Dissertation

Clinical implications of prehospital invasive haemodynamic monitoring in patients with acute brain injury

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Declaration

I hereby declare that this thesis is my own original work and that I have fully acknowledged by name all of those individuals and organizations that have contributed to the research for this thesis. Due acknowledgement has been made in the text to all other material used. Throughout this thesis and in all related publications I followed the "Standards of Good Scientific Practice and Ombuds Committee at the Medical University of Graz".

In the writing process of this thesis generative Artificial Intelligence (AI) (ChatGPT-4) was used as a language editing service to improve the readability and language of parts of the manuscript. No confidential information or results were disclosed to or shared with ChatGPT. All the output was carefully reviewed by myself, and I take full responsibility for the content of this thesis.

Graz, 26.09.2025 Dr. med. univ. Michael Eichlseder eh

Disclosures

This cumulative thesis is based on the following articles:

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I declare that all co-authors consented to the inclusion of their data in this dissertation. The signed co-author agreement is part of the appendix. Since the respective articles were all published open access (Springer Nature) under the Creative Commons CC BY license, which allows unlimited use, distribution, and reproduction in any format as long as the original work is appropriately cited, no additional permissions were required for the reuse of the articles themself as well as the figures and tables contained therein.

Foreword

Initially, a different thesis project, titled “Association of changes in serum neurofilament light chain concentrations and postoperative cognitive dysfunction“ was planned. This prospective observational study aimed to explore the potential relationship between postoperative cognitive dysfunction and perioperative changes in serum neurofilament light chain, a biomarker indicative of axonal damage. The intended sample size was 185 patients undergoing major abdominal surgery with at least one cardiovascular risk factor. Recruitment was completed in March 2024, and the biomarker measurements were finalized in November 2024.

As the project formed a substudy of a larger multicentre trial (INSIGHT study, NCT04753307, planned sample size: 1400 patients), its publication is dependent on the release of the main trial results. However, due to unforeseen delays in the main study—primarily related to intensive care unit capacity constraints for elective procedures—timely publication of the substudy, and consequently of the thesis, is not feasible despite the successful completion of recruitment, measurements, and neurocognitive follow-up.

To enable a timely completion of the thesis, it was agreed with the dean and vice dean of doctoral studies, the speaker of the doctoral school, the thesis committee, and the bureau for doctoral studies, that a change of the thesis topic would be in the best interest of all involved parties.

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List of abbreviations

CPP cerebral perfusion pressure

DBP diastolic blood pressure

IBP invasive Blutdruckmessung

ICP intracranial pressure

MAP mean arterial pressure

SBP systolic blood pressure

// Zusammenfassung

Das prähospitale hämodynamische Management von Patient*innen mit akuter Hirnschädigung ist von zentraler Bedeutung, um Folgeschäden zu vermeiden. Während die invasive Blutdruckmessung (IBP) innerklinisch als Goldstandard gilt, ist ihr Einsatz im prähospitalen Bereich weiterhin umstritten. Zum einen bestehen Bedenken hinsichtlich einer möglichen Verlängerung der Versorgungszeit, zum anderen fehlen Vergleichsstudien, die Unterschiede im Blutdruckmanagement systematisch untersuchen. Ziel dieser Dissertation war es daher, sowohl potenziell negative Auswirkungen (verlängerte Versorgung) als auch mögliche positive Effekte (verbesserte Blutdruckkontrolle) einer präklinischen IBP zu evaluieren.

Zu diesem Zweck wurden zwei retrospektive Studien bei Patient*innen mit akuter Hirnschädigung durchgeführt. Dabei wurden die Zeitspanne vom Eintreffen am Einsatzort bis zur ersten Computertomographie sowie die Blutdruckwerte bei Übergabe im Schockraum zwischen Patientinnen mit präklinischer IBP und solchen mit erst innerklinisch etablierter IBP verglichen. Ergänzend wurde ein Scoping Review erstellt, um die vorhandene Literatur systematisch aufzuarbeiten und klinische Implikationen abzuleiten.

Die Zeit vom Eintreffen am Unfallort bis zur ersten Computertomographie war bei Patient*innen mit präklinischer IBP nicht länger als bei jenen mit innerklinisch begonnener Messung. Die Blutdruckwerte bei Übergabe im Schockraum unterschieden sich jedoch ebenfalls nicht. Die Literaturrecherche ergab, dass eine Arterienpunktion nur in notärztlich besetzten Systemen durchgeführt wird und eine Erfolgsquote von 82% aufwies. Der primäre Punktionsort war die Arteria radialis, schwere Komplikationen waren selten. Angesichts der uneinheitlichen Ergebnisse erscheint eine multizentrische, randomisierte kontrollierte Studie erforderlich, um den Stellenwert der präklinischen IBP bei Patientinnen mit akuter Hirnschädigung zuverlässig zu bewerten.

Abstract

Haemodynamic management is highly important in prehospital patients suffering from acute brain injury to limit secondary damage. While invasive blood pressure monitoring is the in-hospital gold standard, its prehospital use remains debated. Time delays until definitive in-hospital treatment are feared and research evaluating whether it improves blood pressure control compared to non-invasive blood pressure monitoring has not yet been performed. Therefore, this thesis aimed to evaluate both potential negative effects (delays in care) and potential positive effects (improved blood pressure control) of invasive blood pressure monitoring in patients with acute brain injury.

This was done by performing two retrospective studies including adult patients with acute brain injury who were treated in the resuscitation room of the University Hospital of Graz. Time from arrival on scene until first computed tomography and blood pressure at handover in the resuscitation room was compared between patients with prexhospital invasive blood pressure monitoring and those having it initiated in-hospital. Furthermore, a scoping review was performed to summarize the current literature and derive clinical implications.

Time from arrival on scene until first computed tomography was not prolonged in patients with prehospital invasive blood pressure monitoring, compared to those having it initiated in-hospital. However, blood pressure on hospital admission did not differ. Summarizing the current literature, arterial catheter insertion was only performed when physicians were on scene, with the radial artery most frequently accessed. Catheter insertion was successful in 82% of all attempts. The incidence of major complications was low. To evaluate whether prehospital invasive blood pressure monitoring should be the standard of care in patients with acute brain injury, a multicentric randomized controlled trial evaluating patient-centred outcomes is necessary.

Introduction

Prehospital emergency services are frequently confronted with patients suffering from acute brain injury [4]. Acute brain injury may be of either traumatic or non-traumatic origin, with both entities being a major burden for patients and the healthcare system. To reduce this burden as much as possible, the best treatment to reduce morbidity and mortality should be aimed for. While in-hospital treatment is highly specific and dependent on the underlying pathophysiological mechanism, prehospital emergency care of patients with acute brain injury focuses on a fast transport to an appropriate hospital and interventions to minimize secondary brain damage [5, 6]. To reduce secondary brain damage, stable respiratory and haemodynamic conditions are required [7]. Haemodynamic management however, can be challenging in these patients – but remains highly important [8, 9]. Both the underlying disease and necessary medical interventions, for example induction of emergency anaesthesia, have an impact on haemodynamics [10, 11]. Blood pressure is used to guide haemodynamic management with disease-specific targets [5, 6, 12]. In prehospital emergency care, blood pressure in patients with acute brain injury is currently almost exclusively monitored using non-invasive methods. This is different from the in-hospital setting, where invasive blood pressure monitoring via intraarterial catheters and transducer systems is used [13]. Invasive blood pressure monitoring offers beat-to-beat analysis enabling the detection of blood pressure changes more quickly compared to non-invasive methods with the consecutive ability to intervene more rapidly [14, 15]. Apart from the required skill and equipment, the potential time delay for insertion of the intraarterial catheter and setting up the pressure transducer is a major concern regarding prehospital invasive blood pressure monitoring [16].

In the following, information regarding non-invasive and invasive blood pressure monitoring as well as aspects of acute brain injury, including traumatic brain injury and stroke, with a focus on prehospital emergency care, will be provided. Furthermore, the rationale, aim, and hypothesis of this doctoral thesis will be outlined.

Blood pressure monitoring

Blood pressure is the pressure exerted on vascular walls [17]. Arterial blood pressure, measured in the arterial system of the body, is the most frequently used parameter for haemodynamic monitoring and management [18]. It is most commonly reported in millimetres of mercury (mmHg) due to its historical origin, as the first measurement in the 18th century was performed using a column of mercury after cannulating an artery of a horse [19]. Arterial blood pressure monitoring provides a systolic, mean, and diastolic blood pressure [17]. Systolic

arterial blood pressure (SBP) represents the maximum blood pressure generated during contraction of the heart. Mean arterial blood pressure (MAP) is the mean blood pressure during one cardiac cycle and is calculated by dividing the area under the pressure/time curve by the cardiac cycle time. Diastolic arterial blood pressure (DBP) is the minimum blood pressure during relaxation of the heart [17]. Of the three blood pressures, MAP is considered the parameter to represent organ perfusion the most accurate [20]. Arterial blood pressure can be monitored either non-invasively or invasively, which will be further outlined in the following [21].

Non-invasive blood pressure monitoring

Non-invasive methods to monitor arterial blood pressure include the palpatory method, auscultatory method, oscillometric method, volume clamp method, and arterial applanation tonometry [22]. In prehospital emergency care, the auscultatory and oscillometric methods are most frequently used and will be explained in more detail. Both methods use an inflatable air-filled cuff to temporarily occlude the blood supply for measurement purposes. The recommended measurement site is the upper arm of the patient and it is crucial that the correct-sized cuff is chosen. Cuffs that are too small lead to incorrectly high measurements and cuffs that are too large lead to incorrectly low measurements [23]. Non-invasive methods are less accurate compared to invasive blood pressure monitoring [24]. This is especially pronounced in blood pressure extremes, where low arterial blood pressure is measured incorrectly high and high arterial blood pressure is measured incorrectly low [25].

Auscultatory blood pressure monitoring is performed by inflating the cuff until blood flow ceases. After placing the stethoscope over the brachial artery, the cuff is slowly deflated until so-called “Korotkoff sounds” can be heard. These sounds appear as the cuff reaches the patient’s systolic blood pressure, which can be read from the manometer. After further slow deflation, the last heard sound represents the diastolic blood pressure [21]. MAP is classically calculated using the formula $MAP = DBP + \frac{SBP-DBP}{3}$, however, slightly adapted formulas have been proposed as well [26]. An advantage of monitoring blood pressure using auscultation is that it is fully manual and no electronic device is required. Disadvantages include measurement inaccuracies, labor and time consumption, especially if performed intermittently, and difficulties in noisy environments, with the latter two especially relevant in prehospital emergency care [27].

Oscillometric blood pressure monitoring is an automated method with the ability to monitor arterial blood pressure intermittently. The air-filled cuff is inflated to a predefined value

and slowly deflated. During deflation, oscillations occur in the artery and can be detected by the device. The oscillations reach their maximum at mean arterial blood pressure [22]. Systolic and diastolic arterial blood pressures are calculated using manufacturer-specific formulas. Advantages include direct measurement of MAP and reduced personnel requirements and time consumption compared to the auscultatory method. Furthermore, most monitors used in prehospital emergency care have the ability to perform automated intermittent monitoring in selectable time intervals. Apart from general disadvantages of non-invasive blood pressure monitoring, the oscillometric method is prone to measurement inaccuracies due to movement, which can be especially pronounced in prehospital emergency care, for example during transportation [28, 29].

Invasive blood pressure monitoring

Invasive blood pressure monitoring is performed by inserting a catheter into an artery. The most common and also recommended primary catheter insertion site is the radial artery, followed by the brachial, femoral and dorsalis pedis artery. Techniques to insert the catheter include the direct puncture technique and the wire-over-needle ("Seldinger") technique, both of which can be performed using landmarks and palpation or under ultrasound guidance. The catheter is used to conduct the arterial pressure wave via a tubing system, usually filled with saline, to a transducer [30]. The transducer converts the mechanical force into an electrical signal using a strain gauge and a Wheatstone bridge. After the electrical signal is processed using Fourier analysis, the blood pressure and the arterial waveform are displayed on a monitor [31].

Invasive blood pressure monitoring has several advantages compared to non-invasive intermittent blood pressure monitoring. It offers beat-to-beat analysis enabling rapid detection of blood pressure changes, improving the detection of hypotension and reducing hypotension duration and severity during anaesthesia induction in the operating room by more than half [14, 15]. The provided arterial wave form offers additional haemodynamic information and allows advanced haemodynamic monitoring [32]. Furthermore, invasive blood pressure monitoring has an increased accuracy, especially in very low or very high blood pressure ranges as well as in situations where non-invasive blood pressure monitoring fails (e.g. morbid obesity), and permits frequent blood sampling [33, 34]. These advantages, paired with rarely occurring complications resulting from the intraarterial catheters, lead to the recommendation that invasive blood pressure monitoring should be used during surgery whenever there is a high risk of hypo- or hypertension associated complications [35, 36]. This can either be driven by patient

factors (e.g. cardiovascular comorbidities such as heart failure or severe hypertension, aneurysms at risk of rupture, raised intracranial pressure) or the surgery itself (e.g. cardiac and vascular surgery, surgery in the sitting position, intracranial surgery) [13].

Unlike in the surgical in-hospital setting, similar recommendations or guidelines do not exist for prehospital emergency care. Several aspects contribute to this absence, with one major factor being the limited amount of comparative research investigating prehospital invasive blood pressure monitoring. Theoretical assumptions regarding advanced monitoring remain and highly critical patients with both unstable haemodynamic conditions as well as a high risk of hypo- or hypertension associated complications are treated, but trials investigating if outcomes are improved are missing. Evidence regarding the prehospital use of invasive blood pressure monitoring is mostly observational and partly a by-product of trials investigating other interventions (e.g. chest compression effectiveness during cardio-pulmonary resuscitation) only using invasive blood pressure monitoring to measure a trial outcome [3]. This is also true for one of the most common arguments against the prehospital use of invasive blood pressure monitoring, the risk of prolonged on-scene time and delayed in-hospital treatment [16]. While highly variable durations for catheter insertion, setup preparation and time until successful invasive blood pressure monitoring are reported, studies commonly lack a comparison with patients receiving non-invasive blood pressure monitoring, leaving this question unanswered [37-39].

