;2:100049doi:10.1016/j.chstcc.2024.100049.
36 McCarthy CJ, Behravesh S, Naidu SG, Oklu R. Air Embolism: Practical Tips for Prevention and Treatment. *J Clin Med* 2016;5:93. doi:10.3390/jcm5110093
37 Paik JJ, Hirpara R, Heller JA, Hummers LK, Wigley FM, Shah AA. Thrombotic complications after radial arterial line placement in systemic sclerosis: A case series. *Semin Arthritis Rheum* 2016;46:196-9. doi:10.1016/j.semarthrit.2016.03.015
38 Leach RM, Rees PJ, Wilmshurst P. Hyperbaric oxygen therapy. *BMJ* 1998;317:1140-3. doi:10.1136/bmj.317.7166.1140
39 Blanc P, Boussuges A, Henriette K, Sainty JM, Deleflie M. Iatrogenic cerebral air embolism: importance of an early hyperbaric oxygenation. *Intensive Care Med* 2002;28:559-63. doi:10.1007/s00134-002-1255-0
40 Günther SC, Schwebel C, Hamidfar-Roy R, et al. Complications of intravascular catheters in ICU: definitions, incidence and severity. A randomized controlled trial comparing usual transparent dressings versus new-generation dressings (the ADVANCED study). *Intensive Care Med* 2016;42:1753-65. doi:10.1007/s00134-016-4582-2
41 Abbruzzese C, Guzzardella A, Consonni D, et al. Incidence of asymptomatic catheter-related thrombosis in intensive care unit patients: a prospective cohort study. *Ann Intensive Care* 2023;13:106. doi:10.1186/s13613-023-01206-w
42 Timsit JF, Farkas JC, Boyer JM, et al. Central vein catheter-related thrombosis in intensive care patients: incidence, risks factors, and relationship with catheter-related sepsis. *Chest* 1998;114:207-13. doi:10.1378/chest.114.1.207
43 Kearon C, Akl EA, Comerota AJ, et al. Antithrombotic therapy for VTE disease: Antithrombotic Therapy and Prevention of Thrombosis, 9th ed: American College of Chest Physicians Evidence-Based Clinical Practice Guidelines. *Chest* 2012;141(Suppl):e419-96S. doi:10.1378/chest.11-2301

44 Centers for Disease Control and Prevention. Healthcare-Associated Infections Progress Report. 2022. https://www.cdc.gov/hai/data/portal/progress-report.html.
45 Pronovost P, Needham D, Berenholtz S, et al. An intervention to decrease catheter-related bloodstream infections in the ICU. *N Engl J Med* 2006;355:2725-32. doi:10.1056/NEJMoa061115
46 Lafuente Cabrero E, Terradas Robledo R, Civit Cuñado A, et al. Risk factors of catheter- associated bloodstream infection: Systematic review and meta-analysis. *PLoS One* 2023;18:e0282290. doi:10.1371/journal.pone.0282290
47 Wichmann D, Belmar Campos CE, Ehrhardt S, et al. Efficacy of introducing a checklist to reduce central venous line associated bloodstream infections in the ICU caring for adult patients. *BMC Infect Dis* 2018;18:267. doi:10.1186/s12879-018-3178-6
48 Arvaniti K, Lathyris D, Blot S, Apostolidou-Kiouti F, Koulenti D, Haidich AB. Cumulative Evidence of Randomized Controlled and Observational Studies on Catheter-Related Infection Risk of Central Venous Catheter Insertion Site in ICU Patients: A Pairwise and Network Meta-Analysis. *Crit Care Med* 2017;45:e437-48. doi:10.1097/CCM.0000000000002092
49 Lucet JC, Bouadma L, Zahar JR, et al. Infectious risk associated with arterial catheters compared with central venous catheters. *Crit Care Med* 2010;38:1030-5. doi:10.1097/CCM.0b013e3181d4502e
50 Bell T, O'Grady NP. Prevention of Central Line-Associated Bloodstream Infections. *Infect Dis Clin North Am* 2017;31:551-9. doi:10.1016/j.idc.2017.05.007
51 Cook D, Randolph A, Kernerman P, et al. Central venous catheter replacement strategies: a systematic review of the literature. *Crit Care Med* 1997;25:1417-24. doi:10.1097/00003246-199708000-00033
52 McIntyre LA, Hébert PC, Fergusson D, Cook DJ, Aziz A,Canadian Critical Care Trials Group. A survey of Canadian intensivists' resuscitation practices in early septic shock. *Crit Care* 2007;11:R74. doi:10.1186/cc5962
53 Angus DC, Pereira CA, Silva E. Epidemiology of severe sepsis around the world. *Endocr Metab Immune Disord Drug Targets* 2006;6:207-12. doi:10.2174/187153006777442332
