Treatment of the lung injury of drowning: a systematic review

Ogilvie Thom1,2*, Kym Roberts1,2, Susan Devine1, Peter A. Leggat1,3 and Richard C. Franklin1,4

Abstract
Background: Drowning is a cause of significant global mortality. The mechanism of injury involves inhalation of water, lung injury and hypoxia. This systematic review addressed the following question: In drowning patients with lung injury, what is the evidence from primary studies regarding treatment strategies and subsequent patient outcomes?

Methods: The search strategy utilised PRISMA guidelines. Databases searched were MEDLINE, EMBASE, CINAHL, Web of Science and SCOPUS. There were no restrictions on publication date or age of participants. Quality of evidence was evaluated using GRADE methodology.

Results: Forty-one papers were included. The quality of evidence was very low. Seventeen papers addressed the lung injury of drowning in their research question and 24 had less specific research questions, however included relevant outcome data. There were 21 studies regarding extra-corporeal life support, 14 papers covering the theme of ventilation strategies, 14 addressed antibiotic use, seven papers addressed steroid use and five studies investigating diuretic use. There were no clinical trials. One retrospective comparison of therapeutic strategies was found. There was insufficient evidence to make recommendations as to best practice when supplemental oxygen alone is insufficient. Mechanical ventilation is associated with barotrauma in drowning patients, but the evidence predate the practice of lung protective ventilation. There was insufficient evidence to make recommendations regarding adjuvant therapies.

Conclusions: Treating the lung injury of drowning has a limited evidentiary basis. There is an urgent need for comparative studies of therapeutic strategies in drowning.

Keywords: Drowning, Review, Ventilation, Non-invasive ventilation, Lung injury

Background
Drowning is a major cause of preventable death and morbidity worldwide. There are over 295,000 unintentional drowning deaths (excluding boating) per year [1, 2]. Ninety percent of these deaths occur in middle- and low-income countries, and half the fatalities are aged less than 25 years [1]. Despite the modern medical literature on drowning reaching back at least as far as The Lancet in 1878 [3], there have only recently been efforts to standardise definitions [4] and data collection [5] for drowning research. The majority of the published studies focus on three themes—preventative strategies such as secure pool fencing, high-risk groups such as children and factors determining clinical outcome, especially duration of immersion [2, 6–8].

The mechanism of drowning involves aspiration of water into the lung which damages surfactant, disrupts the alveolar capillary membrane and leads to the development of alveolar oedema, resulting in a local acute respiratory distress syndrome (ARDS)-like syndrome [6]. A high proportion of drowning patients are hypoxic and have a PaO2/FiO2 ratio < 300 mm Hg [9, 10]. Treating this...
lungs and reversing the hypoxia are the cornerstone of the management of drowning [7].

However, current ventilation guidelines for drowning patients are adapted from ARDS [7, 11] and as such may not reflect the needs of the drowned patient. The aim of this paper is to review the existing evidence to guide the clinician in the treatment of the lung injury and respiratory distress associated with drowning.

Methods
Research question
The patient, intervention, comparison and outcome (PICO) question being addressed is: In drowning patients with lung injury, what is the evidence from primary studies regarding comparisons of treatment strategies and subsequent patient outcomes?

This is a systematic review using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [12] to explore the treatment of drowning.

Protocol
The protocol for this review is available on Prospero; “Treating the respiratory impairment of drowning: A systematic review” (CRD420203896).

Inclusion criteria
This review included papers with human participants, who had drowned, and that included outcome data for interventions designed to treat the lung injuries associated with drowning. Outcomes of interest were mortality, escalation of ventilation strategy, duration of ventilation, ARDS, pneumonia and barotrauma. There was no restriction on publication date or age of participants. Systematic reviews and meta-analyses, where available, were included if they reported primary data outcome of interest.

Exclusion criteria
Papers in a language other than English and animal studies were excluded. Letters, editorials, reviews and case reports were also excluded. Studies contributing data to included systematic reviews or meta-analyses were not individually included in this review.

Search strategy
The PRISMA methodology for searching the literature was utilised to ensure a systematic approach was taken [12]. The search strategy was constructed for use on Medline and adapted for use on EMBASE, CINAHL, Web of Science and SCOPUS. Searches were conducted on 15 January 2021, with no date limitations. The full search strategy is detailed in Additional file 1 and included MeSH terms for the environment such as “critical care” and “emergency department”, the condition “drowning” and “near drowning” and the intervention such as “non-invasive ventilation”, “mechanical ventilation” and “ECLS treatment”. Reference lists of included articles and relevant reviews were also searched. Screening of the search results by title, abstract and then full text was conducted by two authors (OT and KR) for inclusion. Where agreement was not achieved, these were referred to a third author (RF). Where outcome data were unclear, attempts were made to contact the corresponding author for clarification. The results of the search strategy are presented in Fig. 1.

