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Novel Tourniquet Application Techniques in Austere Combat Environments with Limited Medical Supplies and Prolonged Evacuation Times

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Abstract. The aim of the article is to determine the parameters of effective occlusion and sustained bleeding control in conditions of prolonged evacuation delays. The research methodology was based on a combination of comparative analysis, content analysis, and structural-functional modelling. It was found that the actual evacuation time in Poland, Ukraine, the United States of America, the United Kingdom, and Lithuania consistently exceeded doctrinal guidelines by 15–120 minutes, which was accompanied by an increase in mortality from 8–14 per cent when occlusion was achieved within the first two minutes to 34–51 per cent for delays exceeding five minutes. Detailed analysis revealed that increasing the time to achieve occlusion was associated with a progressive rise in the risk of fatal outcomes regardless of the type of the tourniquet used, and that duplicate occlusion was required in 23–41 per cent of cases, indicating limited durability of primary compression intervention in a dynamic tactical environment. The frequency of technical errors among untrained personnel was 3–5 times higher; in particular, tension errors and incorrect tourniquet positioning were directly associated with increased rates of recurrent bleeding and reduced effectiveness of haemostasis. Additionally, optimal limits of the occlusion pressure of 170–240 millimetres of mercury, a safe duration of occlusion maintenance of 120–180 minutes, and parameters for the use of partial reperfusion were determined, which minimised the ischaemic load and reduced the risk of rebleeding. An optimal equipment configuration was also developed, which included the number of tourniquets, redundant systems, recommended haemostatic materials, and pressure control mechanisms capable of ensuring compression stability during prolonged evacuation delays. The results obtained can be used by military medical units and tactical training instructors to improve bleeding control protocols and enhance the effectiveness of medical support in combat conditions.

Keywords: occlusive pressure, evacuation duration, ischaemic load, limb reperfusion, compression devices, tourniquet.

Naujos turniketo naudojimo technikos sudėtingomis kovos sąlygomis, kai medicinos priemonių yra nedaug, o evakuacija užtrunka ilgai

Santrauka. Šiame straipsnyje aprašomo tyrimo tikslas buvo nustatyti veiksmingos okliuzijos ir ilgalaikio kraujavimo sustabdymo parametrus esant ilgalaikei evakuacijai. Tyrimo metodika rėmėsi lyginamosios analizės, turinio analizės ir struktūrinio-funkcinio modeliavimo deriniu. Nustatyta, kad faktinis ilgalaikės evakuacijos laikas Lenkijoje, Ukrainoje, Jungtinėse Amerikos Valstijose, Jungtinėje Karalystėje ir Lietuvoje nuo-

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sekliai viršijo doktrinines gaires 15–120 minučių, o tai buvo susiję su mirtingumo padidėjimu nuo 8–14 procentų, kai okliuzija buvo pasiekta per pirmąsias dvi minutes, iki 34–51 procento, kai pavėluota daugiau kaip penkias minutes. Išsami analizė parodė, kad ilgesnis laikas, reikalingas kraujavimui sustabdyti, buvo susijęs su progresyviai didėjančia mirtinos baigties rizika, nepriklausomai nuo naudojamo kraujavimui stabdyti raiščio tipo, ir kad 23–41 procento atvejų reikėjo pakartotinai stabdyti kraujavimą, o tai rodo ribotą pirminės kompresinės intervencijos patvarumą dinamiškoje taktinėje aplinkoje. Neapmokyto personalo techninių klaidų dažnis buvo 3–5 kartus didesnis; visų pirma, įtempimo klaidos ir neteisingas raiščio kraujavimui stabdyti uždėjimas buvo tiesiogiai susiję su padidėjusiu pakartotinio kraujavimo dažniu ir sumažėjusiu hemostazės veiksmingumu. Be to, nustatytos optimalios okliuzijos slėgio ribos (170–240 milimetrų gyvsidabrio stulpelio), saugi okliuzijos palaikymo trukmė (120–180 minučių) ir dalinės reperfuzijos taikymo parametrai, kurie sumažino išeminę apkrovą ir pakartotinio kraujavimo riziką. Taip pat buvo sukurta optimali įrangos konfigūracija, apimanti raiščių kraujavimui stabdyti skaičių, rezervines sistemas, rekomenduojamas hemostazines medžiagas ir slėgio kontrolės mechanizmus, galinčius užtikrinti suspaudimo stabilumą ilgalaikių evakuacijų metu. Gauti rezultatai gali būti pravartūs kariniuose medicinos daliniuose ir taktinių pratybų instruktorių darbe, siekiant patobulinti kraujavimo kontrolės protokolus ir padidinti medicininės pagalbos veiksmingumą kovos sąlygomis.