Apart from effects on outcomes and duration of care, the following key aspects can be summarized from the existing literature [3]:

The main indications for prehospital invasive blood pressure monitoring so far published are cardiopulmonary resuscitation and management of return of spontaneous circulation [37, 40-42]. In these studies, the radial artery was the primary catheter insertion site. The femoral artery was the second most frequently stated insertion site, especially in trials investigating interventions during ongoing cardiopulmonary resuscitation. Ultrasound guidance for insertion was rarely used. Intraarterial catheters were only inserted in prehospital systems having physicians on-scene, with one trial reporting successful insertions by paramedics under direct physician supervision [40]. Similar to in-hospital data, non-invasive oscillometric blood pressure monitoring overestimates low blood pressure and underestimates high blood pressure during prehospital care [42, 43].

Acute brain injury

Acute brain injuries can either be traumatic, caused by an external force exerted on the brain, or non-traumatic, due to an underlying neurological disease, most commonly stroke. Independent of the cause, treatment in the initial phase aims to minimize secondary brain damage by ensuring stable cardiorespiratory conditions and adequate cerebral perfusion pressure. To enable this, prehospital induction of emergency anaesthesia is often required, especially in severe cases with impaired consciousness, to maintain airway protection and allow mechanical ventilation [5, 44, 45]. Mechanical ventilation provides full respiratory control with the aim of achieving sufficient oxygen uptake and carbon dioxide removal. Sufficient oxygen uptake and a carbon dioxide partial pressure within normal ranges are required to avoid vasodilatation of cerebral arteries, which can lead to increased intracranial pressure [46-48]. Efforts to keep the intracranial pressure (ICP) low are necessary to maintain an adequate cerebral perfusion pressure (CPP), which is estimated using the formula $CPP = MAP - ICP$ [49]. Additionally, this formula also demonstrates that maintenance of a high enough MAP is essential to achieve an adequate CPP. In the following, traumatic brain injury and stroke, with a focus on acute care aspects, will be described in more detail.

Traumatic brain injury

Traumatic brain injury is the leading traumatic cause of death and long-term disability in high-income countries [50]. In Austria, around 25,000 patients are estimated to have received hospital treatment for traumatic brain injury per year [51]. Approximately 1,500 are severe cases and the overall mortality rate of all patients receiving hospital treatment is 3.6% [51, 52]. A variety of subclassifications and phenotypes exist for traumatic brain injury, with different time points of assessment. In the prehospital setting, severity grading into mild, moderate and severe using the Glasgow Coma Scale is the most frequently used method [53]. This grading also has therapeutic consequences, as current guidelines recommend induction of emergency anaesthesia in patients with severe traumatic brain injury [54]. Within twenty to thirty minutes of the hospital admission, patients with severe traumatic brain injury should receive a computed tomography scan to provide further information regarding the injury according to Austrian recommendations [55]. Frequent findings include epidural or subdural hematomas, subarachnoid haemorrhage, parenchymal haemorrhage, cerebral oedema, and osseous injuries [56]. Depending on the radiographic findings and the patient's clinical condition, rapid surgical interventions can be required. These interventions range from the insertion of devices to measure intracranial pressure for further guidance, to surgical evacuation of a hematoma or

even hemicraniectomy to reduce built up intracranial pressure [53]. In prehospital patients with suspected traumatic brain injury, a systolic blood pressure between 110 and 150 mmHg is currently recommended [5]. In unconscious patients, this should be maintained until ICP can be monitored. Once this is possible, a CPP between 60 and 70 mmHg and an ICP below 22 mmHg should be aimed at [53].

Stroke

Stroke is commonly defined as a neurological deficit attributed to an acute focal injury of the central nervous system by a vascular cause [57]. More than 12 million people have a stroke annually and 6.5 million deaths are attributed to stroke every year [58-60]. Between 2015 and 2019, approximately 100,000 patients have received in-hospital treatment for a stroke in Austria [61]. Stroke is categorised based on the type of brain injury, with the main forms being ischemic and haemorrhagic stroke. In patients with an ischemic stroke, the occlusion of an artery, either caused by an embolus or thrombus, leads to an episode of neurological dysfunction following focal infarction distal to the reduced or ceased blood supply [57]. Reestablishment of blood flow as fast as possible is the main aim of in-hospital treatment, which is either sought by administering thrombolytic drugs intravenously or by mechanical thrombectomy [62]. This type represents around 80-85% of strokes in Austria [61]. Haemorrhagic strokes are further divided into subtypes, namely intracerebral haemorrhage, subarachnoid haemorrhage, and intraventricular haemorrhage [57]. Despite only being the cause of 15-20% of strokes in Austria, the higher mortality and morbidity associated with these types of strokes make haemorrhagic subtypes highly relevant from a patient and public health perspective [63]. Treatment options for haemorrhagic stroke depend on the underlying pathology and include radiological interventional procedures like aneurysm embolization and surgical interventions such as haematoma evacuation, placement of devices to measure intracranial pressure and drain cerebral spinal fluid, and aneurysm clipping [12, 64]. Concurrently, to reduce further bleeding, blood pressure should be lowered to levels around 140 mmHg SBP and anticoagulation has to be reversed [12, 64]. Computed tomography imaging is always required to distinguish between an ischemic or haemorrhagic cause and before any of the specific interventions can be performed [65]. Until a definitive diagnosis can be made and disease-specific treatment is initiated, management is symptomatic with the aim of achieving stable cardiorespiratory conditions. Blood pressures are highly variable in the early, prehospital phase in stroke patients, making haemodynamic management challenging and putting special attention on

haemodynamic monitoring [66, 67]. Severe hypotension must be strictly avoided to allow for sufficient cerebral blood flow [8, 12, 62, 68].

Rationale, aim and hypothesis of the thesis project

Arterial catheter insertion and invasive blood pressure monitoring remain a debated prehospital intervention. Patients with acute brain injury on the one hand have a high blood pressure variability due to their underlying condition, but also as a result of necessary medical interventions such as induction of prehospital emergency anaesthesia. Furthermore, maintaining blood pressure within very narrow predefined targets and avoiding large blood pressure fluctuations is a main pillar of prehospital care. Therefore, patients with acute brain injury could potentially benefit from closer blood pressure monitoring and the ability to intervene faster. On the other hand, key diagnostics and definitive treatment (e.g. surgical haematoma evacuation, thrombolysis, mechanical thrombectomy, repair of a ruptured aneurysm) can only be provided in-hospital and prehospital care should be as short as possible. This requires thoughtful balancing of potential risks and benefits of invasive blood pressure monitoring. Research comparing the duration of prehospital care as well as blood pressure between patients with invasive and non-invasive blood pressure monitoring is scarce. Therefore, it is the aim of this thesis to evaluate both the potential negative effect (prolonged prehospital care) as well as the potential positive effect (blood pressure control) of prehospital arterial cannulation and invasive blood pressure monitoring in patients with acute brain injury. Specifically, the two following hypotheses will be tested:

1.) Prehospital care is not prolonged in patients with acute brain injury who receive prehospital invasive blood pressure monitoring, compared to those with in-hospital initiation of invasive blood pressure monitoring.
2.) Blood pressure at hospital admission is different in patients with acute brain injury who receive prehospital invasive blood pressure monitoring, compared to those with in-hospital initiation of invasive blood pressure monitoring.

Discussion

Time from arrival on scene until the first computed tomography was not prolonged in patients with acute brain injury who had prehospital invasive blood pressure monitoring, compared to those with in-hospital initiation of invasive blood pressure monitoring. Further, there was no difference in blood pressure on hospital admission between the two groups. In the following, these results and their limitations will be discussed. Furthermore, clinical and scientific implications will be derived from these results and the insights gained from a systematic review of the existing literature.

Time

Time from arrival on scene of the prehospital emergency physician team until the first cranial computed tomography was not prolonged in patients receiving prehospital invasive blood pressure monitoring, compared to those having it initiated in-hospital. Median (interquartile range) time until the first cranial computed tomography was of 73 (61 - 92) and 79 (70 - 87) minutes in the prehospital cohort and 75 (60 - 93) and 73 (67 - 81) minutes in the in-hospital cohort for traumatic brain injury and stroke, respectively. This is similar or even less than previously published [69, 70]. For example, mean (standard deviation) time from arrival on scene until the first computed tomography was 87 (33) minutes in the DGU® TraumaRegistry [69]. For patients with non-traumatic brain injury receiving prehospital emergency anaesthesia, median (standard deviation) on scene time already was 77 (22) minutes in an Australian helicopter emergency medical service [70].

Interestingly, while overall comparable to published data from other services, variable results were found regarding the on scene time between the two groups [71-73]. In patients with traumatic brain injury, median (interquartile range) on scene time was not prolonged (41 (28 - 53) versus 37 (28 - 48) minutes, median difference of 3 minutes, 95% confidence interval (-2 - 7)). However, with a median (interquartile range) duration of 45 (37 - 51) minutes, compared to 36 (33 - 43) minutes, stroke patients with prehospital invasive blood pressure monitoring had significantly longer on scene times. Reasons for the difference between patients with traumatic brain injury and stroke are speculative but could include the following: In contrast to trauma patients, patients with a stroke are generally older and frequently burdened with cardiovascular comorbidities. This also includes arteriosclerosis, which may render arterial catheter placement technically challenging and potentially requiring more time for successful insertion. Additionally, prehospital care of trauma patients is strongly driven by the aim to limit on scene times as much as possible and to handover the patient within sixty minutes. This goal might be

less strongly pursued by physicians treating patients with stroke requiring prehospital induction of anaesthesia. Furthermore, another reason could be that, compared to stroke patients, a higher percentage of patients with traumatic brain injury were treated by helicopter emergency medical services. Local helicopter emergency medical service teams each consist only of approximately fifteen physicians and a dozen paramedics, enabling them to collaborate effectively and perform routine tasks efficiently. The physicians commonly have a background in intensive care or anaesthesia, providing extensive experience in inserting arterial catheters and invasive blood pressure monitoring. This, and the mandatory previous experience as ground-based emergency physician, could lead to helicopter emergency medical service teams being better at integrating invasive blood pressure monitoring into the prehospital care process with no or only minimal delay.

Integration and coordination of invasive blood pressure monitoring into the prehospital care process seems to be a key aspect when trying to avoid delay prehospital care. This is underlined by the fact that prehospital arterial catheter insertion itself was described to only take a median of two minutes in a prospective observational study and the invasive blood pressure kit, what can be done in parallel, to be set up within a median of 3 minutes [37]. While the effect on time in this thesis was small and a British retrospective observational study even describing insertion of arterial catheters in-flight, considerable delay was found when prehospital invasive blood pressure monitoring was performed infrequently in a retrospective Australian study [38, 40]. Considering that, on average, less than one patient per month in that retrieval system had invasive blood pressure monitoring and most of the physicians working full time in prehospital care, this could be an essential difference [38].

To summarize, prehospital invasive blood pressure monitoring seems to be possible with minimal to no relevant delay of care in patients with acute brain injury if performed by experienced providers. However, a risk of delaying care remains and relevant time points should be constantly evaluated when implementing the intervention.

Blood Pressure

No difference in admission blood pressure was found between patients with prehospital invasive blood pressure monitoring and those having it initiated in the resuscitation room of the hospital. Median (interquartile range) admission blood pressure in patients with traumatic brain injury was 128 (106 - 150) versus 130 (110 - 147.25) mmHg systolic and 80 (60 - 84) versus 80 (62 - 95.25) mmHg diastolic in the prehospital and the in-hospital group, respectively. Similar results were found in patients with stroke, where the median (interquartile range)

systolic blood pressure was 127 (109 - 150) versus 130 (110 - 160) mmHg and the diastolic blood pressure was 80 (60 - 90) versus 80 (65 - 90) mmHg in the prehospital group and the in-hospital group, respectively.

This missing difference is in contrast to data from patients having anaesthesia for surgical procedures, where invasive blood pressure monitoring was shown to significantly reduce hypotension. For example, in the AWAKE trial 224 patients having elective surgery received invasive blood pressure monitoring before induction of anaesthesia. Patients were then randomized to either continuous invasive blood pressure monitoring or intermittent non-invasive blood pressure monitoring (with the already established invasive blood pressure monitoring blinded to the treating physician and only used to measure blood pressure for the trial). In patients with invasive blood pressure monitoring being displayed, median (interquartile range) time weighted average mean blood pressure below 65 mmHg was 15 (2 - 36) mmHg compared to 46 (7 - 111) mmHg in patients where only intermittent non-invasive blood pressure monitoring was displayed [14].

The fact that no difference was found might - at least partly - be explained by the used methodology. As further outlined in the limitations, the prehospital documentation is lacking the required quality and detail to reliable compare out-of-hospital blood pressures. Therefore, only the blood pressure at the time of handover in the resuscitation room was used for comparison, as it is documented at a standardized timepoint and in a standardized way. However, at the time of patient handover, procedures associated with major haemodynamic instability, for example anaesthetic induction, are already completed, and cardiovascular conditions have often stabilized. Furthermore - unlike in the AWAKE trial - blinded invasive blood pressure monitoring - representing the gold standard - was not available in the in-hospital cohort of this thesis. Therefore, the number of patients being hypotensive or hypertensive could be falsely low, as low blood pressures are measured inaccurately high and high blood pressure inaccurately low by non-invasive oscillometric devices [42, 43].

Considering that approximately half of the patients with traumatic brain injury were either below or above the recommended blood pressure target (110 to 150 mmHg SBP) at handover in the resuscitation room, efforts to improve prehospital haemodynamic monitoring and management seem highly necessary and should be undertaken. This is further underlined by studies that demonstrated that the implementation of a care bundle, which in addition to the avoidance of hypotension also including the prevention of hypoxia and hyperventilation, reduced the mortality in patients with severe traumatic brain injury [74] and that prehospital hypotension and hypertension were associated with an increased mortality in large retrospective

data base analysis of patients having traumatic brain injury [75-77]. Similarly - albeit exact blood pressure target recommendations for patients with undifferentiated stroke are missing - large interquartile ranges of systolic blood pressure on admission also suggest a high variability and haemodynamic fluctuations. However, exactly these fluctuations should be avoided in patients with stroke. For example, a single drop in MAP below 60 mmHg during anaesthesia for mechanical thrombectomy was independently related to an unfavourable outcome at three months in patients with ischemic stroke [78].

To conclude, no difference in blood pressure on admission was found. However, there was a lack of insight into relevant phases of prehospital care due to the lack of high-quality data. A prospective randomized trial comparing invasive to non-invasive blood pressure monitoring evaluating whether haemodynamic control can be improved seems both necessary and justified, especially considering the fact that time to first cranial computed tomography was not prolonged and only half of the patients had a systolic blood pressure within the recommended range at hospital handover.