54 Traoré O, Liotier J, Souweine B. Prospective study of arterial and central venous catheter colonization and of arterial- and central venous catheter-related bacteremia in intensive care units. *Crit Care Med* 2005;33:1276-80. doi:10.1097/01.CCM.0000166350.90812.D4
55 O'Horo JC, Maki DG, Krupp AE, Safdar N. Arterial catheters as a source of bloodstream infection: a systematic review and meta-analysis. *Crit Care Med* 2014;42:1334-9. doi:10.1097/CCM.0000000000000166
56 Scheer B, Perel A, Pfeiffer UJ. Clinical review: complications and risk factors of peripheral arterial catheters used for haemodynamic monitoring in anaesthesia and intensive care medicine. *Crit Care* 2002;6:199-204. doi:10.1186/cc1489
57 Nuttall G, Burckhardt J, Hadley A, et al. Surgical and Patient Risk Factors for Severe Arterial Line Complications in Adults. *Anesthesiology* 2016;124:590-7. doi:10.1097/ALN.0000000000000967
58 Sobolev M, Slovut DP, Lee Chang A, Shiloh AL, Eisen LA. Ultrasound-Guided Catheterization of the Femoral Artery: A Systematic Review and Meta-Analysis of Randomized Controlled Trials. *J Invasive Cardiol* 2015;27:318-23.
59 White L, Halpin A, Turner M, Wallace L. Ultrasound-guided radial artery cannulation in adult and paediatric populations: a systematic review and meta-analysis. *Br J Anaesth* 2016;116:610-7. doi:10.1093/bja/aew097
60 Dong Z, Liu Y, Gai Y, et al. Early rehabilitation relieves diaphragm dysfunction induced by prolonged mechanical ventilation: a randomised control study. *BMC Pulm Med* 2021;21:106. doi:10.1186/s12890-021-01461-2
61 Evans L, Rhodes A, Alhazzani W, et al. Surviving sepsis campaign: international guidelines for management of sepsis and septic shock 2021. *Intensive Care Med* 2021;47:1181-247. doi:10.1007/s00134-021-06506-y
62 Hsu DJ, Feng M, Kothari R, Zhou H, Chen KP, Celi LA. The Association Between Indwelling Arterial Catheters and Mortality in Hemodynamically Stable Patients With Respiratory Failure: A Propensity Score Analysis. *Chest* 2015;148:1470-6. doi:10.1378/chest.15-0516
63 Ou Q, Cai G, Zhou Y, et al. Arterial catheterization and in-hospital mortality in sepsis: a propensity score-matched study. *BMC Anesthesiol* 2022;22:178. doi:10.1186/s12871-022-01722-5
64 Gershengorn HB, Wunsch H, Scales DC, Zarychanski R, Rubenfeld G, Garland A. Association between arterial catheter use and hospital mortality in intensive care units. *JAMA Intern Med* 2014;174:1746-54. doi:10.1001/jamainternmed.2014.3297
65 Beards SC, Doedens L, Jackson A, Lipman J. A comparison of arterial lines and insertion techniques in critically ill patients. *Anaesthesia* 1994;49:968-73. doi:10.1111/j.1365-2044.1994.tb04316.x
66 Dudeck O, Teichgraeber U, Podrabsky P, Lopez Haenninen E, Soerensen R, Ricke J. A randomized trial assessing the value of ultrasound-guided puncture of the femoral artery for interventional investigations. *Int J Cardiovasc Imaging* 2004;20:363-8. doi:10.1023/B:CAIM.0000041949.59255.3f
67 Gu WJ, Wu XD, Wang F, Ma ZL, Gu XP. Ultrasound Guidance Facilitates Radial Artery Catheterization: A Meta-analysis With Trial Sequential Analysis of Randomized Controlled Trials. *Chest* 2016;149:166-79. doi:10.1378/chest.15-1784
68 Moussa Pacha H, Alahdab F, Al-Khadra Y, et al. Ultrasound-guided versus palpation-guided radial artery catheterization in adult population: A systematic review and meta-analysis of randomized controlled trials. *Am Heart J* 2018;204:1-8. doi:10.1016/j.ahj.2018.06.007
69 Wang A, Hendin A, Millington SJ, Koenig S, Eisen LA, Shiloh AL. Better With Ultrasound: Arterial Line Placement. *Chest* 2020;157:574-9. doi:10.1016/j.chest.2019.08.2209
70 Zhao W, Peng H, Li H, et al. Effects of ultrasound-guided techniques for radial arterial catheterization: A meta-analysis of randomized controlled trials. *Am J Emerg Med* 2021;46:1-9. doi:10.1016/j.ajem.2020.04.064
71 Flumignan RL, Trevisani VF, Lopes RD, Baptista-Silva JC, Flumignan CD, Nakano LC. Ultrasound guidance for arterial (other than femoral) catheterisation in adults. *Cochrane Database Syst Rev* 2021;10:CD013585.