Raktažodžiai: okliuzinis slėgis, kraujo išsiurbimo trukmė, išeminė apkrova, galūnių reperfuzija, suspaudimo prietaisai, turniketas.

Introduction

The need for the study is driven by the increasing gap between the actual time parameters of medical evacuation and the capability for timely control of massive bleeding in field conditions, which has resulted in prolonged tourniquet use and increased ischaemic load on tissues. In the practice of combat units, an extension of the transportation time is consistently recorded, highlighting the need to define quantitative limits of occlusive pressure, the duration of its safe application, and thresholds for the use of ischaemia-reduction techniques. The absence of unified standards complicates the standardisation of primary haemostatic intervention, increases the likelihood of technical errors, and reduces the predictability of occlusion outcomes in tactical conditions. The scientific determination of safe pressure ranges, occlusion time intervals, and criteria for transition to partial limb reperfusion protocols provides the basis for reducing the risk of recurrent bleeding and ischaemic injury, enabling the adaptation of occlusion protocols to realistic operational constraints.

Research by A. Jarrassier et al. [1] focused on the initial control of massive bleeding in combat environments and evaluated the effectiveness of various tactical approaches within a rapidly changing operational context. The patterns established by the authors demonstrated that an early tourniquet application and combined techniques significantly reduced the proportion of fatal outcomes in arterial injuries. It was shown that prolonged evacuation delays increased the risk of compromised occlusion stability, necessitating adapted protocols. The study by M. H. Remondelli et al. [2] evaluated the effectiveness of prehospital and *en route* bleeding-control measures in large-scale combat operations, establishing the critical role of the time required to achieve stable occlusion. Their results demonstrated that modern tourniquets retained functionality when applied rapidly, but lost effectiveness when delayed by more than several minutes, while promising pressure-modulation mechanisms required further standardisation.

In the study by I. S. Almalki [3], which focused on the clinical outcomes of tourniquet use in emergency settings, high occlusion performance was established under conditions of correct application. It was proven that the main factor in ineffective haemostasis remained technical errors by the operator, and that the stability of occlusion over prolonged periods had not yet received sufficient quantitative verification. W. Guse et al.'s [4] analysis reflected the role of tactical medicine in developing primary action protocols, and the conclusions confirmed the effectiveness of serial *Combat*

Application Tourniquet (CAT) devices when accurately positioned. M. Blaivas et al. [5] assessed the functioning of point-of-care procedures in resource-limited environments, establishing a dependency of occlusion stability on the ability to adjust tension; however, the limits of safe occlusion duration remained incompletely defined.

The study by S.-H. Tsai et al. [6] summarised the characteristics of combat injuries, enabling identification of the time intervals most strongly associated with fatal outcomes in massive bleeding. The authors found a consistent relationship between delayed occlusion and deterioration of the clinical prognosis, while the issue of combined use of haemostatic materials did not receive comprehensive quantitative evaluation. The study by K. Puchała et al. [7], aimed at assessing evacuation capacities by air, confirmed that prolonged transportation intervals placed a significant load on compression devices required to maintain pressure stability. The work of J. Krygier et al. [8] investigated an intelligent evacuation-support system, the results of which demonstrated potential reduction in technical errors through automated monitoring. The authors emphasised that integrating compression-pressure monitoring into evacuation technology could improve occlusion stability. At the same time, the system did not provide complete control over the risk of recurrent bleeding under dynamic movement conditions, thus requiring further development.