Appraisal of selected studies
Data were independently extracted from selected articles using a standardised form by two authors (OT and KR). All papers were assessed for the quality of the evidence utilising Grading of Recommendations Assessment, Development and Evaluation (GRADE) methodology [13]. Observational studies were defined prior to assessment as having a low quality of evidence [14]. The GRADE evidence profile for included studies is included in Additional file 2.

Results
There were 41 studies which met the inclusion criteria. The summary table of included studies is detailed in Additional file 3. They included data on patients from 20 countries with the USA [15–27] and France [28–31] most frequently represented. Patient data were reported on 1973 patients. Patient demographics were incomplete with regards to gender in eleven papers [19, 20, 25–27, 31–35]. Data presented included 1093 (55.4%) males and 545 (27.6%) females and were similarly incomplete with regards to age groups in seven papers [10, 16, 31, 32, 34, 36, 37], with a minimum of 675 (34.5%) children included. Studies were predominately (30/41, 73.2%) from intensive (critical) care units [10, 16, 20–31, 34–51], 6/41 (14.6%) from inpatient units [9, 15, 17, 18, 41, 52] and five (12.2%) studies were based in the Emergency Department [19, 32, 33, 53, 54]. Three studies utilised the Utstein Style for drowning [28, 29, 44].

A total of 17 papers were identified where the lung injury of drowning was the focus of the research question [9, 10, 20–22, 28-31, 36, 37, 39, 43, 44, 47, 50, 51, 53]. Twenty-four papers where the lung injury of drowning was not the focus of the research question that nevertheless included information relevant to the review were included [15–19, 23–27, 32–35, 37, 38, 40, 41, 45, 46, 48, 49, 52, 54]. All were case series other than one retrospective cohort study [29] and two multicentre registry studies [21, 26]. The GRADE level was universally (41/41, 100%) rated as very low.
Mortality was reported in all papers. There was considerable overlap amongst treatment groups and reported outcomes frequently included multiple treatment groups. Insufficient studies were free of these issues to allow meta-analysis. Extracorporeal life support (ECLS) was the most common theme (21 articles) [20, 21, 23–27, 31, 34, 35, 37, 43–51] followed by ventilatory strategies (14 articles) [9, 10, 15, 17, 19, 28, 29, 32, 38–41, 53, 54], the use of prophylactic antibiotics to prevent aspiration or early onset post-drowning pneumonia (14 articles) [9, 10, 16–18, 30, 33, 36, 38–41], the use of corticosteroids (7 articles) [16, 18, 33, 36, 40, 41, 52] and the use of diuretics (5 articles) [9, 18, 40, 41, 52]. A summary of the aims, the population studied, the study setting, treatment strategies, methodology, results and GRADE level of the selected studies is included in Additional file 3.

**Extra-corporeal life support**

The ECLS studies fall into two categories. Six studies [21, 25–27, 37, 47] report on ECLS in drowning with a survival rate of 156/290 (53.7%). Fifteen studies reported on ECLS for drowning associated with accidental hypothermia [20, 22–24, 31, 34, 35, 43–46, 48–51]. The survival rate was 35/120 (29.2%). Overall, the survival rate for ECLS in drowning is 191/410 (46.6%) (Table 1).
Burke et al. published data on 247 drowning patients on the Extracorporeal Life Support Organization international database, covering a 30-year period. They reported good outcomes in patients who had not experienced cardiac arrest where ECLS was initiated for refractory respiratory failure (60/84, 71.4% survival). In post-cardiac arrest patients, where ECLS was initiated following ROSC, survival was still high but lower (49/86, 57.0%). Survival in drowning patients was lowest when ECLS was initiated during cardiac arrest (18/77, 23.4%).