72 Chowet AL, Lopez JR, Brock-Utne JG, Jaffe RA. Wrist hyperextension leads to median nerve conduction block: implications for intra-arterial catheter placement. *Anesthesiology* 2004;100:287-91. doi:10.1097/00000542-200402000-00017
73 Cheney FW, Domino KB, Caplan RA, Posner KL. Nerve injury associated with anesthesia: a closed claims analysis. *Anesthesiology* 1999;90:1062-9. doi:10.1097/00000542-199904000-00020
74 Hou Q, Zhou B, He J, Chen X, Zuo Y. Complications and related risk factors of transradial access cannulation for hemodynamic monitoring in general surgery: a prospective observational study. *BMC Anesthesiol* 2023;23:228. doi:10.1186/s12871-023-02168-z
75 Bertrand OF, Carey PC, Gilchrist IC. Allen or no Allen: that is the question!*J Am Coll Cardiol* 2014;63:1842-4. doi:10.1016/j.jacc.2014.01.048
76 Brzezinski M, Luisetti T, London MJ. Radial artery cannulation: a comprehensive review of recent anatomic and physiologic investigations. *Anesth Analg* 2009;109:1763-81. doi:10.1213/ANE.0b013e3181bbd416
77 Barbeau GR, Arsenault F, Dugas L, Simard S, Larivière MM. Evaluation of the ulnopalmar arterial arches with pulse oximetry and plethysmography: comparison with the Allen's test in 1010 patients. *Am Heart J* 2004;147:489-93. doi:10.1016/j.ahj.2003.10.038
78 Barone JE, Madlinger RV. Should an Allen test be performed before radial artery cannulation?*J Trauma* 2006;61:468-70. doi:10.1097/01.ta.0000229815.43871.59
79 Valgimigli M, Campo G, Penzo C, Tebaldi M, Biscaglia S, Ferrari R,RADAR Investigators. Transradial coronary catheterization and intervention across the whole spectrum of Allen test results. *J Am Coll Cardiol* 2014;63:1833-41. doi:10.1016/j.jacc.2013.12.043
80 Chang C, Dughi J, Shitabata P, Johnson G, Coel M, McNamara JJ. Air embolism and the radial arterial line. *Crit Care Med* 1988;16:141-3. doi:10.1097/00003246-198802000-00009
81 Davis FM. Radial artery cannulation: influence of catheter size and material on arterial occlusion. *Anaesth Intensive Care* 1978;6:49-53. doi:10.1177/0310057X7800600107
82 Davis FM, Stewart JM. Radial artery cannulation. A prospective study in patients undergoing cardiothoracic surgery. *Br J Anaesth* 1980;52:41-7. doi:10.1093/bja/52.1.41
83 Robertson-Malt S, Malt GN, Farquhar V, Greer W. Heparin versus normal saline for patency of arterial lines. *Cochrane Database Syst Rev* 2014;2014:CD007364. doi:10.1002/14651858.CD007364.pub2
84 Mandel MA, Dauchot PJ. Radial artery cannulation in 1,000 patients: precautions and complications. *J Hand Surg Am* 1977;2:482-5. doi:10.1016/S0363-5023(77)80030-0
85 Gautam NK, Griffin E, Hubbard R, et al. Intraarterial papaverine for relief of catheter-induced peripheral arterial vasospasm during pediatric cardiac surgery: A randomized double-blind controlled trial. *Paediatr Anaesth* 2022;32:764-71. doi:10.1111/pan.14442
86 Panigrahy N, Kumar PP, Chirla DK, Vennapusa SR. Papaverine for Ischemia Following Peripheral Arterial Catheterization in Neonates. *Indian Pediatr* 2016;53:169.