Clinical and scientific implications

Subsuming the new insights gained by a systematic literature search and the conducted studies, the succeeding clinical and scientific implications regarding invasive blood pressure monitoring in prehospital patients with acute brain injury were derived:

- Invasive blood pressure monitoring should not only be regarded as insertion of an arterial catheter by a prehospital physician. Rather, a team approach is required to integrate catheter insertion, transducer setup, monitor connection and interpretation of the measured parameters into the overall prehospital care process and thereby reducing or even eliminate delay of care.
- Invasive and non-invasive blood pressure monitoring lack agreement in prehospital care. This can be especially relevant in patients with acute brain injury, where narrow blood pressure recommendations exist, supporting its use. Whether invasive blood pressure monitoring reduces prehospital hypotension, especially in high risk situations such as induction of emergency anaesthesia, remains to be evaluated in prospective randomized trials.
- In-hospital experience of insertion, use and interpretation of invasive blood pressure monitoring is required.

- The radial artery is the most frequently used artery for insertion and no severe complications have been described so far. Therefore, it is suggested as the primary insertion site.
- Considering the currently limited evidence, prehospital systems using invasive blood pressure monitoring should gather data in a structured way to enable internal improvement and scientific usage.
- As already outlined, a randomized controlled trial is necessary to evaluate whether invasive blood pressure monitoring should be the standard of care for patients with acute brain injury undergoing prehospital emergency anaesthesia. This trial should be multi-centric and specifically evaluate whether duration and severity outside recommended blood pressure targets during the whole prehospital care process is reduced and if on scene time, time until hospital admission and time until first computed tomography differ. Furthermore, the effect on clinical decision making should be evaluated in a standardized way.

Limitations

Several limitations have to be noted. Prehospital emergency care systems vary worldwide and the results from a single system might not be transferable to other systems that operate differently. Data was gathered in a retrospective fashion and patients therefore not randomized. However, patients with and without prehospital invasive blood pressure monitoring had similar baseline characteristics. Furthermore, statistical methods such as propensity score matching and unplanned subgroup analysis were applied to reduce the risk of bias. Another limitation of retrospective data is that it is restricted to the information that was originally documented. To compensate for this, data was evaluated independently by two researchers and time points were matched with the time points recorded by the regional emergency dispatch centre. The group with prehospital invasive blood pressure monitoring only consists of patients with successful arterial cannulation and established monitoring. It does, however, not include those with failed arterial cannulation, again providing potential bias. As prehospital arterial cannulation was successful in 82% when summarizing the data of several studies, the number of those patients should however be modest [3]. Another limitation is that blood pressure was only evaluated at admission in the resuscitation room, while the whole prehospital phase would be of interest. This was, however, not possible, as the mostly hand written protocols of the prehospital emergency physicians do not offer the needed granularity and precision needed for research purposes. When interpreting the results, it also has to be

accounted for that sample size is limited. However, it was decided not to prolong the inclusion period due to anticipating issues in data quality, historically lower utilization rate of prehospital invasive blood pressure monitoring and changes in prehospital emergency care philosophies in the time period, including a stronger focus on timely transport.

Conclusion

Time from arrival on scene until first computed tomography was not prolonged in patients with acute brain injury and prehospital invasive blood pressure monitoring, compared to patients where this was initiated in-hospital. Variable results were found regarding on scene time. Blood pressure on hospital admission did not differ. To evaluate whether prehospital invasive blood pressure monitoring should be the standard of care in patients with acute brain injury, a multicentric randomized controlled trial evaluating patient-centred outcomes is necessary.

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Appendix

The Appendix includes two publications as papers in PDF version, the third publication as manuscript plus letter of acceptance, and the signed author's agreement.

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ORIGINAL RESEARCH **Open Access**

Is time to first CT scan in patients with isolated severe traumatic brain injury prolonged when prehospital arterial cannulation is performed? A retrospective non-inferiority study

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Abstract

Background Invasive blood pressure measurement is the in-hospital gold standard to guide hemodynamic management and consecutively cerebral perfusion pressure in patients with traumatic brain injury (TBI). Its prehospital use is controversial since it may delay further care. The primary aim of this study was to test the hypothesis that patients with severe traumatic brain injury who receive prehospital arterial cannulation, compared to those with in-hospital cannulation, do not have a prolonged time between on-scene arrival and first computed tomography (CT) of the head by more than ten minutes.

Methods This retrospective study included patients 18 years and older with isolated severe TBI and prehospital induction of emergency anaesthesia who received treatment in the resuscitation room of the University Hospital of Graz between January 1st, 2015, and December 31st, 2022. A Wilcoxon rank-sum test was used to test for non-inferiority (margin = ten minutes) of the time interval between on-scene arrival and first head CT.

Results We included data of 181 patients in the final analysis. Prehospital arterial line insertion was performed in 87 patients (48%). Median (25–75th percentile) durations between on-scene arrival and first head CT were 73 (61–92) min for prehospital arterial cannulation and 75 (60–93) min for arterial cannulation in the resuscitation room. Prehospital arterial line insertion was significantly non-inferior within a margin of ten minutes with a median difference of 1 min (95% CI −6 to 7, $p=0.003$).

Conclusion Time-interval between on-scene arrival and first head CT in patients with isolated severe traumatic brain injury who received prehospital arterial cannulation was not prolonged compared to those with in-hospital cannulation. This supports early out-of-hospital arterial cannulation performed by experienced providers.

Keywords Brain Injuries, Traumatic, Emergency medical services, Blood pressure, Arterial pressure, Hemodynamic monitoring, Anaesthesia, Intubation

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Background

Traumatic brain injury (TBI) is the most common injury leading to death and disability in the western world [1]. The estimated incidence of TBI from 2009 to 2011 was around 300 per 100,000 inhabitants per year, accounting for approximately 2000 cases of severe TBI every year in Austria [2, 3].

The initial prehospital management of patients with severe TBI includes minimising secondary brain damage as well as rapid transportation to a centre with specific diagnostic and therapeutic possibilities [4, 5].

To minimise secondary damage and enable an adequate cerebral perfusion pressure, stable hemodynamic conditions as well as adequate oxygenation and decarboxylation are required. The latter two aspects can often only be achieved with prehospital anaesthesia to protect the airway and allow controlled ventilation, especially in cases of severe TBI [5].

However, TBI is often accompanied by hemodynamic compromise which can be even further exacerbated by induction of anaesthesia and positive pressure ventilation [6]. To detect potential hemodynamic changes and enable rapid interventions, arterial cannulation and continuous real-time blood pressure monitoring has become the in-hospital gold standard [7].

While holding the potential for benefits, arterial cannulation and invasive blood pressure measurement are techniques rarely used in the prehospital setting. Apart from technical skills required, the duration spent on scene could also be prolonged. Therefore, all contributing elements demand a comprehensive evaluation. Due to challenging conditions, prehospital cannulation and setup of the invasive blood pressure monitoring could require more time outside the hospital. This could potentially delay the first major and decisive diagnostic step, a computed tomography (CT) of the head. The Austrian working group for improvement of early TBI care suggests a head CT within twenty to thirty minutes after hospital admission, giving a range of ten minutes [8].

Data comparing those time spans is still lacking and has been called for in a recent publication [9]. This was published by a helicopter emergency medical service (HEMS) based in the United Kingdom, offering a retrospective observational review of practice of over one thousand prehospital arterial cannulations in a mixed population, mostly cardiac arrest [9].

The primary aim of this study was to test the hypothesis that patients with severe TBI who receive prehospital arterial cannulation, compared to those with in-hospital cannulation, do not have a prolonged time-interval between on-scene arrival and first head CT by more than ten minutes.

Methods

Study design and setting

This study was a single-centre, retrospective analysis of routine data conducted according to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guideline [10]. It is based on the principles of positivism and guided by an analytical approach.

Data from the local trauma registry, which includes all major trauma patients treated in the resuscitation room, was used to identify eligible patients and extract the relevant data from the resuscitation room treatment.

The University Hospital of Graz is a major trauma centre with a vast catchment area covering approximately 1.5 million individuals. Both physician staffed ground-based response units as well as physician staffed HEMS transfer severely injured patients to this centre. Prehospital emergency physicians undergo specific prehospital training in addition to their background specialty (mostly anaesthesia, internal medicine or intensive care medicine) and are paired with a paramedic. These specialized units are dispatched to severe traumatic, neurologic, pediatric, medical, and toxicological emergencies as well as cardiopulmonary resuscitations and carry equipment for arterial cannulation and invasive blood pressure measurement, which can be performed at the physician's discretion [11].

Selection of participants

Data of missions between 1st January, 2015, and 31st December, 2022, was extracted. Patients 18 years and older with an isolated severe TBI (defined as abbreviated injury scale (AIS) ≥ 3 in the body region "head", an initial Glasgow Coma Scale (GCS) < 9, and no AIS > 2 in any other body region than "head") who received prehospital induction of emergency anaesthesia and airway management were eligible for this study [12, 13].

Patients were excluded if there was no head CT directly after initial treatment in the resuscitation room, if no arterial line insertion prior to head CT was performed, or if data regarding the primary outcome was missing.

Measurements

The time point (dichotomous, either prehospital or in-hospital) of arterial line insertion was extracted from the prehospital record or the resuscitation room record. Patient and case-specific data (age, gender, type of injury, outcome), relevant timepoints (time of on-scene arrival (at the patient), time of transport start, handover time, time of first head CT), admission blood pressure, initial GCS, vasopressor requirement, and transport modality were extracted from the source data of the local trauma registry. Any still missing data were extracted from the prehospital record or the resuscitation room record.

Outcomes

Primary outcome was the time-interval between on-scene arrival of the prehospital physician and first head CT. Secondary endpoints were time between on-scene arrival of the prehospital physician and handover in the resuscitation room, time on-scene of the prehospital physician, time between handover in the resuscitation room and first head CT, and the rate of patients who were hypotensive on arrival in the resuscitation room (defined as a) systolic blood pressure below 90 mmHg and b) below 110 mmHg in patients 18 to 49 years old as well as 70 years old and older and below 100 mmHg in patients 50–69 years old according to the 4th brain trauma foundation guideline) [4].

Analysis

Sample size calculation was based on the assumption that 40% of the patients receive prehospital arterial cannulation, as per internal data from one ground-based response unit. Further, the duration from on-scene arrival until the first head CT was assumed to be 87.7 min (SD ± 33.4 min), based on a prior publication [14]. With a non-inferiority margin of ten minutes based on recommendations for the initial management of TBI by the Austrian TBI improvement working group and a one-sided significance level of 2.5%, 380 patients were required to achieve a power of 80% [8]. Assuming 50 patients with isolated severe TBI per year, the study period of 8 years (2015–2022) was chosen. Sample size calculation was performed using nQuery (Dotmatics, Boston, MA, USA).

Demographic, injury-related and treatment-related data were presented as mean and standard deviation (SD), median and 25–75th percentile, or number (n) and percentages (%), as appropriate.

To evaluate the primary endpoint, a Wilcoxon rank-sum test was used to test for non-inferiority at a non-inferiority margin of ten minutes. A p-value below 0.025 was considered statistically significant.

To evaluate the secondary endpoints (time between on-scene arrival and handover, time on-scene, time from handover to first head CT, patients hypotensive at resuscitation room handover), continuous variables were compared using the Wilcoxon rank-sum test for continuous variables and Fisher's exact test for discrete. Two-sided p-values below 0.05 and one-sided p-values below 0.025 were considered significant.

Although not pre-specified, we conducted a subgroup analysis with respect to mode of transport due to the higher percentage of patients transported by HEMS in the prehospital group. In addition to the descriptive analysis, multiple linear regression with an interaction term between mode of transport and prehospital arterial cannulation was used to test if duration between on-scene arrival and first head CT was significantly affected by the mode of transport and prehospital arterial cannulation.

All analyses were performed using R version 4.3 (R Core Team (2023). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/), graphs were created using R version 4.3 and Microsoft Excel 2016 (Microsoft Corp, Redmond, WA, USA).

Results

Out of a total of 2,266 patients documented in the local trauma registry during the selected timespan, 201 patients with an age of 18 years or older had an isolated severe TBI according to the above outlined definition and received prehospital emergency anaesthesia. After exclusion of eleven patients without an immediate head CT, five patients without arterial cannulation prior to head CT and four patients with missing data regarding the primary endpoint, 181 could be included in the final analysis, falling short of the calculated target sample size. The exact selection process is depicted in Fig. 1. Of these 181 patients, 87 had prehospital arterial cannulation (prehospital group), and 94 had in-hospital arterial cannulation (in-hospital group). In the prehospital group, median (25–75th percentile) age was 66 (49–79) years with 70% (n = 61) males compared to a median age of 66 (52–77) years and 64% (n = 60) males in the in-hospital group. Further baseline patient characteristics and comparisons between the two groups are shown in Table 1.

Primary outcome

Median durations between on-scene arrival and first head CT were 73 (61–92) minutes for prehospital arterial cannulation and 75 (60–93) minutes for arterial cannulation in the resuscitation room, as shown in Fig. 2. Prehospital arterial line insertion was significantly non-inferior within a margin of ten minutes with a median difference of 1 min (95% CI − 6 to 7, $p = 0.003$).

Secondary outcomes

No significant differences were found regarding time between on-scene arrival and handover in the resuscitation room (median difference 0 min, 95% CI (−7, 7)), time on scene (median difference 3 min, 95% CI (−2, 7)), and time between handover in the resuscitation room and first head CT (median difference 0 min, 95% CI (−2, 2)). Further details regarding the selected time intervals are shown in Table 2 and Fig. 3.