Table 1: ECLS and drowning

| Study                        | Outcome measured | Outcome measured | Confounders |
|------------------------------|------------------|------------------|-------------|
| **Drowning**                 |                  |                  |             |
| Steiner et al. [25]          | Mortality        | 3/8 (37.5%) survived | No validated assessment tool used for neurological outcome |
| Weber et al. [27]            | Mortality        | 1/4 (25.0%) survived | No validated assessment tool used for neurological outcome |
| Kim et al. [47]              | Mortality        | 8/9 (88.9%) rapidly worsening ARDS | No validated assessment tool used for neurological outcome |
| Burke et al. [21]            | Mortality        | 60/84 (71.2%) survived (no cardiac arrest prior to ECLS) | No neurologic outcome reported |
| Watson et al. [26]           | Mortality        | 3/4 (75%) survival | No neurologic outcome reported |
| Lee et al. [37]              | Mortality        | 15/18 (83.3%)    | No neurologic outcome reported |
| **Drowning + Hypothermia**   |                  |                  |             |
| Saltiel et al. [22]          | Mortality        | 2/3 (66.6%) survived, 1/3 (33.3%) GNO | No validated assessment tool used for neurological outcome |
| Walpoth et al. [34]          | Mortality        | 0/2 (0.0%) survived | No validated assessment tool used for neurological outcome |
| Mair et al. [48]             | Mortality        | 1/7 (14.3%) survived | No validated assessment tool used for neurological outcome |
| Farstad et al. [45]          | Mortality        | 1/14 (7%) survived | Neurological data presented as group results |
| Wollenek et al. [51]         | Mortality        | 2/3 (66.6%) survived | No validated assessment tool used for neurological outcome |
| Eich et al. [44]             | Mortality        | 5/12 (42%) survived | Paediatric cerebral performance category |
| Scaife et al. [23]           | Mortality        | 1/5 (20%) survived | No validated assessment tool used for neurological outcome |
| Coskun et al. [43]           | Mortality        | 5/13 (38%) survived | No validated assessment tool used for neurological outcome |
| Suominen et al. [49]         | Mortality        | 3/13 (23%) severe neurological deficit | No validated assessment tool used for neurological outcome |
| Wanscher et al. [35]         | Mortality        | 1/9 (11%) survived | Group results given for neurological outcome |
| Skarda et al. [24]           | Mortality        | 0/7 (0%) survived | No validated assessment tool used for neurological outcome |
| Champigneulle et al. [31]    | Mortality        | 2/20 (10%) survived | Validated neurological outcome score used |
| Weuster et al. [50]          | Mortality        | 2/9 (22%) survived | No validated assessment tool used for neurological outcome |
| Khorsandi et al. [46]        | Mortality        | 3/4 survived     | No neurologic outcome reported |
| Bauman et al. [20]           | Mortality        | 3/5 survived     | No validated assessment tool used for neurological outcome |

ECLS, Extra-corporeal life support; GNO, good neurological outcome; ROSC, return of spontaneous circulation; ECPR, ECLS-assisted cardio-pulmonary resuscitation; PCPC, paediatric cerebral performance category; GOSE, Glasgow Outcome Scale Extended; USFD, Utstein Style for Drowning; CPC, cerebral performance category.
Mechanical ventilation

Mechanical ventilation (MV) is often used when supplemental oxygen alone is insufficient [15, 17, 19, 29, 39, 41, 54]. Other indications include decreased conscious state [28, 52] or cardiac arrest [15, 32, 39, 41, 54]. Complications of MV include the development of pneumonia [36] and barotrauma [15, 17, 19]. The reported frequency of barotrauma is high, with an incidence of 75%, 12% and 10% [15, 17, 19], respectively. Since these earlier papers, MV strategies have evolved into the practice termed lung protective ventilation (LPV), which decreases ventilator-associated lung injury [55], and this practice is currently advocated for the treatment of drowning patients [7, 11]. Michelet et al. reports using LPV in 30 drowning patients with no barotrauma reported [28]. Unfortunately, barotrauma was not identified as an outcome of interest in the paper. Duration of mechanical ventilation has not changed greatly. A study of 25 patients reported a mean duration of MV of 4.3 days in 1982 [17], but data from two recent papers [28, 29] demonstrate a mean (SD) duration of 6 (±12) days (n=70).

Other outcomes reported for MV typically include survival and neurological status [15, 32, 41]. Given the co-existence of hypoxic encephalopathy in many of these patients [38], it is impossible to comment on the success or otherwise of mechanical ventilation in aiding survival (Table 2).

Non-invasive ventilation

There were four papers [28, 29, 39, 40] reporting on non-invasive ventilation (NIV) with the majority (3/4, 75%) published since 2017 [28, 29, 39] (Table 3). The earliest report of successful use of NIV dates from 1982, where eleven patients were successfully treated with continuous positive airway pressure (CPAP) [40]. Recently, three larger studies all from France or its overseas territories have been published [28, 29, 39]. Cerland et al. report use of NIV in 28 patients with acute respiratory failure [39]. Outcomes are not explicitly reported, but all deaths (n=45) in their cohort of 144 had experienced pre-hospital cardiac arrest [39]. The other two series of NIV patients are from the same group located in the south of France [28, 29]. Their 2017 paper describes a population of 25 patients who received NIV from emergency medical services (EMS) and additional 23 patients put on NIV in the ED after arrival at hospital. Four of the patients put on NIV by EMS subsequently received MV (three because of worsening respiratory failure), and all patients survived [28]. Patients receiving NIV were different from those receiving MV. They were more alert (Glasgow Coma Score 12±3 NIV vs 7±2 MV, P<0.05) and were not as critically ill with lower Simplified Acute Physiology Scores (28±8 vs 50±19) and Sequential Organ Failure Assessment scores (2.4±2 vs 6.5±4) [28]. The authors noted a similar rate of improvement in oxygenation between NIV and MV after the first six hours [28]. The second paper retrospectively compared 38 matched pairs (n=76) for fresh versus seawater drowning [29]. Thirteen patients received NIV and 40 patients MV. There were no reported failures of NIV [29]. The mean duration of treatment with NIV was 1.4 (±2.4) days when the results are combined from both papers [28, 29] (Table 3).