87 Osman F, Buller N, Steeds R. Use of intra-arterial papaverine for severe arterial spasm during radial cardiac catheterization. *J Invasive Cardiol* 2008;20:551-2.

88 Weiss BM, Gattiker RI. Complications during and following radial artery cannulation: a prospective study. *Intensive Care Med* 1986;12:424-8. doi:10.1007/BF00254675
89 Heulitt MJ, Farrington EA, O'Shea TM, Stoltzman SM, Srubar NB, Levin DL. Double-blind, randomized, controlled trial of papaverine-containing infusions to prevent failure of arterial catheters in pediatric patients. *Crit Care Med* 1993;21:825-9. doi:10.1097/00003246-199306000-00008
90 Buetti N, Mimoz O, Schwebel C, et al. Insertion Site and Infection Risk among Peripheral Arterial Catheters. *Am J Respir Crit Care Med* 2021;203:630-3. doi:10.1164/rccm.202007-3008LE
91 Lorente L, Santacreu R, Martín MM, Jiménez A, Mora ML. Arterial catheter-related infection of 2,949 catheters. *Crit Care* 2006;10:R83. doi:10.1186/cc4930
92 O'Grady NP, Alexander M, Burns LA, et al. Healthcare Infection Control Practices Advisory Committee (HICPAC). Guidelines for the prevention of intravascular catheter-related infections. *Clin Infect Dis* 2011;52:e162-93. doi:10.1093/cid/cir257
93 Safdar N, O'Horo JC, Ghufran A, et al. Chlorhexidine-impregnated dressing for prevention of catheter-related bloodstream infection: a meta-analysis*. *Crit Care Med* 2014;42:1703-13. doi:10.1097/CCM.0000000000000319
94 Card S, Piersa A, Kaplon A, et al. Infectious Risk of Arterial Lines: A Narrative Review. *J Cardiothorac Vasc Anesth* 2023;37:2050-6. doi:10.1053/j.jvca.2023.06.037
95 Russotto V, Myatra SN, Laffey JG, et al. INTUBE Study Investigators. Intubation Practices and Adverse Peri-intubation Events in Critically Ill Patients From 29 Countries. *JAMA* 2021;325:1164-72. doi:10.1001/jama.2021.1727
96 Jaber S, Jung B, Corne P, et al. An intervention to decrease complications related to endotracheal intubation in the intensive care unit: a prospective, multiple-center study. *Intensive Care Med* 2010;36:248-55. doi:10.1007/s00134-009-1717-8
97 Amalric M, Larcher R, Brunot V, et al. Impact of Videolaryngoscopy Expertise on First-Attempt Intubation Success in Critically Ill Patients. *Crit Care Med* 2020;48:e889-96. doi:10.1097/CCM.0000000000004497
98 Jung W, Kim J. Factors associated with first-pass success of emergency endotracheal intubation. *Am J Emerg Med* 2020;38:109-13. doi:10.1016/j.ajem.2019.09.001
99 Hansel J, Rogers AM, Lewis SR, Cook TM, Smith AF. Videolaryngoscopy versus direct laryngoscopy for adults undergoing tracheal intubation. *Cochrane Database Syst Rev* 2022;4:CD011136.