Median blood pressure at handover in the resuscitation room was 128 (106–150) mmHg systolic and 80 (60–84) mmHg diastolic in the prehospital group compared to

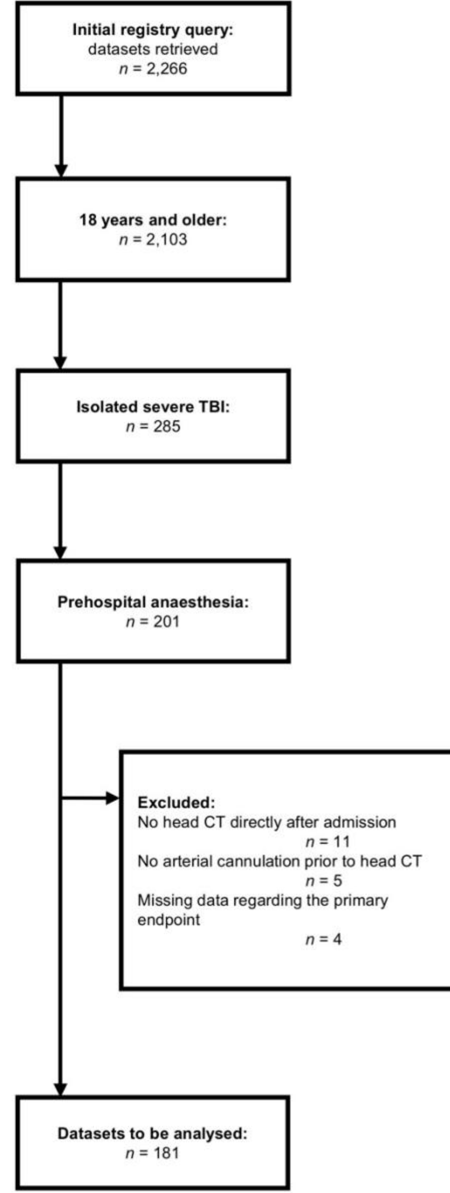

Fig. 1 Study flow chart. TBI = traumatic brain injury, CT = computed tomography

Table 1 Characteristics of the study population (n = 181)

Characteristic	Prehospital cannulation	In-hospital cannulation
n	87	94
Age [years]—median (25–75th percentile)	66 (49–79)	66 (52–77)
Male sex—n (%)	61 (70.1)	60 (63.8)
Mechanism of injury—n (%)		
Violence	8 (9.2)	9 (9.6)
Fall < 3 m	54 (62.1)	54 (57.4)
Fall > 3 m	6 (6.9)	8 (8.4)
Traffic	16 (18.4)	20 (21.3)
Other	3 (3.4)	3 (3.2)
Injury Severity Score—median (25–75th percentile)	25 (20–26)	25 (21–29)
Abbreviated Injury Scale Head—n (%)		
3	10 (11.5)	7 (7.4)
4	22 (25.3)	20 (21.3)
5	55 (63.2)	66 (70.2)
6	0 (0)	1 (1.1)
Initial Glasgow Coma Scale—median (25–75th percentile)	4 (3–6)	4 (3–6)
Mode of Transport—n (%)		
Ground based	28 (32.9)	42 (45.2)
HEMS	57 (67.1)	51 (54.8)
Prehospital vasopressor—n (%)		
Applied	26 (34.2)	27 (30.7)
Prehospital fluid volume [ml]—median (25–75th percentile)	500 (500–1000)	500 (500–1000)
28-day mortality—n (%)	36 (41.4)	47 (50)

m meter, *HEMS* helicopter emergency medical service, *ml* milliliter

130 (110–147.25) mmHg systolic and 80 (62–95.25) mmHg diastolic in the in-hospital group. No significant differences in the rates of admission blood pressure below 90 mmHg systolic (prehospital group: 8 out of 79 (10%); in-hospital group: 9 out of 90 (10%), $p = 0.98$) nor according to the recommended blood pressure targets according to the 4th TBI guideline (prehospital group: 20 out of 79 (25%); in-hospital group: 19 out of 90 (21%), $p = 0.52$) were found.

Exploratory subgroup analysis

Data was divided into two subgroups according to mode of transportation. In the HEMS subgroup, the median duration from on-scene arrival to the first head CT was 71 (61–93) minutes and on-scene time was 38 (26–54) minutes in the prehospital group. In the in-hospital group, a median of 67 (58–82) minutes passed from on-scene arrival to the head CT and a median of 34 (25–43)

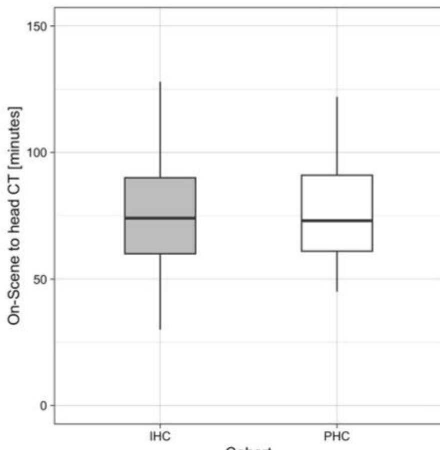

Fig. 2 Boxplot comparison of the time-interval between on-scene arrival and the first head CT after hospital admission between the in-hospital and prehospital arterial cannulation groups. CT = computed tomography, IHC = in-hospital cannulation, PHC = prehospital cannulation

minutes were spent on scene. For the primary outcome duration from on-scene arrival to the first head CT, the least-square means of the group differences between prehospital versus in-hospital are 6.1 min (95% CI: −5.3 to 17.5) in the HEMS subgroup and -6.2 min (95% CI −20.6 to 8.2) in the subgroup of ground-based transportation, with a *p*-value of 0.19 for interaction resulting non-significant.

Discussion

In this retrospective study, the duration between on-scene physician arrival and first head CT was almost identical in patients with prehospital arterial cannulation and patients with arterial cannulation in the resuscitation room (73 versus 75 min) and prehospital arterial line insertion was significantly non-inferior.

This can be attributed to several potential factors. In the study's specific region, physicians specialising in prehospital emergency care predominantly possess backgrounds in anaesthesiology or intensive care medicine where arterial cannulation is a routine practice.

Additionally, the observation of prehospital arterial cannulation in nearly every second patient underlines its sustained and frequent utilisation as a standard intervention in these prehospital services. This regular exposure ensures that teams as a whole can perform the procedure of arterial cannulation and invasive blood pressure monitoring in a timely fashion. This is further supported by the noteworthy fact that the median time between on-scene arrival and head CT in this study is 74 min in contrast to the average of 87.7 min described in the German Trauma Registry [14].

Median on-scene times was 41 (28–53) min and 37 (28–46) min in the prehospital and in-hospital cohort, respectively. This aligns with earlier data from *Wildner* et al. investigating the feasibility of out-of-hospital arterial cannulation [11]. In their prospective observational study, prehospital arterial cannulation in a mixed patient population required a median of two minutes and setup of the invasive blood pressure monitoring three minutes. Time between on-scene arrival and handover in the resuscitation room was almost alike (58 versus 57 min) in the two groups and similar to previously published data from other prehospital physician staffed services in Europe. For example, median total mission time was 69 (53–92) min in a study investigating severe TBI from Finland and 66 (51–80) min in a Dutch TBI cohort receiving prehospital induction of emergency anaesthesia by a physician staffed HEMS service [15, 16]. These data show, that arterial cannulation in the out of hospital setting does not prolong treatment times in a, to our opinion, clinically relevant fashion.

No difference between the two groups regarding the admission blood pressure was found. This is in contrast

Table 2 Median duration in minutes of the selected time-intervals in the overall, prehospital cannulation and in-hospital cannulation cohort

Characteristic	Overall	Prehospital cannulation	In-hospital cannulation
n	181	87	94
On-Scene to head CT [minutes]—median (25–75th percentile)	74 (61–93)	73 (61–92)	75 (60–93)
On-Scene to handover [minutes]—median (25–75th percentile)	58 (45–77)	58 (44–76)	57 (46–79)
On-Scene to transport [minutes]—median (25–75th percentile)	38 (28–49)	41 (28–53)	37 (28–46)
Handover to head CT [minutes]—median (25–75th percentile)	15 (11–19)	15 (12–20)	15 (11–19)

CT computed tomography

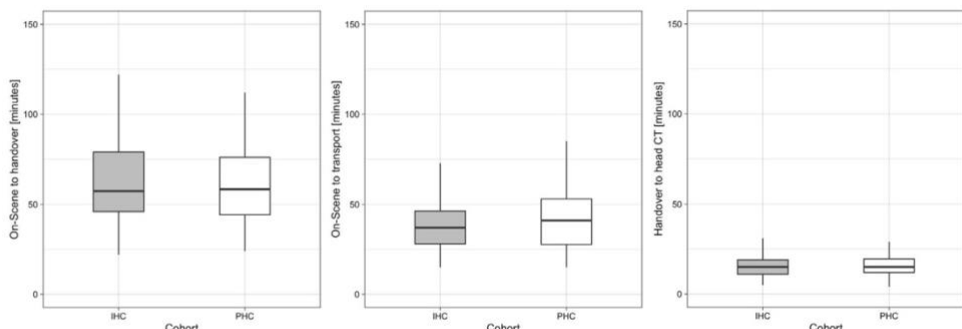

Fig. 3 Boxplot comparisons of the time-interval between (**A**) on-scene arrival and hospital handover, (**B**) on-scene arrival and transport, and (**C**) hospital handover and first head CT after hospital admission between the in-hospital and prehospital arterial cannulation groups. CT = computed tomography, IHC = in-hospital cannulation, PHC = prehospital cannulation

to in-hospital data where invasive blood pressure monitoring enhanced the detection of hypotension and also reduced hypotension during the anaesthesia induction process significantly, which also led to the recommendation to establish invasive blood pressure prior to anaesthetic induction in high risk in-hospital patients [17–19]. This discrepancy could be attributed to the methodology employed in our study, wherein only the blood pressure at a single time point (handover in the resuscitation room) could be evaluated. A state of hemodynamic equilibrium is frequently attained by the time of patient handover, as critical interventions with a high risk of hypotension, for instance induction of anaesthesia, have already been performed on-scene. Therefore, the out-of-hospital hemodynamic parameters would be of great interest. However, the prehospital blood pressures could not be compared as the handwritten prehospital records do not provide the necessary granularity and accuracy of vital parameters to use them for scientific purposes. To thoroughly assess the potential impact on blood pressure and 28-day mortality—which was 41% in the prehospital group compared to 50% in the in-hospital group—a prospective trial appears necessary.

Despite similar injury and baseline characteristics, a higher percentage of patients who received prehospital arterial line placement were treated by HEMS. An explanation for this phenomenon could be that HEMS doctors, often experienced prehospital physicians, may exhibit more familiarity and routine in prehospital arterial cannulation, thus maintaining a lower threshold for its utilisation. To further evaluate this, an unplanned subgroup analysis was performed. It revealed similar time intervals compared to the overall cohort and the time from on-scene arrival to head CT as well as on-scene time between the prehospital and in-hospital group were almost identical in the HEMS subgroup. Furthermore, multiple linear regression indicated no significant interaction of prehospital arterial cannulation with the mode of transport in explaining the duration from on-scene arrival to the first head CT.

Limitations

There are several limitations to this study. The planned sample size of 380 was not met as fewer isolated severe traumatic brain injuries than anticipated occurred in the selected timespan. Although the initially planned sample size was reached, the inclusion period was not prolonged due to sufficient data for answering the research question with highly significant results. Furthermore, with potential practice changes over time and a decrease in data quality, a prolonged inclusion period would also increase the risk of bias. It is a retrospective study and patients were therefore not randomised. Still, both groups had a similar injury severity as shown in Table 1. A major limitation arises from the fact that only patients with successful arterial cannulation could be included. With a previously published success rate of approximately 84% at the local prehospital physician response unit, this fraction of patients should, however, only be small [11]. Additionally, due to its retrospective design, the data is confined to its originally documented content. Nevertheless, the use of a standardised resuscitation room record, data re-evaluation by two members of the study team, and comparison of time points with those documented by the emergency medical dispatch centre contribute to the overall quality of the data.

Conclusion

In summary, prehospital arterial cannulation appears to be non-inferior compared to cannulation in the resuscitation room regarding time between on-scene arrival and first head CT in patients with isolated severe TBI, although further research is needed to confirm. This supports the early, out-of-hospital arterial cannulation performed by an experienced provider.

Abbreviations

AIS Abbreviated injury scale
CT Computed tomography
CI Confidence interval
GCS Glasgow coma scale
HEMS Helicopter emergency medical service
SD Standard deviation
TBI Traumatic brain injury

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Author contributions

ME1 (Michael Eichlseder), SL, AP, ME2 (Michael Eichinger), PhZ, BH, PZ conceived and designed the study, ME1, ME2, BH, FS, PZ collected the data. The data analysis was performed by ME1, AP, TK, FS, NS while the manuscript was drafted by ME1, SL, TK, PhZ, NS, PZ.

Funding

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Ethical approval was sought and granted by the Ethics Committee of the Medical University of Graz (IRB00002556, decision number 35-299 ex 22/23) prior to data retrieval and study conduction. Informed consent was not deemed necessary since data was retrieved and analysed retrospectively and in a pseudonymised fashion.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Association of prehospital invasive blood pressure measurement and treatment times of intubated patients with suspected stroke – a retrospective study

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Abstract

Background Invasive blood pressure measurement is commonly used in in-hospital patients with stroke requiring general anesthesia, but is much less established in the prehospital setting. While it allows for more precise blood pressure management, it might also lead to prehospital treatment delays. Therefore, this study aims to evaluate the potential impact of prehospital invasive blood pressure measurement on treatment times.

Methods Adult patients (≥ 18 years) with suspected stroke (both ischemic and hemorrhagic) and prehospital induction of emergency anesthesia by physicians admitted to the University Hospital of Graz between January 1st, 2018 and December 31st, 2023, were included. Optimal one-to-one matching using a propensity score for prehospital invasive blood pressure measurement based on patient age, patient sex, treatment by helicopter emergency medical services and Glasgow coma scale on scene was performed. Primary outcome was the time-interval between on-scene arrival of the prehospital physician and first cranial computed tomography (CCT).

Results One hundred patients with suspected stroke and prehospital emergency anesthesia were identified, of whom 67 (67%) had prehospital invasive blood pressure measurement. After matching, 33 patients of each cohort were used for main analysis. Median (25th to 75th percentile) time between on-scene arrival and first CCT was 79 (70–87) minutes in the prehospital measurement group, compared to 73 (67–81) minutes in the group with in-hospital initiation of invasive measurement ($p=0.21$). On-scene time was longer in the prehospital group [45 (37–51) vs. 36 (33–43) minutes, $p=0.009$], while transport duration [18 (11–25) vs. 20 (13–31) minutes, $p=0.20$] and time spent in the resuscitation room [16 (12–20) vs. 16 (12–21) minutes, $p=0.391$] did not differ.

Conclusion In summary, among patients with suspected stroke who underwent prehospital intubation, time from on-scene arrival to the first CCT was not prolonged in those who received prehospital invasive blood pressure measurement compared to those who received it in-hospital.

Keywords Emergency medical services, Blood pressure, Arterial pressure, Stroke, Hemodynamic monitoring, Anesthesia, Intubation

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Background

Stroke constitutes one of the most frequent emergencies, putting a major burden on patients, societies and healthcare systems alike. With more than 12 million people having a stroke annually and 6.5 million deaths attributed to stroke every year, optimal care is of utmost importance [1–3]. Suspected strokes commonly lead to an activation of prehospital emergency systems, with up to one tenth of the missions being due to a neurological origin [4].