Hi-flow nasal prongs

There was a single article reporting on the use of HFNP [53]. Fifty-seven patients were treated with HFNP, and 12 were converted to MV for worsening ARDS with two patients ultimately requiring ECLS. There were two deaths in the series [53].

Prophylactic antibiotics

Prophylactic antibiotics were used in 562 (28.5%) patients from 14 studies. Outcome data were only available on 311 patients from seven studies [9, 16, 33, 38, 41, 47, 52]. The mortality rate was 23/311 (7.4%). A single study [16] reported mortality in the patients that did not receive antibiotics (2/36, 5.6%). Two studies reported no improvement from the use of prophylactic antibiotics without including outcome data [18, 36] (Table 4).

Prophylactic steroids

The outcomes reported from seven papers for prophylactic steroids showed no benefit [16, 18, 33, 36, 40, 41, 52]. Overall, 264 patients received prophylactic steroids and 31 (11.7%) died. Ninety-one patients were reported as not being treated with prophylactic steroids and two died (2.2%). One paper reported an increased hospital length of stay (LOS) in patients who received steroids but did not require mechanical ventilation compared with those not receiving steroids (3.2 vs 1.7 days, supporting data not presented) [41]. A second paper described performing regression analysis to measure the effect of steroids [36] and concluded that there was no effect, but no data supporting this were included [36].

Prophylactic diuretics

Prophylactic use of diuretics has been reported as having no clinical benefit [18, 40, 41]. However, pre-hospital use of forced diuresis with frusemide by EMS is described in a series of 69 drowning patients from the Dead Sea [52]. There were no fatalities in this study [52]. Similar results are reported in a series of 43 patients from Greece, where only two patients required escalation of therapy secondary to respiratory compromise [9].
Table 2 Outcomes of mechanical ventilation in drowning

| Study                      | Outcome measured | Outcome | Confounders                                      |
|----------------------------|------------------|---------|-------------------------------------------------|
| Fandell et al. [15]        | Mortality        | 12/34 (35%) MV | Not controlled for other interventions          |
|                            | Barotrauma       | 6/12 (50%) died |                                                  |
|                            |                  | 9/12 (75%) pneumothorax, 8/12(66%) pneumomediastinum |                                                  |
| Petersen [19]              | Mortality        | 7/72 (10%) died | Unclear number of MV patients; outcomes not group specific |
|                            | Pneumonia        | 10/72 (14%) barotrauma (all MV) |                                                  |
|                            | ARDS             | 29/72 (40%) pneumonia |                                                  |
|                            | Barotrauma       | 6/72 (9%) ARDS |                                                  |
| Corbin [41]                | Mortality        | 3/8 (38%) died | Not controlled for other interventions          |
| Oakes et al. [17]          | Mortality Barotrauma | 25/40 (63%) MV | Not controlled for other interventions; outcomes not group specific |
|                            | Pneumonia        | 3/25 (12%) barotrauma |                                                  |
|                            |                  | 16/40 (40%) pneumonia |                                                  |
|                            |                  | 10/40 (25%) died |                                                  |
| van Berkel et al. [36]     | Mortality        | 25/102 (25%) MV | Not controlled for other interventions          |
|                            | Pneumonia        | 11/25 (52%) pneumonia (RR 17.3, P < 0.001) |                                                  |
|                            |                  | 6/25 (25%) died |                                                  |
| Lee [10]                   | Pneumonia        | 8/17 (47.1%) MV | Not controlled for other interventions; outcomes not group specific |
|                            |                  | 0/17 (0.0%) pneumonia |                                                  |
| al-Talafieh et al. [32]    | Mortality        | 14/34 MV | Outcomes not group specific                      |
|                            | Pneumonia        | 5/34 (15%) died |                                                  |
|                            | Barotrauma       | 6/34 (18%) pneumonia |                                                  |
|                            |                  | 1 PTX |                                                  |
| Saidel-Odes et al. [52]    | Mortality        | 11/69 (16%) MV patients | Not controlled for other interventions; outcomes not group specific |
|                            | Pneumonia        | 26/69 (38%) pneumonia |                                                  |
|                            | ARDS             | 3/69 (4%) ARDS |                                                  |
|                            |                  | No deaths |                                                  |
| Ballesteros et al. [38]    | Mortality        | 21/43 (49%) MV | Not controlled for other interventions; outcomes not group specific |
|                            |                  | 15/43 (33%) died |                                                  |
| Kotsiou et al. [54]        | Mortality        | 8/20 (40%) MV | Not controlled for other interventions           |
|                            | ARDS             | 0 deaths | ? Definition of ARDS                             |
|                            |                  | 8/20 (40%) mod/severe ARDS |                                                  |
| Michelet et al. [28]       | Mortality        | 30/88 (34%) MV | Not controlled for other interventions          |
|                            | Pneumonia        | 6/30 (20%) pneumonia |                                                  |
|                            | Duration MV      | 5/30 (17%) sepsis shock |                                                  |
|                            |                  | No deaths | 3±2 days |                                                  |
| Cerland et al. [39]        | Mortality        | 64/144 (44%) MV | Not controlled for other interventions; outcomes not group specific |
|                            | Pneumonia        | 35/144 (24%) pneumonia |                                                  |
|                            | ARDS             | 23/144 (16%) ARDS |                                                  |
|                            | ECLS             | 45/144 (31%) died |                                                  |
|                            |                  | 2/64 (3%) ECLS |                                                  |
| Michelet et al. [29]       | Mortality        | 40/76 (53%) MV | Unclear ventilatory modes and outcomes          |
|                            | Duration MV      | 15/76 (20%) died |                                                  |
|                            |                  | 8 (±16) days |                                                  |