The study by T. Miłowski et al. [9] made it possible to trace the evolution of emergency care and identify the limitations of traditional approaches to tourniquet application. It was found that the absence of clear standards for the long-term use of compression devices in combat conditions increased the likelihood of ischaemic complications. The analysis by F. Butler et al. [10] demonstrated a clear distinction between the effectiveness of serial tourniquets and improvised devices, which enabled a better understanding of the optimal choice of technical means in tactical settings. The work also confirmed the importance of rapid occlusion but did not provide quantitative limits necessary for determining the duration of safe use.

In the study by L. L. Lawry et al. [11], the quality of prehospital care was assessed under conditions of limited availability of medical devices, enabling the identification of a significant contribution of time delays to lethal outcomes. It was emphasised that the effectiveness of occlusion was determined by the promptness of initial intervention and the ability to maintain subsequent pressure control. In the work of W. Kamysz and P. Kleczkowska [12], attention was directed to the properties of biopolymer haemostatic materials, and the results demonstrated high efficiency of such agents in complex wounds with tissue defects. At the same time, the potential for combining these materials with tourniquet technologies was not examined in detail.

The synthesis of the results showed that scientific studies covered a wide spectrum of aspects of massive bleeding control, including analyses of tourniquet technical characteristics, the influence of tactical conditions, evacuation capabilities, the use of biomaterials, and automated monitoring systems. Socioclinical factors, operational constraints, wound characteristics, and diverse care-organisation models were addressed. However, a comprehensive quantitative justification of prolonged occlusion parameters, ischaemic safety limits, and partial reperfusion algorithms under delayed evacuation conditions remained absent. Questions regarding the integration of pressure-sensor control systems, the optimal number of tourniquets for redundancy, and the interaction between compression devices and haemostatic materials were insufficiently explored. The identified gaps indicated the need to establish a standardised model of long-term haemostatic control capable of functioning across variable tactical scenarios.

The aim of this study is to substantiate the parameters of an applied model for a modernised tourniquet-use protocol for Polish military units under prolonged evacuation delays, by using comparative evidence from Poland, Ukraine, the United States, the United Kingdom, and Lithuania. To achieve this aim, the following tasks were defined: to establish the relationships between the time re-

quired to achieve occlusion, evacuation duration, and the effectiveness of haemostatic interventions; to assess the effectiveness of innovative techniques and technical solutions for controlling massive bleeding in the context of long-term tourniquet use; to develop a structured model of the occlusion protocol, including regulatory pressure parameters, partial reperfusion algorithms, and equipment configuration requirements.

The novelty of the proposed model lies not in replacing the currently existing TCCC recommendations, but in integrating prolonged-evacuation parameters, comparative evacuation-delay data, occlusion-pressure and duration thresholds, partial reperfusion decision points, equipment redundancy, pressure monitoring, and personnel-training requirements into a single operational framework adapted to Polish military units.

Materials and Methods

The study was applied and analytical in nature and was conducted as a multicomponent analysis of empirical, clinical, and field data covering the period of the years 2021–2025. The processing of quantitative parameters was performed by summarising absolute and relative indicators (evacuation time, mortality rate, frequency of recurrent bleeding, number of tourniquets applied), followed by their aggregation and comparative evaluation across country samples. The selected time period ensured the recording of current trends in massive bleeding control and allowed monitoring of the transformation of tourniquet application approaches in the modern tactical environment. Poland, Ukraine, and Lithuania were included in the study because Poland demonstrated active implementation of updated bleeding-control protocols, Ukraine provided the largest empirical dataset from high-intensity combat conditions, and Lithuania represented a model of medical support for rapid response units operating under resource limitations. The sample also included the United Kingdom, which has an established system for standardising military medical interventions, and the United States, which provides benchmark training parameters and tourniquet-use standards, enabling a comparison across different levels of tactical care. Poland was therefore treated as one of the five comparative cases and as the primary implementation context for the applied model, rather than as the sole empirical study setting.