Ensuring stable cardiorespiratory conditions and facilitating a prompt transfer to a hospital with the ability to perform disease-specific diagnostics and interventions are the primary objectives during the prehospital phase. Both ischemic and hemorrhagic stroke can lead to a reduction in consciousness. In these patients, maintaining adequate oxygenation and carbon dioxide elimination may necessitate the administration of prehospital emergency anesthesia to secure the airway and facilitate individualized ventilatory support [5, 6]. Induction of emergency anesthesia, however, is associated with hemodynamic disturbances [7, 8]. Special attention is required due to the common occurrence of blood pressure variations in the early phase following a stroke. Both severe hypotension and hypertension, with varying ranges between ischemic and hemorrhagic stroke, must be strictly avoided [9–12].

Consequently, invasive blood pressure monitoring, enabling beat-to-beat analysis and rapid pharmacological intervention, is considered the gold standard in the in-hospital management of unconscious patients with stroke [13]. In the prehospital setting, however, arterial cannulation and invasive blood pressure measurement are only occasionally performed. Arguments against this practice are the required skill level, necessary equipment, and potential delays to diagnostics and treatment. Whether the latter actually holds true is however unknown.

This study aims to investigate if there is a difference in treatment time between patients with prehospital arterial cannulation and invasive blood pressure measurement in comparison to patients having it performed in-hospital.

Methods

This manuscript was written according to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guideline [14].

Study design and setting

This study was a single-center, retrospective analysis of routinely collected data. The University Hospital of Graz is a tertiary academic center. As a comprehensive stroke center, care is provided for patients with both ischemic and hemorrhagic stroke, covering approximately 1.500.000 individuals. Patients without prehospital airway management are primarily seen by neurologists in the emergency department. Whenever patients already receive prehospital induction of emergency anesthesia or are defined as critical by the prehospital team, they bypass the regular emergency department and are treated in the resuscitation room by a team of anesthesiologists and neurologists. Prehospital emergency anesthesia is solely performed by prehospital physicians, who staff both ground-based response units and helicopter emergency medical services (HEMS). They undergo specific prehospital training in addition to their background specialty (mostly anesthesiology, internal medicine or intensive care medicine) and are dispatched to severe emergencies potentially requiring advanced medical treatment on-scene together with paramedics. Units are equipped for arterial cannulation and invasive blood pressure measurement, which can be performed at physicians' discretion [15].

Selection of participants

Admission logs from the resuscitation room were screened for adult patients (≥ 18 years) admitted due to an acute neurological cause between 1 st January, 2018, and 31 st December, 2023. All patients fulfilling the following criteria were included: primary mission (no transfers from other hospitals), prehospital induction of emergency anesthesia and airway management, and stroke (ischemic and/or hemorrhagic) suspected by the prehospital team.

If patients were treated by two or more prehospital physician systems (e.g., ground-based initial treatment and subsequent transport by HEMS), if no cranial computed tomography (CCT) directly after initial treatment in the resuscitation room was performed, or if data regarding the primary outcome was missing, patients were excluded. Finally analyzed patients were divided into two groups (prehospital invasive blood pressure measurement group and in-hospital invasive blood pressure measurement group), according to the time point of invasive blood pressure measurement initiation.

Measurements

Initiation point of invasive blood pressure measurement, either prehospital or in-hospital, was determined by reviewing prehospital records and resuscitation room documentation. Demographic and case-specific data (age, sex, suspected diagnosis), time-points (time of on-scene arrival, time of transport start, handover time, time of first CCT), Glasgow coma scale (GCS) at arrival on-scene, vasopressor application, and transport mode were extracted from the prehospital record, resuscitation room record, and hospital record.

Outcomes

The primary outcome was the time-interval between on-scene arrival of the prehospital physician and first CCT. Secondary endpoints were time between on-scene arrival of the prehospital physician and handover in the resuscitation room, time on-scene of the prehospital physician, duration of transport, and time between handover in the resuscitation room and first CCT. Additionally, exploratory outcomes were systolic and diastolic blood pressure resuscitation room arrival.

Matching

To mitigate implications of physician' decision making (e.g., baseline patient characteristics, degree of impairment of consciousness) on group balancing and emulate a randomized experiment, a propensity score *e* for prehospital invasive blood pressure measurement was calculated using logistic regression. Variables factoring into this propensity score *e* were: age, sex, treatment by HEMS and GCS at arrival on-scene. Using this propensity score, optimal matching using a one-to-one ratio was performed. Covariate balance after matching was assessed using Standardized Mean Differences (SMDs), with SMDs below 0.2 considered not indicative of a potentially relevant magnitude of difference. Missing data were imputed using Multiple Imputation by Chained Equations (MICE) to retain all patients in the propensity score matching.

Statistical analysis

Demographic, injury-related, and treatment-related data were presented as median and 25 th to 75 th percentile, or number (*n*) and percentages (%), as appropriate. To assess for between-group differences before matching, Wilcoxon rank-sum test (for interval-scale data) or Pearson's Chi-squared test (for nominal-scale data) were used. To assess for between-group differences after matching, Wilcoxon signed-rank test was used. *P*-values below 0.05 were considered significant.

Matching and all statistical analyses were conducted using R version 4.4.0 (The R Foundation for statistical computing, Institute for Statistics and Mathematics, Vienna University of Economics and Business, Vienna, Austria), with the MatchIt and MICE packages, alongside base R functions.

Results

In the selected timespan, 437 adult patients were treated in the resuscitation room for an assumed acute neurological cause. Of those, 196 were primary missions with a suspected stroke who received prehospital induction of emergency anesthesia and airway management. After exclusion of 47 patients who were treated by two or more prehospital physician systems, six without an immediate CCT, and 43 patients with missing data regarding the primary endpoint, 100 patient data sets were available for analyses (Fig. 1). Of those, 67 received prehospital invasive blood pressure

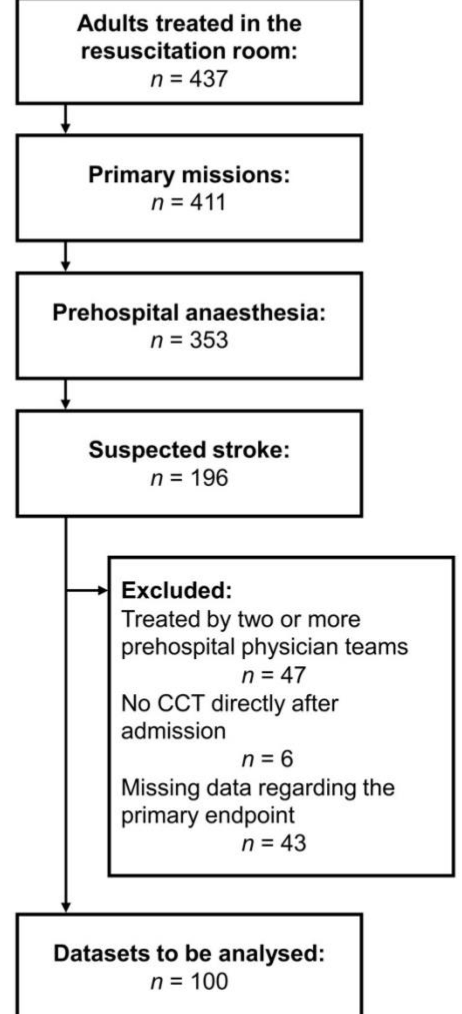

Fig. 1 Study flow chart. CCT = cranial computed tomography

measurement, with the remaining 33 having invasive blood pressure measurement initiated in the hospital.

Overall, median (25 th to 75 th percentile) patient age was 72 (61–80) years, 57% were male, and patients were mostly transported by ground-based ambulance (75/100, 75%). Further baseline patient characteristics are presented in Table 1. Datapoints were missing in four patients (twice age and twice GCS at arrival on-scene) and imputed as described in the methods section.

One-to-one propensity-score matching yielded two groups of 33 patients each and acceptable balance measures (Table 2).

In the matched cohort, median time between on-scene arrival and first CCT was 79 (77–87) minutes in the prehospital group compared to 73 (67–81) minutes the in-hospital group ($p = 0.21$) (Table 3, Fig. 2). Time spent on scene [45 (37–51) vs. 36 (33–43) minutes, $p = 0.009$] was significantly prolonged in the prehospital invasive blood pressure group, while time from arrival on-scene until handover [65 (52–73) vs. 56 (51–65) minutes, $p = 0.08$], duration of transport [18 (11–25) vs. 20 (13–31) minutes, $p = 0.20$] and time spent in the resuscitation room [16 (12–20) vs. 16 (11–21) minutes, $p = 0.39$] were not different (Table 3, Fig. 3).

No differences were found upon resuscitation room arrival in systolic [127 (109–150) vs. 130 (110–160) mmHg, $p = 0.99$] and diastolic blood pressure [80 (60–90) vs. 80 (65–90) mmHg, $p = 0.57$].

Table 1 Study population characteristics

Characteristic	Overall	In-hospital IBP, unmatched sample	Prehospital IBP, unmatched sample	In-hospital IBP, matched sample	Prehospital IBP, matched sample
n	100	33	67	33	33
Age [years] – median (25 th to 75 th percentile)	72 (61–80)	71 (62–79)	72 (59–81)	71 (62–79)	72 (61–80)
Male sex – n (%)	57 (57)	21 (64)	36 (54)	21 (64)	19 (58)
Initial Glasgow Coma Scale – median (25 th to 75 th percentile)	5 (4–7)	5 (4–7)	5 (4–7)	5 (4–7)	5 (4–7)
Mode of Transport – n (%)					
Ground based	75 (75)	21 (64)	54 (81)	22 (67)	24 (73)
HEMS	25 (25)	12 (36)	13 (19)	11 (33)	9 (27)
Prehospital vasopressor usage – n (%)	49 (49)	17 (52)	32 (48)	17 (52)	16 (48)
Prehospital fluid volume [ml] –median (25 th to 75 th percentile)	500 (500–1000)	500 (500–1000)	500 (500–1000)	500 (500–1000)	500 (500–1000)
In-hospital diagnosis – n (%)					
Hemorrhagic stroke	55 (55)	16 (48)	39 (58)	16 (48)	16 (48%)
Ischemic stroke	19 (19)	7 (21)	12 (18)	7 (21)	7 (21%)
Other	26 (26)	10 (33)	16 (24)	10 (33)	10 (30%)

HEMS Helicopter emergency medical service, *IBP* invasive blood pressure, *ml* millilitre

Table 2 Standardized Mean Differences of the variables before and after matching

Characteristic	In-hospital IBP, unmatched sample	Prehospital IBP, unmatched sample	SMD (unmatched)	In-hospital IBP, matched sample	Prehospital IBP, matched sample	SMD (matched)
n	33	67		33	33	
Age [years] – median (25 th to 75 th percentile)	71 (62–79)	72 (59–81)	0.0187	71 (62–79)	72 (61–80)	0.0340
Male sex – n (%)	21 (64)	36 (54)	0.0991	21 (64)	19 (58)	0.0606
Initial Glasgow Coma Scale – median (25 th to 75 th percentile)	5 (4–7)	5 (4–7)	−0.3064	5 (4–7)	5 (4–7)	−0.1519
Mode of Transport – n (%)			−0.1696			−0.0303
Ground based	21 (64)	54 (81)		22 (67)	24 (73)	
HEMS	12 (36)	13 (19)		11 (33)	9 (27)	

HEMS helicopter emergency medical service, *IBP* invasive blood pressure, *SMD* Standardized Mean Difference

Table 3 Median duration in minutes of the selected time-intervals in the overall, prehospital IBP and in-hospital IBP cohort in the unmatched and matched sample

Characteristic	Overall	In-hospital IBP, unmatched sample	Prehospital IBP, unmatched sample	*p*-value*	In-hospital IBP, matched sample	Prehospital IBP, matched sample	*p*-value**
n	100	33	67		33	33	
On-Scene to CCT [minutes] – median (25 th to 75 th percentile)	79 (67–91)	73 (67–81)	79 (67–93)	0.15	73 (67–81)	79 (70–87)	0.21
On-Scene to handover [minutes] – median (25 th to 75 th percentile)	59 (51–75)	56 (51–65)	65 (50–78)	0.11	56 (51–65)	65 (52–73)	0.08
On-Scene to transport [minutes] – median (25 th to 75 th percentile)	43 (33–51)	36 (33–43)	45 (34–53)	0.01	36 (33–43)	45 (37–51)	0.009
Duration of transport [minutes] – median (25 th to 75 th percentile)	18 (13–26)	20 (13–31)	18 (13–25)	0.53	20 (13–31)	18 (11–25)	0.20
Handover to CCT [minutes] – median (25 th to 75 th percentile)	16 (11–20)	16 (11–21)	17 (12–20)	0.67	16 (11–21)	16 (12–20)	0.39

CCT cranial computed tomography, *IBP* invasive blood pressure

* Wilcoxon rank-sum test

** Wilcoxon signed-rank test

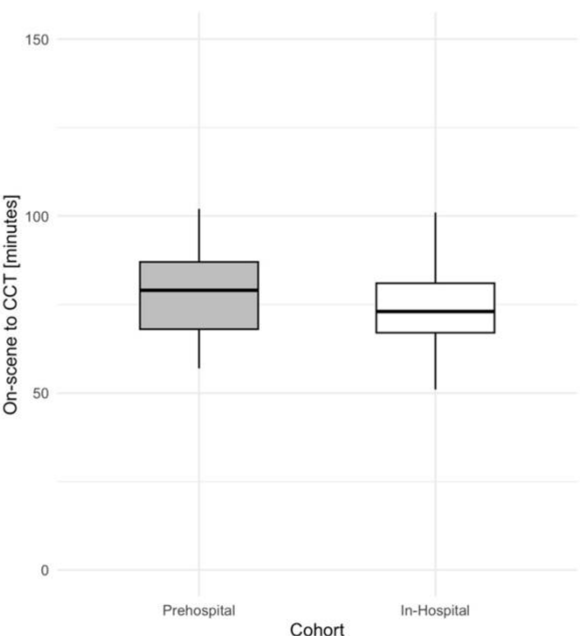

Fig. 2 Boxplot comparison of the time-interval between on-scene arrival and the first CCT after hospital admission between the prehospital and in-hospital invasive blood pressure measurement groups. CCT = cranial computed tomography