MV, mechanical ventilation; ARDS, Acute Respiratory Distress Syndrome; ECLS, extra-corporeal life support

Other treatment modalities
One paper reports the use of bronchodilators (aminophylline) in 22/98 patients with a minimum of one and potentially two deaths, as well as the use of plasma in 12/98 patients with a minimum of one and potentially three deaths [41]. Mortality results were extrapolated from grouped data.

Discussion
The key finding from this review is the lack of evidence informing the treatment of the lung injuries associated with drowning. There was a single retrospective comparison of treatments [28]. This is in stark contrast to eight included studies [10, 15, 16, 18, 29, 36, 37, 41] that compare outcomes of drownings between fresh and salt water.
In 1973, it was reported that the lung injury associated with drowning was rapidly reversible with the application of positive pressure mechanical ventilation [56]. Following this, several studies reported a high incidence of barotrauma when treating drowning with MV [15, 17, 19]. Subsequently, the similarities between the lung injury in drowning and ARDS have been established [6]. Randomised trials have established the safety and efficacy of LPV in ARDS [57], and it has been adopted as best practice in the management of the lung injury associated with drowning [7, 11]. This may explain the decrease in reported barotrauma associated with MV in recent studies; however, it was not documented as a measured outcome [28, 29, 39].

The use of NIV in drowning was first reported in 1982 [40]; however, it has only been recently that any substantive evidence has been presented regarding the efficacy of NIV in the drowning patient [28, 29, 39]. When compared with MV for the treatment of drowning patients, NIV is similarly effective as MV in reversing hypoxia but is required for a significantly shorter duration (1.4 ± 2.4 vs 6 ± 12 days, P = 0.004) [28, 29]. This has to be interpreted with caution given different indications for both treatments [15, 32, 39, 52, 54], but a recent study also established the efficacy and safety of NIV in mild to moderate ARDS [58].

Oxygen therapy using HFNP has been adopted widely from the treatment of bronchiolitis to many other causes of respiratory insufficiency in children and adult patients [59]. There is a single report of its use in drowning [53]. There is, however, a lack of evidence that we can only recommend clinical judgement be applied when deciding on therapeutic strategies when supplemental oxygen alone is insufficient.

It was surprising that the majority of published studies regarding the treatment of drowning are on the use of ECLS. The Extracorporeal Life Support Organization international database has over 400 centres contributing data [21]. Despite this, there were only 247 drowning patients included over a 30-year period. Clearly, the use of ECLS in drowning patients is not a common occurrence. However, the survival rates in patients with cardiac arrest (57% with ROSC, 23% with ECLS) compare favourably to published survival rates post-drowning associated cardiac arrest in Germany (18%) [60], Sweden (14%) [61] and France (9%) [62]. There were one meta-analysis and one systematic review examining ECLS in the treatment of drowning and hypothermia that were not included in this paper [63, 64]. Both studies grouped drowning and avalanche patients in ‘asphyxial’ groups, and the drowning outcomes could not be separated. However, the outcomes for this group of patients were much worse when compared with isolated hypothermic cardiac arrest with 23.4% vs 67.7% survival [63] and an odds ratio for survival of 0.19 (0.11–0.35) [64].