100 Acquisto NM, Mosier JM, Bittner EA, et al. Society of Critical Care Medicine Clinical Practice Guidelines for Rapid Sequence Intubation in the Critically Ill Adult Patient. *Crit Care Med* 2023;51:1411-30. doi:10.1097/CCM.0000000000006000
101 Apfelbaum JL, Hagberg CA, Connis RT, et al. 2022 American Society of Anesthesiologists Practice Guidelines for Management of the Difficult Airway. *Anesthesiology* 2022;136:31-81. doi:10.1097/ALN.0000000000004002
102 Kornas RL, Owyang CG, Sakles JC, Foley LJ, Mosier JM,Society for Airway Management's Special Projects Committee. Evaluation and Management of the Physiologically Difficult Airway: Consensus Recommendations From Society for Airway Management. *Anesth Analg* 2021;132:395-405. doi:10.1213/ANE.0000000000005233
103 Higgs A, McGrath BA, Goddard C, et al. Difficult Airway SocietyIntensive Care SocietyFaculty of Intensive Care MedicineRoyal College of Anaesthetists. Guidelines for the management of tracheal intubation in critically ill adults. *Br J Anaesth* 2018;120:323-52. doi:10.1016/j.bja.2017.10.021
104 Casey JD, Janz DR, Russell DW, et al. PreVent Investigators and the Pragmatic Critical Care Research Group. Bag-Mask Ventilation during Tracheal Intubation of Critically Ill Adults. *N Engl J Med* 2019;380:811-21. doi:10.1056/NEJMoa1812405
105 Janz DR, Semler MW, Joffe AM, et al. Check-UP Investigators*Pragmatic Critical Care Research Group. A Multicenter Randomized Trial of a Checklist for Endotracheal Intubation of Critically Ill Adults. *Chest* 2018;153:816-24. doi:10.1016/j.chest.2017.08.1163
106 Frat JP, Ricard JD, Quenot JP, et al. FLORALI-2 study groupREVA network. Non-invasive ventilation versus high-flow nasal cannula oxygen therapy with apnoeic oxygenation for preoxygenation before intubation of patients with acute hypoxaemic respiratory failure: a randomised, multicentre, open-label trial. *Lancet Respir Med* 2019;7:303-12. doi:10.1016/S2213-2600(19)30048-7
107 Russotto V, Tassistro E, Myatra SN, et al. Peri-intubation Cardiovascular Collapse in Patients Who Are Critically Ill: Insights from the INTUBE Study. *Am J Respir Crit Care Med* 2022;206:449-58. doi:10.1164/rccm.202111-2575OC
108 Koroki T, Kotani Y, Yaguchi T, et al. Ketamine versus etomidate as an induction agent for tracheal intubation in critically ill adults: a Bayesian meta-analysis. *Crit Care* 2024;28:48. doi:10.1186/s13054-024-04831-4
109 Driver BE, Semler MW, Self WH, et al. BOUGIE Investigators and the Pragmatic Critical Care Research Group. Effect of Use of a Bougie vs Endotracheal Tube With Stylet on Successful Intubation on the First Attempt Among Critically Ill Patients Undergoing Tracheal Intubation: A Randomized Clinical Trial. *JAMA* 2021;326:2488-97. doi:10.1001/jama.2021.22002
110 Okada Y, Nakayama Y, Hashimoto K, Koike K, Watanabe N. Ramped versus sniffing position for tracheal intubation: A systematic review and meta-analysis. *Am J Emerg Med* 2021;44:250-6. doi:10.1016/j.ajem.2020.03.058
111 Brodsky MB, Levy MJ, Jedlanek E, et al. Laryngeal Injury and Upper Airway Symptoms After Oral Endotracheal Intubation With Mechanical Ventilation During Critical Care: A Systematic Review. *Crit Care Med* 2018;46:2010-7. doi:10.1097/CCM.0000000000003368
112 Shinn JR, Kimura KS, Campbell BR, et al. Incidence and Outcomes of Acute Laryngeal Injury After Prolonged Mechanical Ventilation. *Crit Care Med* 2019;47:1699-706. doi:10.1097/CCM.0000000000004015
113 Tadié JM, Behm E, Lecuyer L, et al. Post-intubation laryngeal injuries and extubation failure: a fiberoptic endoscopic study. *Intensive Care Med* 2010;36:991-8. doi:10.1007/s00134-010-1847-z