The analysis incorporated the publication NATO Standard AMedP-7.1 [13] and NATO Standard AJP-4.10 [14], the content of which enabled comparative analysis of time to achieve occlusion, duration of safe compression retention, frequency of recurrent bleeding, and alignment of actual evacuation intervals with doctrinal recommendations. Materials from the NATO Centre of Excellence for Military Medicine [15] were also included, as they contain structured information regarding medical-support models and the distribution of functions across levels of care. The Joint Trauma System [16] clinical guidelines provided quantitative parameters for time to achieve complete mechanical occlusion, mortality rate depending on the tourniquet interval, rebleeding rate, and the average need for duplicate occlusion, which enabled a comparison between tourniquet types (Combat Application Tourniquet, Special Operations Forces Tactical Tourniquet, and improvised devices). Documents from the Ministry of Defence [17] and the Ministry of National Defence of the Republic of Lithuania [18] reports were used to compare the minimum, maximum, and median evacuation times, as well as the discrepancy between the median actual values and doctrinal norms for time to occlusion.

Analytical reviews – including materials from the Draft of the Military Medical Doctrine of Ukraine [19], field evacuation reports [20], and issues of the International Committee of Military Medicine [21] – formed the basis for content analysis. This allowed the identification of recurring patterns in the evacuation duration, workload intensity on medical units, and the effectiveness of primary haemostatic intervention, where prehospital haemostasis effectiveness was assessed by

achieving complete mechanical occlusion, absence of rebleeding, and reduced mortality within the first five minutes. To organise and unify the collected time parameters, a systematisation method was applied, involving grouping minimum, maximum, and median evacuation times and determining their deviation from *Tactical Combat Casualty Care* (TCCC) doctrinal standards. In addition, clinical studies on tourniquet application were reviewed, including research on the correctness of application techniques in combat conditions [22], a review of damage-control resuscitation approaches [23], and Emergency Medical Service materials [24] summarising prehospital haemostasis effectiveness. Content analysis of these sources enabled structured extraction of quantitative indicators – time to occlusion, occlusive pressure, duration of occlusion, frequency of technical errors, and proportion of duplicate occlusions – necessary for subsequent modelling.

U.S. Army Medical Department materials, including the Casualty Transport and Evacuation [25] and Military Medical Evacuation [26] sections, were used to implement the structural-functional modelling approach, as they provided information on physiological changes during prolonged compression and parameters of safe occlusion. The same approaches were applied to Deployed Medicine training modules, including the Care under fire/Threat [27] and in Tactical Combat Casualty Care the "TCCC Guidelines 2024" [28], which formalised occlusive pressure limits, safe maintenance intervals, and the logic of the partial limb reperfusion protocol algorithm, as well as tourniquet pressure-cycling techniques, combined "tourniquet+deep haemostatic packing" protocols, and sensor-based compression-pressure monitoring systems. Within the framework of structural-functional modelling, pressure-feedback devices were also evaluated as sensor systems for automated compression-pressure control, assessed in terms of their ability to maintain stable occlusion and reduce the risk of recurrent bleeding during prolonged evacuation delays. The use of this method enabled the formation of a structured model describing the interaction between the mechanical characteristics of tourniquets, the physiological parameters of tissue perfusion, and operational constraints.

As part of the content analysis, additional reviews on the organisation of medical evacuation were examined, including studies of the European Civil Protection and Humanitarian Aid Operations [29], materials devoted to the characteristics of evacuation in combat conditions [30], publications describing the modernisation of evacuation capabilities [31], and resources on tactical medicine [32]. These sources enabled the identification of key logistical constraints, structural differences between evacuation systems, and parameters influencing the practical implementation of compression protocols. The assessment of compatibility of innovative techniques was conducted with consideration of Poland's logistical capabilities as the primary platform for implementing the research results, owing to its integration of military medical support with the North Atlantic Treaty Organization (NATO) standards, its multi-level deployed evacuation system, and the representativeness of Polish units for scaling up the findings to other Alliance countries.

Compatibility with Poland's logistical capabilities was classified qualitatively according to the availability of the required equipment within existing unit resources, the need for additional technical infrastructure or specialised maintenance, and additional personnel-training requirements. High compatibility indicated implementation with limited additional logistical requirements; average compatibility indicated a need for additional equipment or training that remained operationally feasible; low compatibility indicated dependence on specialised equipment, maintenance, or infrastructure that is not routinely available to field units.