No study reported on the efficacy of any of the adjuvant therapies in isolation. Added to this was the confounder that all treatments were administered at the clinicians’ discretion and, almost certainly, there was significant treatment bias with sicker patients more likely to receive MV and adjuvant therapies, such as steroids and antibiotics. van Berkel et al. (1996) did conduct a regression analysis attempting to control for confounding variables and concluded that there was no

### Table 3: Outcomes of non-invasive ventilation in drowning

| Study          | Outcome measured | Outcome | Confounders                      |
|----------------|------------------|---------|----------------------------------|
| Modell et al.  | Mortality        | 24 spontaneously ventilating patients received intermittent positive end expiratory pressure | Not controlled for other interventions; outcomes not group specific |
| Dick et al.    | Mortality        | 11/18 (61%) NIV, 2/18 (11%) died | Not controlled for other interventions; outcomes not group specific |
| Cerland et al. | Mortality, Pneumonia, ARDS | 28/144 (19%) NIV, 35/144 (24%) pneumonia, 23/144 (16%) ARDS | Not controlled for other interventions; outcomes not group specific |
| Michelet et al.| Mortality, Conversion to MV, Pneumonia, Duration NIV | 48/88 (55%) NIV, 4/48 (8%) escalated to MV, 1/48 (2%) pneumonia, 1.4 ± 0.7 days | Not controlled for other interventions |
| Michelet et al.| Mortality, Pulmonary Complications, Duration NIV | 13/76 (17%) NIV, 4/76 (5%) pneumonia, 15/76 (20%) died, 1.3 ± 5 days | Outcomes not group specific |

NIV, non-invasive ventilation; ARDS, Acute Respiratory Distress Syndrome; MV, mechanical ventilation
benefit from any of the adjuvant therapies with regards to duration of MV, hospital or ICU LOS [36]. They also concluded that MV was a risk factor for developing pneumonia post-drowning without presenting the data or outlining the variables included in the analysis [36]. Clinical trials in ARDS have established a lack of efficacy for steroids [65] and surfactant [66, 67]. The evidence for or against diuretic therapy in ARDS is less clear [68, 69]. The lack of evidence in drowning prevents any recommendations.

**Implications for future research**

While drowning is a common cause of death worldwide [1], it is neither a common cause of ED presentations [70, 71] nor hospital admissions [72]. This may explain the apparent lack of evidence regarding its management. The lack of comparative studies and scarcity of multi-centre collaborations are of concern and must be addressed urgently. This is especially so given the demonstrated value of the Extracorporeal Life Support Organization’s international registry in informing the use of ECMO in drowning patients.

---

Table 4  Outcomes of antibiotic prophylaxis

| Study                | Outcome measured | Outcome                          | Confounders                                                                                     |
|----------------------|------------------|----------------------------------|--------------------------------------------------------------------------------------------------|
| Modell et al. [16]   | Mortality        | 54/90 (60%) ABP, 7/54 (13%) died | Not controlled for other interventions                                                          |
| Orlowski [18]       | Unclear          | “The use of corticosteroids, antibiotic prophylaxis and diuretics did not improve prognosis“ (data not shown) | Not controlled for other interventions; outcomes not group specific                          |
| Corbin [41]         | Mortality        | 79 patients treated. Minimum of one death, potentially three | Not controlled for other interventions; outcomes not group specific                              |
| Dick et al. [40]    | Mortality        | 16/18 (89%) ABP                  | Not controlled for other interventions; outcomes not group specific                              |
| Oakes et al. [17]   | Mortality/Pneumonia | 31/40 (78%) ABP, 16/40 (40%) pneumonia | Not controlled for other interventions; outcomes not group specific                              |
| Simcock [33]        | Mortality/Pneumonia/ARDS | 68/121 (56%) ABP, 12/68 (18%) died (1 from pneumonia, 1 from ARDS) | Not controlled for other interventions; outcomes not group specific, Treatment determined by severity of illness |
| van Berkel et al. [36] | Mortality/Pneumonia | 45/102 (44%) ABP, 15/102 (15%) pneumonia | Not controlled for other interventions; outcomes not group specific                              |
| Lee [10]            | Pneumonia        | 16/17 (94.1%) ABP, 0/17 (0.0%) pneumonia | Not controlled for other interventions                                                          |
| Saidel-Odes et al. [52] | Mortality/Pneumonia/ARDS | 42/69 (61%) ABP, 26/69 (38%) pneumonia, 3/69 (4%) ARDS | Not controlled for other interventions; outcomes not group specific                              |
| Gregorakos et al. [9] | Pneumonia/ARDS | 43/43 ABP, 4/43 (9%) pneumonia, 1/43 (2%) died from pneumonia | Not controlled for other interventions                                                          |
| Ballesteros et al. [38] | Mortality/Septic outcomes | 27/43 (62.8%) ABP, 15/43 (35%) died, 1/43 (2%) died from pneumonia | Not controlled for other interventions; outcomes not group specific                              |
| Kim [47]            | Mortality        | 9/9 (100%) ABP, 2/9 (22.2%) died | All patients received ECLS                                                                       |
| Cerland et al. [39] | Mortality/ARDS   | 85/144 (59%) ABP, 35/144 (24%) pneumonia, 23/144 (16%) ARDS | Not controlled for other interventions; outcomes not group specific                              |
| Robert et al. [30]  | Mortality/Pneumonia/ARDS | 44/74 (59%) ABP, 36/74 (49%) pneumonia, 25/74 (34%) ARDS, 19/74 (26%) died | Outcomes not group specific                                                                     |