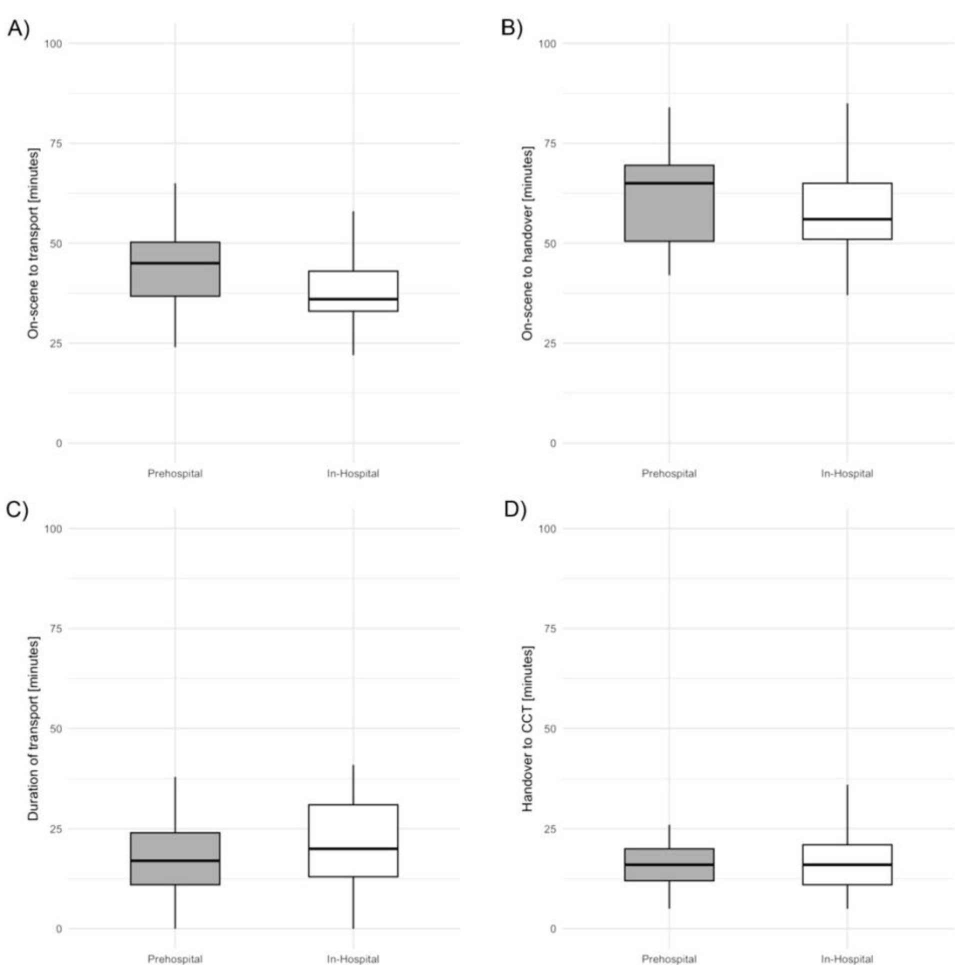

Fig. 3 Boxplot comparisons of the time-interval between (**A**) on-scene arrival and transport, **B** on-scene arrival and hospital handover, **C** transport and hospital handover, and (**D**) hospital handover and first CCT after hospital admission between the prehospital and in-hospital invasive blood pressure measurement groups. CCT = cranial computed tomography

Discussion

Time from arrival on-scene until initial CCT in this study was 79 min in patients receiving prehospital invasive blood pressure measurement and 73 min in those who had it initiated in the resuscitation room, revealing no significant difference. However, the on-scene time of the physician response units (45 min vs. 36 min) was prolonged in those with prehospital invasive blood pressure measurement.

Data of on-scene times for prehospital induction of emergency anesthesia in similar systems varies. In a retrospective study from Finland evaluating 4496 patients with both traumatic and non-traumatic indications for prehospital intubation, median on-scene time was 33 (23–45) minutes in case of first pass success and 40 (29–52) minutes if two or more intubation attempts were required [16]. Two Australian studies showed markedly longer on-scene times. In an investigation of patients

with stroke (both ischemic and hemorrhagic) and advanced airway management, mean time from arrival on-scene to transport was 58 min [17]. In a more heterogenous group of patients with non-traumatic brain injury, median time on-scene was 77 min [18].

The nominal difference of six minutes in the time from arrival on-scene to CCT is slightly longer compared to previously published data. In a previous study in our system by *Wildner* et al., prehospital arterial cannulation required a median of two minutes and preparation of the invasive blood pressure set, which is usually carried out simultaneously, a median of three minutes [15]. Furthermore, time between arrival on-scene and initial CCT did not differ in patients with isolated traumatic brain injury and on-scene times were prolonged only by a median of three minutes in the prehospital invasive blood pressure measurement cohort [19].

Reasons for this difference remain speculative and the following aspects might play a role in this:

In this study patients suffering from stroke were investigated. Compared to trauma victims, these patients are frequently older and may have pre-existing cardiovascular disease, for example arteriosclerosis. These comorbidities can make arterial cannulation difficult and time-consuming. In addition, a lot of emphasis by emergency medical systems is put on achieving short on-scene times—ideally within one hour—in trauma patients. This focus might be less pronounced in the care of non-traumatic patients.

Interestingly, in the exploratory analysis of the admission blood pressure, no difference between the two groups was found. Improved hemodynamic management due to invasive blood pressure measurement was previously shown in the in-hospital setting: improved hypotension detection and substantial decrease of hypotension during anesthetic induction led to the recommendation to establish invasive monitoring prior to induction in high-risk hospitalized patients [20, 21]. The observed discrepancy may be explained by our study's methodology, which restricted blood pressure assessment to a single time point during handover in the resuscitation room. At handover, situations with a high risk of hemodynamic disturbances, such as anesthetic induction, have already been performed, and a steady state is commonly achieved. Further, blood pressure measured non-invasively could possibly underestimates the incidence of hypotension [22–24].

The question remains whether prehospital arterial cannulation for invasive blood pressure measurement, despite its association with a prolonged on-scene time in this study, provides sufficient clinical benefit to justify its out-of-hospital use. To fully answer this question, a large prospective randomized trial is necessary. However, the following aspects may potentially support it:

In the study by *Fouche* et al., longer on-scene times were associated with a higher probability of survival in patients with hemorrhagic stroke and prehospital rapid sequence intubation [25]. In contrast, the probability of survival decreased with longer on-scene times in patients with traumatic brain injury. Of course, an association of prolonged on-scene time and improved survival generally seems unplausible and the referenced study has a high risk of bias. However, this could still potentially indicate that there is some room and time for additional advanced prehospital interventions in patients with stroke and airway management providing a benefit despite slight on-scene time prolongation. Invasive blood pressure measurement is the in-hospital gold standard for these patients. This is primarily due to its capacity for rapid interventions facilitated by beat-to-beat analysis and the inherent advantages it offers in measurement accuracy compared to non-invasive methods. The authors of a retrospective study from a HEMS service in the United Kingdom, which concurrently measured invasive and non-invasive blood pressure values, concluded that non-invasive values are frequently inaccurate, particularly in patients with hemodynamic instability, and direct measurement should be considered [22]. A similar conclusion was reported in a study comparing invasive and non-invasive measurements in in-hospital patients with stroke. Patients with systolic blood pressures above 180 mmHg had a mean non-invasive value 19.8 mmHg (95% confidence interval 12.2–27.4) below the invasive measurement [26]. This is, especially in patients having hemorrhagic stroke, of high relevance. In these patients, close blood pressure monitoring with narrow limits is recommended in guidelines [9, 27].

A recent randomized trial evaluated prehospital blood pressure management in patients with stroke and provided neutral outcomes. However, in the subgroup of patients with hemorrhagic stroke, a lower odds ratio for poor functional outcome was shown if strict blood pressure management (aiming at a systolic blood pressure of 140 mmHg) was performed in the prehospital phase compared to usual care (treatment only of systolic blood pressure was above 220 mmHg) [28]. In a retrospective study conducted in Australia, the intracranial blood volume measured in the admission CCT was positively correlated with the prehospital systolic blood pressure in patients with intracranial hemorrhage [29]. At the same time, it has been shown that critical blood pressure drops, which frequently happen during induction of anesthesia, are associated with worse outcomes in patients with ischemic stroke injury [30, 31].

Limitations

There are several limitations to this study. Due to the retrospective nature and hence absence of randomization, causal inference cannot be drawn and an indication bias might be present. To address this, stringent propensity score matching was performed to mitigate potential biases and strengthen the reliability of the findings. Prehospital systems vary worldwide and therefore, these findings may not be directly translatable to countries with different out-of-hospital structures. Moreover, because only patients with documented arterial access were included, patients with failed cannulation could not be identified, introducing potential bias that could not be accounted for. However, in two studies evaluating arterial access in a prehospital population, unsuccessful cannulation was rare [15, 32]. Hemodynamic parameters obtained in the prehospital setting would be of great interest and offer additional valuable insights. Nevertheless, a direct comparison of prehospital blood pressure measurements was not possible, as not all prehospital records provided the necessary detail and precision required for scientific analysis. Furthermore, the sample size is limited, which has to be accounted for when interpreting the results.

Conclusion

In summary, in patients with suspected stroke who were intubated prehospitally, time from arrival on-scene to the first CCT was not prolonged in the cohort with prehospital invasive blood pressure measurement compared to the cohort with in-hospital establishment. On-scene time, however, was. Further research evaluating hemodynamic and functional consequences of prehospital blood pressure management is required to put this into perspective.

Abbreviations

CCT	Cranial computed tomography
GCS	Glasgow coma scale
HEMS	Helicopter emergency medical services
SMD	Standardized Mean Differences
STROBE	Strengthening the Reporting of Observational Studies in Epidemiology

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Authors' contributions

ME1 (Michael Eichlseder), NS, AP, ME2 (Michael Eichinger), SL, BH, PZ, SFH conceived and designed the study, ME1, NS, AP, ME2, BH collected the data. The data analysis was performed by ME1, NS, AP, SO, PZ while the manuscript was drafted by ME1, NS, SL, SO, PZ, SFH.

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Data availability

The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request. Data are located in controlled access data storage at the Medical University of Graz.

Declarations

Ethics approval and consent to participate

Ethical approval was sought and granted by the Ethics Committee of the Medical University of Graz (IRB00002556, decision number 35–299 ex 22/23) prior to data retrieval and study conduction. Informed consent was waived.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Title

Intraarterial blood pressure monitoring in prehospital emergency care: A scoping review

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Abstract

Background

Blood pressure is a key vital sign in prehospital emergency care and essential for assessing the hemodynamic status and guiding treatment. In the prehospital setting, blood pressure is usually measured intermittently with non-invasive cuff-techniques. However, intraarterial blood pressure monitoring with an arterial catheter offers continuous and more accurate measurements. This scoping review aimed to synthesize and analyze the current literature on intraarterial blood pressure monitoring in prehospital emergency care.

Methods

PubMed, EMBASE, MEDLINE, Cochrane Central, and CINAHL were searched on April 15, 2025, following PRISMA-ScR guidelines and Joanna Briggs Institute methodology. Studies involving adults (≥18 years) having prehospital intraarterial blood pressure monitoring were included.

Results

1456 studies were screened and 24 studies finally included. The most frequent indications for intraarterial blood pressure monitoring were cardiopulmonary resuscitation and post resuscitation care. Arterial cannulation was performed by physicians in 92% of the cases. The radial artery was the most frequently used cannulation site. Arterial cannulation was successful in 82% of the patients. Major complications were very rare, with brachial artery cannulation bearing the highest risk for complications. Low agreement between intraarterial and non-invasive blood pressure measurements was reported. Actions based on intraarterial blood pressure monitoring were performed in 53% of the patients. Arterial cannulation was performed during different timepoints and had varying effects on prehospital time.

Conclusions

Intraarterial blood pressure monitoring has been studied across a wide range of indications in prehospital emergency care with an acceptable cannulation success rate and low risk of complications. However, the included studies were mostly observational, necessitating randomized controlled trials analyzing patient-centered outcomes in defined populations.

Keywords: Arterial cannulation; arterial catheter; arterial pressure; emergency medicine; hemodynamic monitoring; out-of-hospital

Text

Background

Blood pressure is a key vital sign in prehospital emergency care. It is essential for assessing the hemodynamic status and guiding treatment in patients with traumatic brain injury, cardiogenic shock, and cardiopulmonary resuscitation [1-4]. Measuring blood pressure accurately is thus important in prehospital emergency care.

Blood pressure can be measured non-invasively or invasively. Non-invasive measurements are performed intermittently using an inflatable upper-arm cuff, either manually (auscultation or palpation) or automatically (oscillometric) [5]. Intraarterial blood pressure measurement with an arterial catheter is the clinical reference method and enables continuous blood pressure monitoring, but is invasive [6]. Continuous intraarterial blood pressure monitoring detects hypotension more effectively than intermittent non-invasive blood pressure monitoring and helps clinicians intervene earlier to reduce hypotension during surgery [7, 8]. In addition, intermittent non-invasive blood pressure monitoring, compared to intraarterial blood pressure monitoring, overestimates low blood pressures and underestimates high blood pressures, leading to undetected hypotension and hypertension [9, 10]. Therefore, intraarterial blood pressure monitoring is the gold standard for blood pressure monitoring in high-risk surgical and critically ill patients.

Despite its clinical advantages, intraarterial blood pressure monitoring is rarely used in prehospital emergency care due to concerns including distraction, delay of care, required expertise, and equipment availability [11]. However, clinical utilization is increasing lately and the body of evidence is growing. In this scoping review we aim to synthesize and analyze the current literature on intraarterial blood pressure monitoring in the prehospital setting.

Methods

This scoping review was developed and conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) extension for scoping reviews and the Joanna Briggs Institute Collaboration manual for evidence synthesis [12, 13]. This work is exempt from ethics committee review as it is a synthesis of published literature. The protocol was registered on the open science framework database (https://doi.org/10.17605/OSF.IO/MJ4DU).

Research question

In this scoping review we aim to synthesize and analyze the current literature on intraarterial blood pressure monitoring in prehospital emergency care. The scoping review design was chosen as prehospital intraarterial blood pressure monitoring is rarely performed and we thus expected a limited, but broad variety of studies investigating different outcomes.