Interpretation of the obtained results was performed by combining descriptive statistical analysis with structural-logical interpretation, which enabled the assessment of both statistically confirmed patterns and structural factors influencing the effectiveness of tourniquet use in tactical settings. The resulting parameters were evaluated in terms of their operational suitability, providing the basis for the subsequent development of an applied model of a modernised occlusion protocol.

Results

Operational conditions determining the need to improve technologies for massive bleeding control

Analysis of the time parameters of medical evacuation makes it possible to delineate the real operational limitations that influence the effectiveness of the primary control of massive bleeding in combat conditions. The synthesis of data from Poland, Ukraine, the USA, the UK, and Lithuania revealed substantial discrepancies between the doctrinal guidelines and actual evacuation intervals. Identification of these discrepancies is of critical importance, as they directly affect the ability of standard tourniquets to maintain stable occlusion under conditions of delayed evacuation and determine the need to adapt technological solutions.

To systematise the identified temporal differences, comparative values of minimum, maximum, and median evacuation times are presented, together with the gap between the median values and TCCC regulatory requirements. A structured representation of these indicators enables assessment of the degree of conformity between the actual evacuation processes and doctrinal assumptions, and facilitates identification of systemic deviations characteristic of different countries. These parameters are summarised and presented in Table 1.

Table 1. Comparison of actual medical evacuation time indicators and TCCC doctrinal parameters

Country	Minimum evacuation time (min)	Maximum evacuation time (min)	Median actual time (min)	TCCC doctrinal guide (min)	Gap between median and standard (min)
Poland	70	210	145	≤60	+85
Ukraine	90	300	180	≤60	+120
USA	45	120	75	≤60	+15
United Kingdom	55	160	95	≤60	+35
Lithuania	60	180	120	≤60	+60

Note: median is the central value of a series of observations; a 'gap' in the table indicates the median evacuation time exceeding the TCCC guideline.
Source: compiled by the author based on NATO Standard AMedP-7.1. Medical management of CBRN casualties [13], NATO Centre of Excellence for Military Medicine [15], Ministry of Defence [17], Ministry of National Defence of the Republic of Lithuania [18], Draft of the Military Medical Doctrine of Ukraine [19], S. Olsen [20], International Committee of Military Medicine [21], N. J. Scallan et al. [22], M. Latos et al. [24], C. A. B. Mclaren et al. [26], European Civil Protection and Humanitarian Aid Operations [29], World Health Organization [30], MEDEVAC – keeping the wounded alive [31].

Analysis of the data presented in Table 1 shows a systematic excess of the actual medical evacuation time over the doctrinal TCCC standards in all studied countries, thus confirming a persistent gap between the regulatory assumptions and the real operational conditions. The largest deviations were recorded in the units in Ukraine and Poland, where the median transportation time exceeded the TCCC guideline by 85–120 minutes. Such an excess directly affects the risk of ischaemic complications during the prolonged tourniquet use, as occlusive pressure must be maintained for significantly longer periods than anticipated in the baseline protocols. In the USA, the indicators were closest to the normative values, yet, even in this case, the median time exceeded the doctrinal guideline, indicating that the established limits remain unattainable in a considerable proportion of real scenarios. Data from the UK and Lithuania demonstrated intermediate intervals but also failed to meet the TCCC requirements [28], thereby indicating the universal nature of the trend and the need to adapt bleeding-control technologies to conditions of a delayed evacuation.

The increase in the incidence of major vascular injuries correlates with the evolving character of modern warfare, which is marked by a combination of gunshot wounds, blast injuries, and fragmentary trauma. These factors generate a substantial proportion of cases requiring prolonged tourniquet application, exceeding the basic recommendations of TCCC [28]. Under such conditions, the compression device must ensure not only rapid achievement of primary occlusion but also the stability of fixation during casualty movement, transportation, and continued exposure to a dynamic tactical environment. The analysed data confirmed that the risk of incomplete occlusion increases with a longer tourniquet application due to gradual tension loss characteristic of strap-based devices.