ABP, antibiotic prophylaxis; ARDS, Acute Respiratory Distress Syndrome; ECLS, extracorporeal life support
Limitations
This structured evidence-based review was aimed at establishing the primary evidence behind the treatment of the lung injuries associated with drowning. The World Health Organisation published a uniform definition of drowning and its outcomes in 2005 [4]. More than half of the studies included in this review were published after 2005. Unfortunately, only four of them use the correct definition [28–30, 50]. Without a consistent definition of a drowning patient, it is hard to integrate the published evidence.

The search strategy excluded any papers written in languages other than English. Given the very low quality of evidence, one or two high-quality English language papers may have changed the findings of the review.

Conclusions
There is a dire lack of evidence informing the management of the drowning patient. This makes any recommendations regarding best practice impossible other than to follow local guidelines and clinical judgement. There is an urgent need for high-quality research on the treatment of drowning. Duration of immersion is a critical factor in patient prognosis [8], and as such, prevention is currently the most effective strategy in reducing drowning mortality.

Abbreviations
ABP: Antibiotic prophylaxis; ARDS: Acute respiratory distress syndrome; CPC: Cerebral performance category; ECLS: Extra-corpooreal life support; ECPR: ECLS-assisted cardio-pulmonary resuscitation; EMS: Emergency medical services; GNO: Good neurological outcome; GOSE: Glasgow outcome scale extended; GRADE: Grading of recommendations assessment, development and evaluation methodology; HFNP: High flow nasal prongs; ICU: Intensive care unit; LOS: Length of stay; LPV: Lung protective ventilation; MV: Mechanical ventilation; NIV: Non-invasive ventilation; PCPC: Paediatric cerebral performance category; PRISMA: Preferred reporting items for systematic reviews and meta-analyses; ROSC: Return of spontaneous circulation; USFD: Utstein style for drowning.

Supplementary Information
The online version contains supplementary material available at https://doi.org/10.1186/s13054-021-03687-2.

Additional file 1. Medline search strategy.
Additional file 2. GRADE evidence summary of included studies.
Additional file 3. Summary Table of included studies.

Acknowledgements
Not applicable.

Authors’ contributions
OT, KR, SD, PL, RF participated in study concept and design, OT and KR conducted the acquisition of the data, OT and KR conducted the analysis and interpretation of the data, OT drafted the manuscript, OT, KR, SD, PL, RF conducted critical revision of the manuscript and OT and KR participated in acquisition of funding. All authors read and approved the final manuscript.

Funding
This study was supported by an Australian Government Research Training Program Scholarship. Two authors (OT and KR) have also been supported by the Doctoral Cohort programme Division of Tropical Health and Medicine, James Cook University and the Emergency Department, Sunshine Coast University Hospital.

Availability of data and materials
All data generated or analysed in this study are included in this published article (and its Additional files).

Declarations

Ethical approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Author details
1 College of Public Health, Medical and Veterinary Sciences, James Cook University, Townsville, QLD, Australia. 2 Department of Emergency Medicine, Sunshine Coast Hospital and Health Service, Sunshine Coast, QLD, Australia. 3 School of Medicine, National University of Ireland Galway, Galway, Ireland. 4 Royal Life Saving – Australia, National Office, Broadway, Sydney, Australia.