Search strategy

We screened PubMed, EMBASE, MEDLINE, the Cochrane Central Register of Controlled Trials, and CINAHL databases. PubMed was searched directly. We used Ovid to search EMBASE, MEDLINE, and Cochrane Central Register of Controlled Trials and EBSCOhost to search CINAHL. All databases were searched from their

respective start of recording. The final search was performed on April 15, 2025. The used search strategies are shown in the additional file (additional file 1, Table S1-S5). As an example, the search strategy used for EMBASE is provided in Table 1.

Table 1 – Search strategy used for EMBASE.

EMBASE	emergency care/ or emergency transport/ or (prehospital emergency or prehospital or pre-hospital or prehospital critical care or out of hospital or out-of-hospital).ab,kf,ti. AND artery catheter/ or arterial cannula/ or arterial pressure/ or (Prehospital arterial cannulation or arterial blood pressure measurement or invasive blood pressure or IBP or radial artery or intra-arterial blood pressure or arterial line or invasive arterial pressure).ab,kf,ti.

Study selection

Studies on adults (≥18 years) having prehospital arterial cannulation for intraarterial blood pressure monitoring, published in English, German, or French were included. We restricted our analysis to studies on arterial cannulation for intraarterial blood pressure monitoring but not for interventions such as resuscitative endovascular balloon occlusion of the aorta or extracorporeal membrane oxygenation. Studies not involving humans, secondary literature, case reports, and papers using opinion as the main resource were excluded.

Two independent reviewers (ME, SL) screened the literature in three steps using Rayyan (rayyan.ai; Cambridge, MA, USA): title screening, abstract screening, and full text screening. After each screening round, conflicts could be resolved through

discussion under the supervision of a third reviewer (HBC). After completing the screening process, a forward-reference search with Google Scholar was performed to minimize the risk of missing relevant literature.

Data extraction

For data extraction, we used a datasheet in Microsoft Excel 2023 (Microsoft Corp, Redmond, WA, USA) with the following entities: title, authors, date of publication, country, type of study, patients, intervention/aim, indication for intraarterial blood pressure monitoring, medical profession of the operator, cannulation site, cannulation technique, cannulation success, complications, measurement agreement, actions based on intraarterial blood pressure monitoring, and prehospital time. Two independent researchers (ME, SL) extracted the data. Finally, the data sheets were compared and aligned.

Data synthesis

We used descriptive statistics and report the results in a narrative way. Weighted averages were calculated by multiplying each data point by the corresponding number of patients, summing these products, and then dividing this by the sum of the in total included patients.

Results

Selection of sources of evidence

We identified a total of 1456 records. After removal of 141 duplicates, we screened titles and abstracts. Finally, we screened 37 full-text articles of which we included 24 (Figure 1) [14-37].

Insert Figure 1 here.

Figure 1 – Flow diagram of study selection.

Description of sources of evidence

The selected studies were published between 1988 and 2025 and are shown in Table 2. Publications originated from the United Kingdom (n=7) [14, 16, 25, 28, 31, 32, 35], France (n=5) [17-19, 26, 34], Finland (n=3) [22, 27, 33], Norway (n=3) [15, 30, 37], Australia (n=2) [21, 23], Austria (n=2) [20, 36], and the United States of America (n=2) [24, 29]. Of the included studies, two were randomized controlled trials that used intraarterial blood pressure monitoring and reported blood pressure as an endpoint, but did not compare intraarterial to non-invasive blood pressure monitoring [19, 29]. Eleven were prospective observational studies, of which six evaluated intraarterial blood pressure monitoring as a prehospital intervention [18, 24, 31, 32, 34, 36] and five used it solely to measure blood pressure as study endpoint [17, 22, 26, 27, 33]. Additionally, two were post-hoc analyses of prospective studies that had used intraarterial blood pressure monitoring to measure blood pressure as study endpoint [15, 37]. The remaining nine studies were retrospective studies [14, 16, 20, 21, 23, 25, 28, 30, 35]. Data regarding the indication for intraarterial blood pressure monitoring, operator profession, cannulation site, cannulation technique, cannulation success, complications, measurement agreement, actions based on intraarterial blood pressure monitoring, and prehospital time were extracted (Additional file 1, Table S6).

Insert Table 2 here.

Table 2 – Included studies.

We initially planned to assess the risk of bias, but finally did not, due to the heterogeneity of study designs and the fact that intraarterial blood pressure monitoring was often not the study intervention. This decision is consistent with established scoping review methodology [12, 13].

Indications for intraarterial blood pressure monitoring

All but one study provided information on the indication for performing prehospital intraarterial blood pressure monitoring. In ten studies, intraarterial blood pressure monitoring was initiated for research purposes during cardiopulmonary resuscitation and post resuscitation care [14, 15, 17, 19, 22, 26, 27, 29, 33, 37]. Nine studies provided a range of indications, including cardiopulmonary resuscitation, post resuscitation care, trauma, shock, respiratory failure, unconsciousness, sepsis, and stroke [16, 18, 20, 23, 28, 30, 34-36]. In four studies, intraarterial blood pressure monitoring was used for secondary transports only [24, 25, 31, 32].

Operator profession

The profession of the person performing arterial cannulation was reported in 13 studies. In twelve studies including 1497 patients in total, cannulation was solely performed by physicians [14, 15, 18, 20-22, 27, 29, 30, 33, 34, 37]. In the remaining study, which described the profession of the operator performing arterial cannulations in 893 patients, 704 (79%) were done by physicians and 189 (21%) by critical care paramedics [16]. Weighted average for physicians performing arterial cannulation across all studies was 92%.

Cannulation site

Cannulation site was reported in 16 studies. Cannulation sites included the radial, brachial, femoral, and dorsalis pedis arteries. In nine studies including 1932 patients in total, 1438 (74%) arterial catheters were inserted in the radial artery, 297 (15%) in the femoral artery, 98 (5%) in the brachial artery, and six (0.3%) in the dorsalis pedis artery [14, 16, 18, 24, 28, 31, 32, 34, 35]. In 93 (5%) patients, the cannulation site was not reported. In six studies including 311 patients in total, arterial catheters were explicitly inserted in the femoral artery [15, 17, 19, 26, 29, 33]. One study only stated that arterial catheters were either inserted in the radial or femoral artery [27].

Cannulation technique

Eleven studies described the technique used for arterial cannulation. In five studies, including 101 patients in which only the femoral artery was cannulated, a guidewire technique was used for arterial catheter insertion [17, 19, 26, 29, 33]. In three other studies including 1485 patients, a guidewire technique was used for the femoral artery and direct puncture techniques for the radial and brachial artery [14, 16, 35]. In one study each, only direct puncture (137 patients) or only guidewire technique (94 patients) were used for arterial catheter insertion, irrespective of the cannulation site [34, 36]. Ultrasound guidance was used in one study per clinical preference, and was mandatory for femoral cannulation in two studies [14, 16, 27].

Cannulation success

Overall cannulation success was reported in five studies, ranging between 74% and 100%, with a weighted average success of 82% [18, 19, 34, 36, 37]. One study provided data on the required mean cannulation attempts to establish femoral artery access during ongoing cardiopulmonary resuscitation, which was 3.4 attempts [29].

Complications

Five studies with a total of 1682 included patients reported the incidence of cannulation-associated complications. Major complications occurred in two studies. In each of the two studies, a brachial occlusion (0.1%; 1/1083 patients and 0.3%; 1/322 patients, respectively) requiring fasciotomy was reported [16, 35]. Individual studies reported the rate of minor complications, such as delayed capillary refill time resolving after catheter removal (0.6%; 2/322 patients), localized skin erythema (1%; 4/322 patients), disturbance of patient care process (2%; 3/137 patients), and minor hematoma (13%; 12/94 patients) [34-36]. One study with 46 patients reported no complications at all [18]. The association between time of arterial catheter insertion

and complications was evaluated in one study. Arterial catheters inserted in the prehospital setting that remained for five days or more, compared to arterial catheters removed within the first four days, had a higher odds ratio for complications (odds ratio: 6.8, 95% confidence interval: 1.5 to 31.4) [35].

Measurement agreement

Six studies compared simultaneous intraarterial and non-invasive blood pressure measurements. Five of these studies used Bland–Altman analysis or reported the standard deviation of the differences, consistently demonstrating low agreement between methods [24, 25, 31, 32, 34]. One study defined thresholds for clinically acceptable agreement (<20 mmHg for systolic and diastolic pressures, <10 mmHg for mean arterial pressure). Within these ranges, agreement was acceptable in 64% of systolic, 76% of diastolic, and 55% of mean arterial pressure measurements [28].

Actions based on intraarterial blood pressure monitoring

Two studies evaluated the incidence of actions based on intraarterial blood pressure monitoring. Prehospital intraarterial blood pressure monitoring led to direct actions in 51% of patients in one study (administration of vasoactive therapy or fluids) and a modification of vasoactive treatment in 54% of patients in another study, providing a weighted average of 53% [34, 36].

Prehospital time

In total, nine studies reported data regarding time investigating variable intervals. One study individually described the median (interquartile range) time required for arterial cannulation (2 (1-3) minutes) and intraarterial blood pressure monitoring set preparation (3 (2-4) minutes) [36]. Two studies reported the time of kit opening until successful measurement, reporting a mean (standard deviation) of 6.1

(3) minutes and a median (interquartile range) of 12 (10-13) minutes, respectively [18, 34]. Median (interquartile range) time from arrival on-scene until successful intraarterial blood pressure monitoring was 27 (15-42) minutes in one study [16]. In a retrospective study including patients with severe traumatic brain injury that specifically compared time from arrival on-scene until first head computed tomography between patients with and without prehospital intraarterial blood pressure monitoring, there was no clinically meaningful difference between groups [20]. In a study evaluating the impact of prehospital interventions on time, prehospital intraarterial blood pressure monitoring prolonged on-scene time for an average of 23.8 (95% confidence interval: 8.8 to 38.8) minutes [21].

Discussion

In this scoping review we aimed to synthesize and analyze the current literature on intraarterial blood pressure monitoring in prehospital emergency care. Twenty-four studies were identified, providing evidence for prehospital intraarterial blood pressure monitoring including indication, operator profession, cannulation site, cannulation technique, cannulation success, complications, measurement agreement, actions based on intraarterial blood pressure monitoring, and prehospital time (Figure 2). Insert Figure 2 here.

Figure 2 – Graphical summary of the scoping review.

Main indications identified for intraarterial blood pressure monitoring were cardiopulmonary resuscitation and post resuscitation care. In both conditions, patient care might be improved when using intraarterial blood pressure monitoring because continuous monitoring may improve chest compression quality, help identify return of spontaneous circulation in states of low cardiac output, and enable more precise

hemodynamic monitoring and management in post resuscitation care [38-40]. Furthermore, intraarterial blood pressure monitoring is recommended in the early post resuscitation care by current guidelines, as hypotension in this phase is frequent and associated with adverse outcomes [4, 41]. Other frequently reported indications included traumatic brain injury, shock, prehospital emergency anesthesia, and mixed medical conditions. In any case, a careful risk-benefit assessment is necessary, considering the advantages of intraarterial blood pressure monitoring versus the potential risks and time-delays associated with arterial cannulation.

Major complications resulting from arterial cannulation were rare and occurred only following brachial artery cannulation. This finding is consistent with a retrospective in-hospital study including more than 60 000 arterial cannulations that reported a major complication rate of 3.4 per 10 000 arterial catheters – with brachial artery cannulation carrying the highest risk for complications [42]. Arterial catheters inserted in the prehospital setting that remained for five days or more were associated with increased complications. Similarly, arterial catheters placed in the hospital also have an increased risk of colonization and infection with prolonged insertion time, especially when inserted for a week or longer [43, 44]. It remains to be determined if and at what time point arterial catheters inserted in prehospital settings might need to be exchanged in the hospital.

Arterial cannulation was almost exclusively performed by physicians. Physicians commonly perform arterial cannulation and use intraarterial blood pressure monitoring in the hospital. This provides the necessary skills and familiarity with the method to also use it in prehospital settings. However, many emergency care systems do not routinely utilize prehospital emergency physicians. Nonetheless, data on arterial cannulation by critical care paramedics demonstrate that intraarterial blood

pressure monitoring can also be initiated by highly specialized non-physician personnel when adequate training and supervision are provided.

The radial and femoral arteries were the main cannulation sites. The radial artery was most commonly cannulated for prehospital intraarterial blood pressure monitoring. This aligns with in-hospital guidelines, recommending the radial artery as primary site of cannulation [45-47]. The femoral artery was frequently used for arterial cannulation in studies using intraarterial blood pressure monitoring to measure blood pressure as study endpoint during cardiopulmonary resuscitation. Cannulation of the femoral artery was almost always performed using a guidewire technique. Using a guidewire technique enables the cannulation of deeper vessels and insertion of longer catheters – which is often required during femoral artery cannulation [48]. In contrast, the radial artery is more superficial allowing a direct puncture with shorter catheters. Only three studies described the use of ultrasound for cannulation. Ultrasound guidance can increase first-pass and overall cannulation success in in-hospital radial and femoral artery cannulation, if used by trained providers [49-51]. A reason that only three included studies reported the use of ultrasound for arterial cannulation might be that handheld ultrasound devices were not broadly available in the past.

The reported success rate ranged between 74% to 100%, with a weighted average of 82%, which is similar to in-hospital data. A success rate of 90% was found in a study investigating in-hospital radial artery cannulation using a palpatory approach by anesthesiologists and dropped to 75% when pulse was weak [52]. Radial artery cannulation was successful with fewer than three attempts in 78% in another study in the in-hospital setting [53].

Low agreement between intraarterial blood pressure measurement and non-invasive blood pressure measurement was reported in the included studies. While this

low agreement is of general concern, certain situations require especially accurate blood pressure monitoring and management during prehospital emergency care. This includes for example traumatic brain injury with very narrow recommended blood pressure ranges or a ruptured unsecured aneurysm causing subarachnoid hemorrhage, as further bleeding might have catastrophic consequences [1, 54]. There is evidence from in-hospital studies that the agreement between non-invasive and intraarterial blood pressure monitoring is worse than generally assumed [9, 10, 55]. This reduced agreement is especially pronounced at very low and high blood pressures, which are common in critically ill patients [9, 56, 57].

Only two studies evaluated if prehospital intraarterial blood pressure monitoring leads to medical actions, which was the case in approximately half of the assessed patients. While this might indicate clinically relevant consequences from intraarterial blood pressure monitoring, further research is needed.