Tactical factors significantly influence the quality of primary haemostatic intervention, as intense fire engagement, manoeuvring under fire, and a limited access to cover reduce the likelihood of precise tourniquet placement. Pooled data from five countries demonstrated a rise in the frequency of application errors in highly dynamic combat situations, and particularly the insufficient strap tension and incorrect positioning. During prolonged transport, an additional negative factor is micromovement, which gradually reduces the occlusive pressure and increases the likelihood of recurrent bleeding [33; 34]. The combination of these conditions creates the need for regular monitoring of the tourniquet performance or the implementation of technologies capable of automatically maintaining the required pressure level.

The duration of the stabilisation phase is a critical parameter that determines the need for periodic monitoring of the occlusive pressure in cases where the injured person remains at the site of injury or within a temporary care area for more than two hours [35; 36]. The study data showed that tourniquets with fixed-tension mechanisms demonstrate a gradual decline in effectiveness due to anatomical changes in tissues, oedema formation, and micro displacements that occur during movement or changes in the body position. These physiological processes lead to a reduction in the compression force, which may go unnoticed in tactical environments owing to limited opportunities for repeated verification of fixation. In the absence of automated pressure-control systems, maintaining stable occlusion under such conditions becomes significantly more challenging.

To assess the impact of personnel training on the quality of primary haemostatic intervention, the frequency of errors during tourniquet application in combat conditions was analysed. Aggregated data from units in Poland, Ukraine, the USA, the United Kingdom, and Lithuania showed a clear difference between the performance of trained military personnel and individuals who had not undergone standardised training programmes. Table 2 presents the key types of technical violations that most significantly affect the quality of occlusion and the stability of compression during casualty transport, enabling the identification of structural needs for improving training.

Table 2. Frequency of errors in applying tourniquets among trained and untrained personnel (Aggregated data from the analysed countries)

Error type	Trained personnel (%)	Untrained personnel (%)
Insufficient belt tension	6	27
Incorrect tourniquet placement	4	22
Loss of fixation during movement or transportation	3	19
Need for reapplication	2	17

Note: trained personnel are military personnel who have completed formal TCCC training or other certified bleeding control programs; untrained personnel are individuals without standardised training. Percentages reflect the proportion of each type of error in the total number of tourniquet applications in the pooled sample.
Source: compiled by the author based on Joint Trauma System [16], Draft of the Military Medical Doctrine of Ukraine [19], D. O. Samofalov et al. [23], M. Latos et al. [24], C. U. Kharod et al. [25], C. A. B. Mclaren et al. [26], World Health Organization [30], MEDEVAC – keeping the wounded alive [31].

The analysis of the data presented in Table 2 demonstrates a clear dependence of the tourniquet-application quality on the level of personnel training. In groups without standardised training programmes, a significantly higher frequency of critical errors was observed, particularly insufficient strap tension and incorrect tourniquet positioning, which resulted in incomplete occlusion and prolonged bleeding. Trained personnel exhibited lower rates of technical violations, thus confirming the effectiveness of formalised instruction and regular practical modules. These findings emphasise that systematic enhancement of training programmes is an essential requirement for ensuring stable quality of primary haemostatic intervention in combat conditions.

The generalisation of operational factors identified within the analysis demonstrated structural limitations that reduce the effectiveness of standard tourniquet application in Polish units. The aggregated dataset indicates the necessity of adapting the technological parameters of compression devices and updating haemostatic algorithms in response to conditions in which the evacuation duration and resource constraints consistently exceed the doctrinal guidelines. A detailed understanding of these constraints forms the basis for assessing the effectiveness of existing tourniquet techniques and identifying areas for further optimisation in the context of real tactical requirements. These findings provide the operational component of the first research task by establishing the evacuation constraints within which the relationship between the time to occlusion and haemostatic effectiveness was subsequently assessed.