114 Campbell BR, Shinn JR, Kimura KS, et al. Unilateral Vocal Fold Immobility After Prolonged Endotracheal Intubation. *JAMA Otolaryngol Head Neck Surg* 2020;146:160-7. doi:10.1001/jamaoto.2019.3969
115 Sue RD, Susanto I. Long-term complications of artificial airways. *Clin Chest Med* 2003;24:457-71. doi:10.1016/S0272-5231(03)00048-0
116 Al-Shathri Z, Susanto I. Percutaneous Tracheostomy. *Semin Respir Crit Care Med* 2018;39:720-30. doi:10.1055/s-0038-1676573
117 Kandaswamy C, Bird G, Gill N, Math E, Vempilly JJ. Severe tracheomalacia in the ICU: identification of diagnostic criteria and risk factor analysis from a case control study. *Respir Care* 2013;58:340-7. doi:10.4187/respcare.01866
118 Guarnieri M, Andreoni P, Gay H, et al. Tracheostomy in Mechanically Ventilated Patients With SARS-CoV-2-ARDS: Focus on Tracheomalacia. *Respir Care* 2021;66:1797-804. doi:10.4187/respcare.09063
119 Fernandez-Bussy S, Mahajan B, Folch E, Caviedes I, Guerrero J, Majid A. Tracheostomy Tube Placement: Early and Late Complications. *J Bronchology Interv Pulmonol* 2015;22:357-64. doi:10.1097/LBR.0000000000000177
120 Scalise P, Prunk SR, Healy D, Votto J. The incidence of tracheoarterial fistula in patients with chronic tracheostomy tubes: a retrospective study of 544 patients in a long-term care facility. *Chest* 2005;128:3906-9. doi:10.1378/chest.128.6.3906
121 Zouk AN, Batra H. Managing complications of percutaneous tracheostomy and gastrostomy. *J Thorac Dis* 2021;13:5314-30. doi:10.21037/jtd-19-3716
122 Talekar CR, Udy AA, Boots RJ, Lipman J, Cook D. Tracheal cuff pressure monitoring in the ICU: a literature review and survey of current practice in Queensland. *Anaesth Intensive Care* 2014;42:761-70. doi:10.1177/0310057X1404200612
123 Sultan P, Carvalho B, Rose BO, Cregg R. Endotracheal tube cuff pressure monitoring: a review of the evidence. *J Perioper Pract* 2011;21:379-86. doi:10.1177/175045891102101103
124 Letvin A, Kremer P, Silver PC, Samih N, Reed-Watts P, Kollef MH. Frequent Versus Infrequent Monitoring of Endotracheal Tube Cuff Pressures. *Respir Care* 2018;63:495-501. doi:10.4187/respcare.05926
125 Trouillet JL, Collange O, Belafia F, et al. Tracheotomy in the intensive care unit: guidelines from a French expert panel. *Ann Intensive Care* 2018;8:37. doi:10.1186/s13613-018-0381-y
126 Brass P, Hellmich M, Ladra A, Ladra J, Wrzosek A. Percutaneous techniques versus surgical techniques for tracheostomy. *Cochrane Database Syst Rev* 2016;7:CD008045. doi:10.1002/14651858.CD008045.pub2
127 Roy CF, Silver JA, Turkdogan S, Siafa L, Correa JA, Kost K. Complication Rate of Percutaneous Dilatational Tracheostomy in Critically Ill Adults With Obesity: A Systematic Review and Meta-analysis. *JAMA Otolaryngol Head Neck Surg* 2023;149:334-43. doi:10.1001/jamaoto.2022.4824
128 Battaglini D, Premraj L, White N, et al. Tracheostomy outcomes in critically ill patients with COVID-19: a systematic review, meta-analysis, and meta-regression. *Br J Anaesth* 2022;129:679-92. doi:10.1016/j.bja.2022.07.032
129 Putensen C, Theuerkauf N, Guenther U, Vargas M, Pelosi P. Percutaneous and surgical tracheostomy in critically ill adult patients: a meta-analysis. *Crit Care* 2014;18:544. doi:10.1186/s13054-014-0544-7
130 Ghiani A, Tsitouras K, Paderewska J, et al. Tracheal stenosis in prolonged mechanically ventilated patients: prevalence, risk factors, and bronchoscopic management. *BMC Pulm Med* 2022;22:24. doi:10.1186/s12890-022-01821-6
131 Newman H, Clunie G, Wallace S, Smith C, Martin D, Pattison N. What matters most to adults with a tracheostomy in ICU and the