Varying results regarding differences in prehospital time between patients with and without intraarterial blood pressure monitoring were reported in the included studies. Several studies showed that intraarterial blood pressure monitoring can be established within minutes and does not or only slightly prolong on-scene time. However, one study retrospectively evaluating the impact of interventions on on-scene time in a physician-led retrieval system in Australia found significantly prolonged on-scene times with prehospital intraarterial blood pressure monitoring – with an average increase in on-scene time of more than 20 minutes [21]. With only 19 patients having intraarterial blood pressure monitoring during the twenty-month study period, limited routine and selection bias could contribute to this observation. Furthermore, large distances are commonly encountered in Australian prehospital emergency care, limiting generalizability and increasing the need for hemodynamic stabilization on-

scene and accompanying interventions before transport, potentially leading to additional bias [58]. The reported median duration of 27 minutes from on-scene arrival to successful monitoring in a helicopter emergency medical service based in the United Kingdom suggests that much of prehospital care occurs before intraarterial blood pressure monitoring is established [16]. Yet, this duration should not be equated with time delay. Half of the included patients in this study received cardiopulmonary resuscitation and another third suffered from severe injuries, indicating that the teams had to perform lifesaving interventions before being able to initiate intraarterial blood pressure monitoring. Furthermore, with first intraarterial blood pressure monitoring initiated en route in 39% of the cases, this study also shows that tasks can be performed in parallel and highlights the necessity of effective scene management.

The summarized evidence must, however be considered limited, as no randomized controlled trial comparing prehospital intraarterial versus non-invasive blood pressure monitoring was found. Data mostly stems from observational and retrospective single-center studies. Considering this, randomized controlled trials comparing intraarterial with non-invasive blood pressure monitoring in well-defined populations are necessary. Open research questions include whether prehospital intraarterial blood pressure monitoring during cardiopulmonary resuscitation improves detection of return of spontaneous circulation and increases hemodynamic stability once return of spontaneous circulation is achieved. Furthermore, in patients with acute brain injury, it remains to be determined in randomized trials whether intraarterial blood pressure monitoring reduces duration and severity outside recommended blood pressure targets and if it prolongs time until hospital admission and first computed tomography.

Clinical implications

Based on the findings of this scoping review, the following clinical implications can be drawn:

- Cardiopulmonary resuscitation and return of spontaneous circulation are the main indications for intraarterial blood pressure monitoring. Furthermore, situations requiring precise blood pressure monitoring and management (e.g. acute brain injury) are also potential indications, however, a risk-benefit assessment is required.
- The person performing arterial cannulation requires high expertise and should have frequent in-hospital exposure to intraarterial blood pressure monitoring.
- The radial artery is a reasonable primary site of cannulation. When the femoral artery is cannulated, a guidewire technique should be used.
- Prehospital intraarterial blood pressure monitoring seems possible with little delay in care, if performed by experienced teams. However, there is a not to be denied risk of delaying care, necessitating structured, predefined processes within systems and regular training of prehospital teams.
- Prehospital systems performing intraarterial blood pressure monitoring should systematically collect data for quality management, clinical governance and research.

Limitations

The studies included in this scoping review are almost exclusively observational or retrospective. Additionally, several of the included studies are considered old and since their conduction, prehospital practice has changed remarkably. Prehospital practice in general is highly variable around the world, making comparison

challenging. Comparison between studies was also challenged by variable ways of reporting similar endpoints. Lastly, it cannot be excluded that data from patients are double reported, as some working groups published multiple studies.

Conclusion

In this scoping review evaluating intraarterial blood pressure monitoring in prehospital emergency care, 24 studies were synthesized and analyzed. Intraarterial blood pressure monitoring was used for a variety of indications, especially cardiopulmonary resuscitation and post resuscitation care. Arterial cannulation was almost exclusively performed by physicians, with the radial artery as the main cannulation site. Successful cannulation was described in approximately four out of five attempts, with varying effects on prehospital time and a low incidence of major complications. However, the included studies were mostly observational, necessitating randomized controlled trials comparing intraarterial blood pressure monitoring to non-invasive blood pressure monitoring.

List of abbreviations

None.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used are available from the corresponding author on reasonable request.

Competing interests

Michael Eichlseder, Sebastian Labenbacher, Nikolaus Schreiber Alexander Pichler, Michael Eichinger and Paul Zajic published one of the studies used in the scoping review.

Karim Kouz is a consultant for and has received honoraria for giving lectures from Edwards Lifesciences (Irvine, California, USA). KK is a consultant for Vygon (Aachen, Germany).

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Authors' contributions

ME1 (Michael Eichlseder), SL, NS, MM, HBC conceived and designed the review, ME1, SL, HBC collected the data. The data analysis was performed by ME1, SL, NS, AP, HBC while the manuscript was drafted by ME1, SL, NS, KK, AP, ME2, MM, PZ, SFH, HBC, BS. All authors read and approved the final manuscript.

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Legends for illustrations

Figure 1 – Flow diagram of study selection.

Figure 2 – Graphical summary of the scoping review.

Table 1 – Search strategy used for EMBASE.

Table 2 – Included studies.

Table 2 – Included studies.

Author (Year)	Country	Type	n	Data extracted for the scoping review
Low (1988)	USA	prospective	20	indication, cannulation site, measurement agreement
Runcie (1990)	UK	prospective	22	indication, cannulation site, measurement agreement
Runcie (1990)	UK	prospective	44	indication, cannulation site, measurement agreement
Duchateau (2003)	FRA	prospective	46	indication, operator profession, cannulation site, cannulation success, prehospital time, complications
Pirrallo (2005)	USA	RCT	22	indication, operator profession, cannulation site, cannulation technique, cannulation success, prehospital time, complications
Sende (2009)	FRA	prospective	94	indication, operator profession, cannulation site, cannulation technique, cannulation success, prehospital time, measurement agreement, actions based on IBP monitoring
Duchateau (2010)	FRA	prospective	29	indication, cannulation site, cannulation technique
Wildner (2011)	AUT	prospective	137	indication, cannulation site, cannulation technique, cannulation success, prehospital time, complications, actions based on IBP monitoring
Hoppu (2011)	FIN	prospective	2	indication, operator profession, cannulation site, prehospital time
Ducors (2011)	FRA	RCT	25	indication, cannulation site, cannulation technique, cannulation success
McMahon (2012)	UK	retrospective	56	indication, measurement agreement
Sainio (2015)	FIN	prospective	39	indication, operator profession, cannulation site, cannulation technique
Joynes (2016)	AUS	prospective	67	indication
Mirek (2017)	FRA	prospective	21	indication, cannulation technique
Fok (2019)	AUS	retrospective	506	operator profession, prehospital time
Berve (2022)	NOR	RCT (post hoc)	210	indication, operator profession
Nelskylä (2022)	FIN	prospective	75	indication, operator profession, cannulation technique, cannulation success

Eichlseder (2024)	AUT	retrospective	181	indication, operator profession, prehospital time
Perera (2024)	UK	retrospective	221	indication, cannulation site, measurement agreement
Butterfield (2024)	UK	retrospective	108 3	indication, operator profession, cannulation site, cannulation technique, prehospital time, complications
Yin (2024)	NOR	RCT (post hoc)	56	indication, operator profession, cannulation success, prehospital time,
Aziz (2024)	UK	retrospective	80	indication, operator profession, cannulation site, cannulation technique
Ringen (2024)	NOR	retrospective	708	indication, operator profession
Sin (2025)	UK	retrospective	322	indication, cannulation site, cannulation technique, complications

AUS, Australia; AUT, Austria; FIN, Finland; FRA, France; IBP, intraarterial blood pressure; NOR, Norway; UK, United Kingdom; USA, United states of American; RCT, randomized controlled trial

Figure 1 – Flow diagram of study selection.

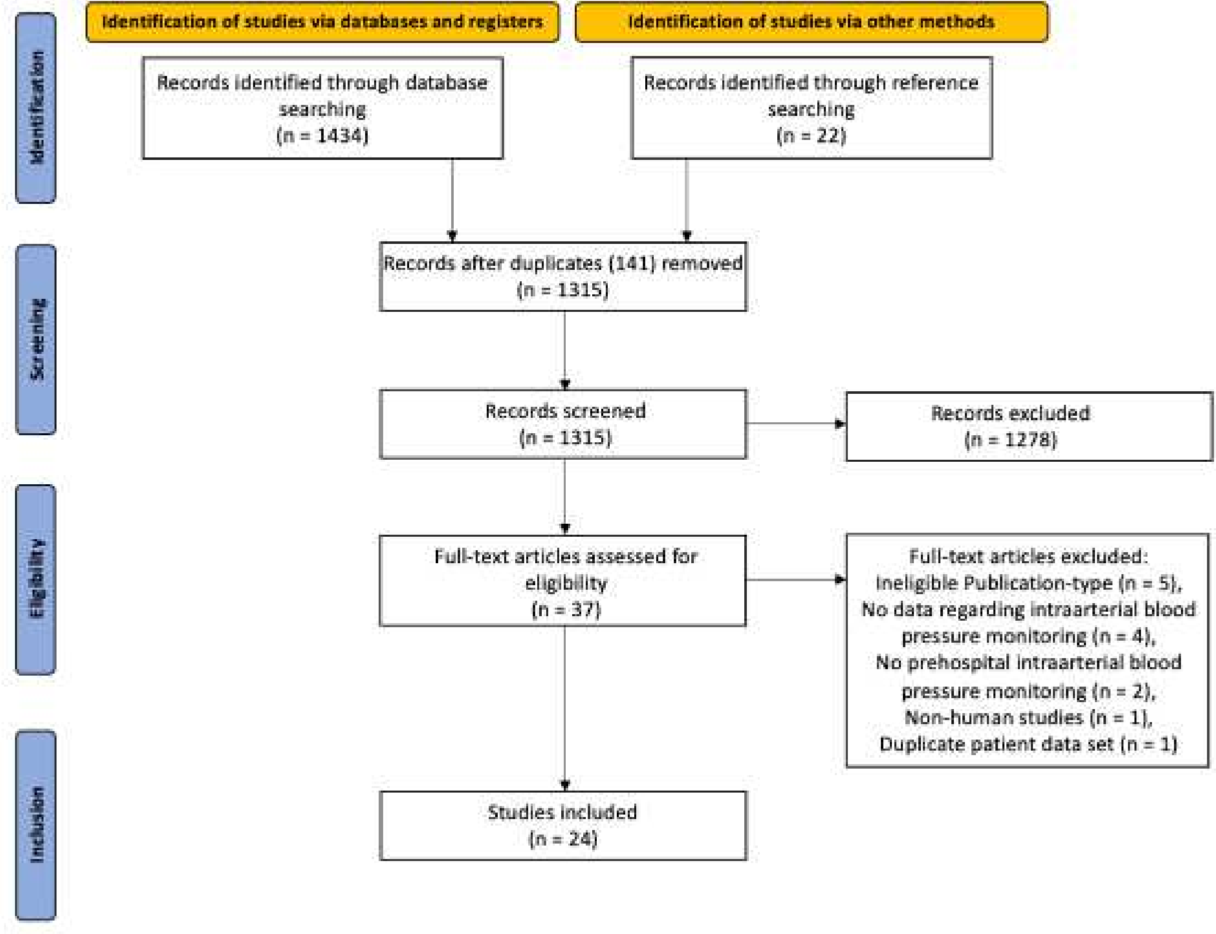
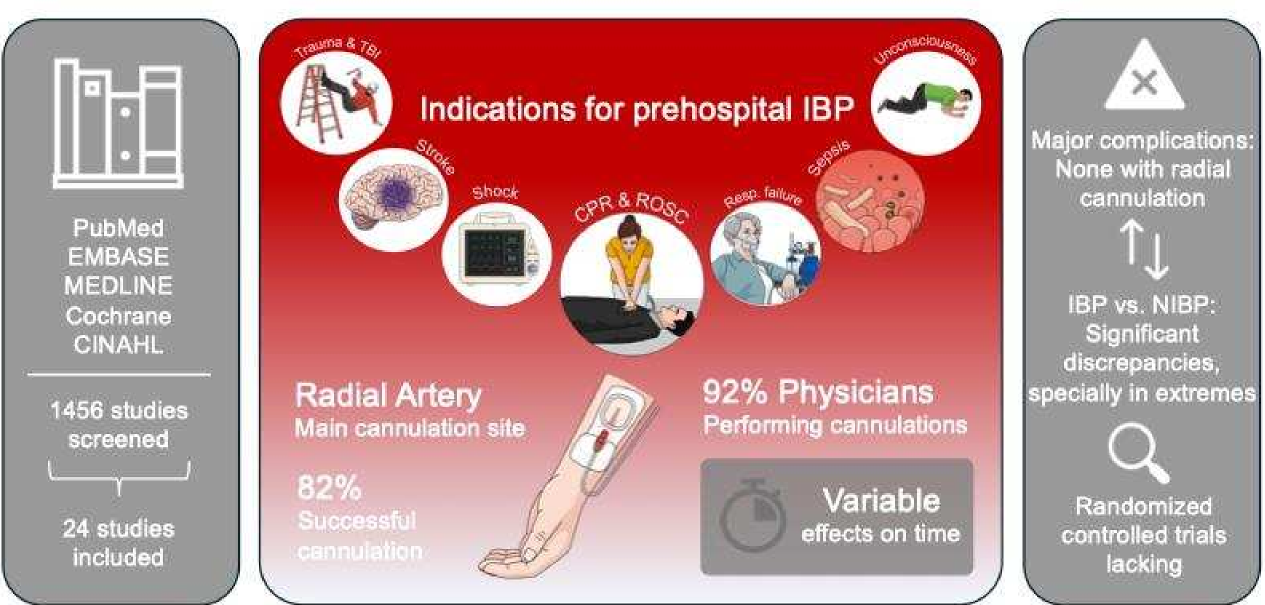


Figure 2 – Graphical summary of the scoping review.



[EXT] Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine: Decision on "Intraarterial blood pressure monitoring in prehospital emergency care: A scoping review"

Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine <do-not-reply@springernature.com>

Do 04.09.2025 14:49

An:Eichlseder, Michael <michael.eichlseder@medunigraz.at>;

Dear Dr EICHLSEDER,

Re: "Intraarterial blood pressure monitoring in prehospital emergency care: A scoping review"

We are delighted to let you know that the above submission, which you co-authored, has been accepted for publication in Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine.

Please contact the corresponding author if you would like further details on this decision, including any reviewer feedback.

Thank you for choosing Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine and we look forward to publishing your article.

Kind regards,

Editorial Assistant
Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine

Author's agreement

The following authors actively contributed to this research and by signature agreed to the use of their data in this thesis:

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