Empirical assessment of the effectiveness of tourniquet application based on generalised clinical and field data

Establishing a relationship between the time required to achieve occlusion and the mortality rate is an essential condition for quantitatively assessing the effectiveness of tourniquet application in combat environments. Generalised clinical data obtained from the analysis of materials from Poland, Ukraine, the USA, the United Kingdom and Lithuania demonstrated a consistent relationship between the time interval from injury to the establishment of stable mechanical occlusion and the probability of fatal outcomes. The identified patterns showed that the effectiveness of tourniquet application is determined not only by the design characteristics of the compression device but also by the duration of ongoing active bleeding. This approach forms the foundation for further assessment of the clinical limits of effectiveness of different tourniquet models in situations where primary intervention is delayed.

To systematise these relationships, comparative mortality rates are presented across three-time intervals for achieving occlusion, and the differences between the results typical of CAT, SOF-T and improvised devices are illustrated. Structuring these data provides an opportunity to trace the distinctions between the mechanical properties of different types of tourniquets and to determine the extent to which the time factor influences survival prognosis. The inclusion of three-time intervals enables quantitative delineation of critical thresholds at which delays in occlusion lead to a sharp rise in the proportion of fatal outcomes. These indicators are summarised and presented in Table 3.

Table 3. Mortality rates depending on the time interval to achieve occlusion and the type of tourniquet (aggregated data)

Time interval to achieve occlusion	Mortality when using CAT (%)	Mortality when using SOF-T (%)	Mortality when using improvised tourniquets (%)
0-2 minutes	8	9	14
2-5 minutes	18	20	29
More than 5 minutes	34	37	51

Note: The term 'mortality' in the table refers to the percentage of fatal cases among the wounded with massive bleeding of the extremities in the corresponding group. The time interval for achieving occlusion is determined from the moment of injury to the moment of establishing stable mechanical occlusion.
Source: compiled by the author based on Joint Trauma System [16], S. Olsen [20], D. O. Samofalov et al. [23], M. Latos et al. [24], C. U. Kharod et al. [25], Deployed Medicine [27], World Health Organization [30].

Analysis of the data presented in Table 3 shows a clear dependence of the mortality rate on the time interval required to achieve occlusion and on the type of the tourniquet used. The lowest mortality rates were recorded in cases where stable occlusion was achieved within the first 0–2 minutes, thus confirming the critical importance of prompt primary haemostatic intervention. Extending this interval to 2–5 minutes was accompanied by a substantial increase in the proportion of fatal cases across all types of compression devices, thus reflecting the rapid loss of a favourable clinical prognosis after the first minutes of uncontrolled bleeding. A delay of more than five minutes demonstrated the highest mortality rates, especially in the improvised-tourniquet group, indicating insufficient mechanical reliability and limited suitability of improvised devices in situations characterised by high blood loss dynamics. A comparison between CAT and SOF-T models showed similar performance, which may be related to their common use of a standardised windlass-based tightening mechanism that provides controlled circumferential compression and secure fixation. In contrast, improvised devices lack comparable standardisation and reproducible tension control, which may contribute to their poorer performance across the analysed time intervals.

Within the framework of assessing the structural parameters of haemostatic effectiveness, an important task is to determine the average number of tourniquets applied per casualty, as well as the frequency of cases requiring duplicate occlusion. These indicators provide insight into the real logistic burden placed on compression-device supply systems and allow estimation of the optimal number of devices necessary to ensure stable mechanical occlusion in situations involving high-intensity injuries. Aggregated data from Poland, Ukraine, the USA, the UK, and Lithuania make it possible to quantitatively compare different tactical tourniquet-application models and evaluate the degree of correspondence between injury patterns and the required volume of resources. Presentation of these indicators in the structured format of Table 4 enables a comprehensive assessment of the frequency of duplicate occlusion and the average need for compression devices in diverse operational scenarios.

Table 4. Average number of tourniquets per casualty and proportion of cases with duplicate occlusion (aggregated data from five countries)

Country	Average number of tourniquets per injured person (units)	Proportion of cases requiring duplicate occlusion (%)
Poland	1.4	34
Ukraine	1.6	41
USA	1.2	23
United Kingdom	1.3	28
Lithuania	1.3	31

Note: the indicator 'average number of tourniquets' reflects the average number of compression devices applied per casualty within a specific sample. 'Duplicate occlusion' indicates cases where the primary tourniquet was insufficient to achieve complete occlusion, requiring the application of a second device.
Source: compiled by the author based on Joint Trauma System [16], D. O. Samofalov et al. [23], M. Latos et al. [24], C. U. Kharod et al. [25], Deployed Medicine [27], World Health Organization [30], MEDEVAC – keeping the wounded alive [31].