implications for clinical practice: a qualitative systematic review and metasynthesis. *J Crit Care* 2022;72:154145. doi:10.1016/j.jcrc.2022.154145
132 Freeman-Sanderson AL, Togher L, Elkins MR, Phipps PR. Return of Voice for Ventilated Tracheostomy Patients in ICU: A Randomized Controlled Trial of Early-Targeted Intervention. *Crit Care Med* 2016;44:1075-81. doi:10.1097/CCM.0000000000001610
133 Freeman-Sanderson A, Togher L, Phipps P, Elkins M. A clinical audit of the management of patients with a tracheostomy in an Australian tertiary hospital intensive care unit: Focus on speech-language pathology. *Int J Speech Lang Pathol* 2011;13:518-25. doi:10.3109/17549507.2011.582520
134 Nunez JI, Gosling AF, O'Gara B, et al. Bleeding and thrombotic events in adults supported with venovenous extracorporeal membrane oxygenation: an ELSO registry analysis. *Intensive Care Med* 2022;48:213-24. doi:10.1007/s00134-021-06593-x
135 Chung M, Cabezas FR, Nunez JI, et al. Hemocompatibility-Related Adverse Events and Survival on Venoarterial Extracorporeal Life Support: An ELSO Registry Analysis. *JACC Heart Fail* 2020;8:892-902. doi:10.1016/j.jchf.2020.09.004
136 Doyle AJ, Hunt BJ. Current Understanding of How Extracorporeal Membrane Oxygenators Activate Haemostasis and Other Blood Components. *Front Med (Lausanne)* 2018;5:352. doi:10.3389/fmed.2018.00352
137 Zhang H, Xu J, Yang X, et al. Narrative Review of Neurologic Complications in Adults on ECMO: Prevalence, Risks, Outcomes, and Prevention Strategies. *Front Med (Lausanne)* 2021;8:713333. doi:10.3389/fmed.2021.713333
138 Teijeiro-Paradis R, Gannon WD, Fan E. Complications Associated With Venovenous Extracorporeal Membrane Oxygenation-What Can Go Wrong?*Crit Care Med* 2022;50:1809-18. doi:10.1097/CCM.0000000000005673
139 Patel B, Arcaro M, Chatterjee S. Bedside troubleshooting during venovenous extracorporeal membrane oxygenation (ECMO). *J Thorac Dis* 2019;11(Suppl 14):S1698-707. doi:10.21037/jtd.2019.04.81
140 Rao P, Khalpey Z, Smith R, Burkhoff D, Kociol RD. Venoarterial Extracorporeal Membrane Oxygenation for Cardiogenic Shock and Cardiac Arrest. *Circ Heart Fail* 2018;11:e004905. doi:10.1161/CIRCHEARTFAILURE.118.004905
141 Lorusso R, Shekar K, MacLaren G, et al. ELSO Interim Guidelines for Venoarterial Extracorporeal Membrane Oxygenation in Adult Cardiac Patients. *ASAIO J* 2021;67:827-44. doi:10.1097/MAT.0000000000001510
142 Gajkowski EF, Herrera G, Hatton L, Velia Antonini M, Vercaemst L, Cooley E. ELSO Guidelines for Adult and Pediatric Extracorporeal Membrane Oxygenation Circuits. *ASAIO J* 2022;68:133-52. doi:10.1097/MAT.0000000000001630
143 Wilcox ME, Jaramillo-Rocha V, Hodgson C, Taglione MS, Ferguson ND, Fan E. Long-Term Quality of Life After Extracorporeal Membrane Oxygenation in ARDS Survivors: Systematic Review and Meta-Analysis. *J Intensive Care Med* 2020;35:233-43. doi:10.1177/0885066617737035
144 Kanschik D, Bruno RR, Wolff G, Kelm M, Jung C. Virtual and augmented reality in intensive care medicine: a systematic review. *Ann Intensive Care* 2023;13:81. doi:10.1186/s13613-023-01176-z
145 Bruno RR, Wolff G, Wernly B, et al. Virtual and augmented reality in critical care medicine: the patient's, clinician's, and researcher's perspective. *Crit Care* 2022;26:326. doi:10.1186/s13054-022-04202-x
146 Huang CY, Thomas JB, Alismail A, et al. The use of augmented reality glasses in central line simulation: "see one, simulate many, do one competently, and teach everyone". *Adv Med Educ Pract* 2018;9:357-63. doi:10.2147/AMEP.S160704
147 Wolf J, Wolfer V, Halbe M, Maisano F, Lohmeyer Q, Meboldt M. Comparing the effectiveness of augmented reality-based and conventional instructions during single ECMO cannulation training. *Int J Comput Assist Radiol Surg* 2021;16:1171-80. doi:10.1007/s11548-021-02408-y