Received: 19 May 2021   Accepted: 6 July 2021
Published online: 19 July 2021

References
1. World Health Organization. Global report on drowning: preventing a leading killer. Geneva: World Health Organization; 2014.
2. Franklin RC, Peden AE, Hamilton EB, et al. The burden of unintentional drowning: global, regional and national estimates of mortality from the Global Burden of Disease 2017 Study. Inj Prev. 2020; 26(Suppl 2): i83–i95.
3. Howard B. The direct method of artificial respiration for the treatment of apnoea from drowning, anaesthetics, still-birth, etc.; with a typical case of each, treated by the author, in which other methods were not immediately practicable. Lancet. 1878; 111:748–52.
4. Van Beeck EF, Branche CM, Szpilman D, Modell JH, Bierens JJLM. A new definition of drowning: towards documentation and prevention of a global public health problem. Bull World Health Organ. 2005;83:853–6.
5. Idris AH, Berg RA, Bierens J, et al. Recommended guidelines for uniform reporting of data from drowning: the “Utstein style”. Resuscitation. 2003;59:45–57.
6. Bierens JJLM, Lunetta P, Tipton M, Warner DS. Physiology of drowning: a review. Physiology. 2016;31:147–66.
7. Szpilman D, Bierens JJ, Handley AJ, Orlovski JP. Drowning. N Engl J Med. 2012;366:2102–10.
8. Quan L, Bierens J, Lis R, Rowhani-Rahbar A, Morley P, Perkins GD. Predicting outcome of drowning at the scene: a systematic review and meta-analyses. Resuscitation. 2016;104:63–75.
9. Gregorakos L, Mavrou N, Psalida V, et al. Near-drowning: clinical course of lung injury in adults. Lung. 2009;187:93–7.
10. Lee KH. A retrospective study of near-drowning victims admitted to the intensive care unit. Ann Acad Med Singap. 1998;27:344–6.
11. Schmidt AC, Semsrott JR, Hawkins SC, Arastu AS, Cushing TA, Auerbach PS. Wilderness medical society practice guidelines for the prevention and treatment of drowning. Wilderness Environ Med. 2016;27:236–51.
12. Moher D, Liberati A, Tetzlaff J, Altman DG, Group P. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ 2009;339:b2535.
61. Claesson A, Djarv T, Nordberg P, et al. Medical versus non medical etiology in out-of-hospital cardiac arrest—changes in outcome in relation to the revised Utstein template. Resuscitation. 2017;110:48–55.
62. Hubert H, Escunhaire J, Michelet P, et al. Can we identify termination of resuscitation criteria in cardiac arrest due to drowning: results from the French national out-of-hospital cardiac arrest registry. J Eval Clin Pract. 2016;22:924–31.
63. Dunne B, Christou E, Duff O, Merry C. Extracorporeal-assisted rewarming in the management of accidental deep hypothermic cardiac arrest: a systematic review of the literature. Heart Lung Circ. 2014;23:1029–35.
64. Saczkowski RS, Brown DJA, Abu-Laban RB, Fradet G, Schulze CJ, Kuzak ND. Prediction and risk stratification of survival in accidental hypothermia requiring extracorporeal life support: an individual patient data meta-analysis. Resuscitation. 2018;127:51–7.
65. Steinberg KP, Hudson LD, Goodman RB, et al. Efficacy and safety of corticosteroids for persistent acute respiratory distress syndrome. N Engl J Med. 2006;354:1671–84.
66. Willson DF, Thomas NJ, Markowitz BP, et al. Effect of exogenous surfactant (calfactant) in pediatric acute lung injury: a randomized controlled trial. JAMA. 2005;293:470–6.
67. Willson DF, Truwit JD, Conaway MR, Traul CS, Egan EE. The adult calfactant in acute respiratory distress syndrome trial. Chest. 2015;148:356–64.
68. National Heart Lung and Blood Institute Acute Respiratory Distress Syndrome Clinical Trials Network, Wiedemann HP, Wheeler AP, et al. Comparison of two fluid-management strategies in acute lung injury. N Engl J Med. 2006;354:2564–75.
69. Semler MW, Wheeler AP, Thompson BT, et al. Impact of initial central venous pressure on outcomes of conservative versus liberal fluid management in acute respiratory distress syndrome. Crit Care Med. 2016;44:782–9.
70. El Sibai R, Bachir R, El Sayed M. Submersion injuries in the United States: patients characteristics and predictors of mortality and morbidity. Injury. 2018;49:543–8.
71. Willis BA, Watt K, Franklin RC, Nixon JW, Kimble RM. Drowning mortality and morbidity rates in children and adolescents 0–19 yrs: a population-based study in Queensland, Australia. PLoS ONE. 2015;10:e117948-e.
72. Peden AE, Mahony AJ, Bamsley PD, Scarr J. Understanding the full burden of drowning: A retrospective, cross-sectional analysis of fatal and non-fatal drowning in Australia. BMJ Open 2018;8:e024868.

**Publisher’s Note**
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.