148 Gan A, Cohen A, Tan L. Augmented Reality-Assisted Percutaneous Dilatational Tracheostomy in Critically Ill Patients With Chronic Respiratory Disease. *J Intensive Care Med* 2019;34:153-5. doi:10.1177/0885066618791952
149 Teh JJ, Pascoe DJ, Hafeji S, et al. Efficacy of virtual reality for pain relief in medical procedures: a systematic review and meta-analysis. *BMC Med* 2024;22:64. doi:10.1186/s12916-024-03266-6
150 Ismail SNA, Nayan NA, Jaafar R, May Z. Recent Advances in Non-Invasive Blood Pressure Monitoring and Prediction Using a Machine Learning Approach. *Sensors (Basel)* 2022;22:6195. doi:10.3390/s22166195
151 Couture EJ, Laferrière-Langlois P, Denault A. New Developments in Continuous Hemodynamic Monitoring of the Critically Ill Patient. *Can J Cardiol* 2023;39:432-43. doi:10.1016/j.cjca.2023.01.012
152 Torres A, Niederman MS, Chastre J, et al. International ERS/ESICM/ESCMID/ALAT guidelines for the management of hospital-acquired pneumonia and ventilator-associated pneumonia: Guidelines for the management of hospital-acquired pneumonia (HAP)/ventilator-associated pneumonia (VAP) of the European Respiratory Society (ERS), European Society of Intensive Care Medicine (ESICM), European Society of Clinical Microbiology and Infectious Diseases (ESCMID) and Asociación Latinoamericana del Tórax (ALAT). *Eur Respir J* 2017;50:1700582. doi:10.1183/13993003.00582-2017
153 Collet JP, Thiele H, Barbato E, et al. ESC Scientific Document Group. 2020 ESC Guidelines for the management of acute coronary syndromes in patients presenting without persistent ST-segment elevation. *Eur Heart J* 2021;42:1289-367. doi:10.1093/eurheartj/ehaa575
154 Wunsch H. Mechanical Ventilation in COVID-19: Interpreting the Current Epidemiology. *Am J Respir Crit Care Med* 2020;202:1-4. doi:10.1164/rccm.202004-1385ED
155 Abe T, Madotto F, Pham T, et al. LUNG-SAFE Investigators and the ESICM Trials Group. Epidemiology and patterns of tracheostomy practice in patients with acute respiratory distress syndrome in ICUs across 50 countries. *Crit Care* 2018;22:195. doi:10.1186/s13054-018-2126-6
156 Schwitzer E, Schwab Jensen K, Brinkman L, et al. Survival ≠ Recovery: A Narrative Review of Post-Intensive Care Syndrome. *Chest Critical Care.* 2023;1:100003doi:10.1016/j.chstcc.2023.100003.
157 Franks ZM, Alcock JA, Lam T, Haines KJ, Arora N, Ramanan M. Physical Restraints and Post-Traumatic Stress Disorder in Survivors of Critical Illness. A Systematic Review and Meta-analysis. *Ann Am Thorac Soc* 2021;18:689-97. doi:10.1513/AnnalsATS.202006-738OC
158 De Jonghe B, Constantin JM, Chanques G, et al. Group Interfaces Sédation. Physical restraint in mechanically ventilated ICU patients: a survey of French practice. *Intensive Care Med* 2013;39:31-7. doi:10.1007/s00134-012-2715-9
159 Mehta S, Burry L, Cook D, et al. SLEAP InvestigatorsCanadian Critical Care Trials Group. Daily sedation interruption in mechanically ventilated critically ill patients cared for with a sedation protocol: a randomized controlled trial. *JAMA* 2012;308:1985-92. doi:10.1001/jama.2012.13872
160 Gershengorn HB, Patel S, Mallow CM, et al. Association of language concordance and restraint use in adults receiving mechanical ventilation. *Intensive Care Med* 2023;49:1489-98. doi:10.1007/s00134-023-07243-0
161 Rose L, Sutt AL, Amaral AC, Fergusson DA, Smith OM, Dale CM. Interventions to enable communication for adult patients requiring an artificial airway with or without mechanical ventilator support. *Cochrane Database Syst Rev* 2021;10:CD013379.