Analysis of the data presented in Table 4 shows significant variability in the average number of tourniquets applied per wounded person, which was directly related to the nature of injuries sustained and the level of availability of compression devices within their units. The highest rates were recorded in the Ukrainian sample, where the proportion of cases requiring duplicate occlusion reached 41%, which may be associated with the high frequency of combined injuries and instability of primary occlusion under complex combat conditions. In Poland and Lithuania, the values were

intermediate, indicating the need to maintain a reserve of tourniquets to ensure stable bleeding control. The lowest rates were observed in the USA, which likely reflected a higher degree of standardisation in the use of serial tourniquet models and a more consistent quality of primary occlusion. The overall findings confirmed that duplicate occlusion is a common phenomenon and must be accounted for in logistical planning and in the development of tactical protocols.

The generalisation of these indicators formed a set of quantitative benchmarks enabling assessment of the effectiveness of various technical and procedural solutions for controlling massive bleeding. A comparison of data from the five countries demonstrated that occlusion effectiveness is determined by a combination of tourniquet mechanical properties, the level of personnel training, and operational parameters associated with the evacuation process. The establishment of such a benchmark system provides a basis for selecting and adapting innovative technologies to Polish tactical protocols, while taking into account realistic mobility constraints, resource availability, and typical evacuation time intervals. The findings define the direction for further analytical work relating to the assessment of opportunities for improving compression solutions under conditions of delayed transportation of the wounded. Together with the evacuation-time analysis conducted in Section 3.1, these results address the first research task by quantifying the relationship between the time to occlusion and haemostatic effectiveness under prolonged evacuation conditions.

Study of the effectiveness of innovative methods of ensuring haemostasis under conditions of delayed evacuation

Evaluation of the effectiveness of the partial reperfusion technique is a key element in assessing the potential to reduce ischaemic load during prolonged tourniquet use in a tactical environment. Dividing the process into a relaxation phase and a reocclusion phase makes it possible to determine the safety limits and the parameters that ensure stable haemostasis while preserving the minimum necessary level of tissue perfusion [37]. The parameters derived through analysis of the secondary sources and structural-functional modelling reflected systemic patterns that allowed assessment of the potential suitability of partial reperfusion in scenarios where evacuation exceeds 180 minutes.

To systematise the identified dependencies, generalised parameters of three partial reperfusion modes are presented, reflecting the duration of the relaxation and reocclusion phases, the level of restored compression pressure, and the proportion of recurrent bleeding. The inclusion of these indicators within a comparative framework enables comprehensive evaluation of the safety and effectiveness of different compression modes, which is essential for determining the application limits of this technique when transportation of the wounded is delayed. Comparison of the generalised characteristics presented in Table 5 allows tracing how variation in the phase duration influences the ischaemic load and haemostasis stability in a dynamic tactical environment.

Table 5. Partial limb reperfusion protocol parameters

Protocol option	Duration of pressure relief phase (min)	Duration of the reocclusion phase (min)	Minimum required pressure after re-compression (mmHg)	Predicted level of tissue ischemia*	Rebleeding rate (%)
Protocol A	2-3	20-25	180-200	Low	4-6
Protocol B	3-4	15-20	180-210	Moderate	7-10
Protocol C	4-5	10-15	190-220	Increased	11-15

Note: partial limb reperfusion protocol is a technique for partial limb reperfusion that involves a short phase of controlled pressure relief followed by reocclusion. The predicted level of ischemia is determined based on the total duration of compression, relief intervals, and the amount of re-pressure.
Source: compiled by the author based on Joint Trauma System [16], S. Olsen [20], D. O. Samofalov et al. [23], M. Latos et al. [24], C. U. Kharod et al. [25], C. A. B. Mclaren et al. [26], Deployed Medicine [27].

The parameters presented in Table 5 were derived from the secondary evidence and structural-functional modelling used in this study; the predicted ischaemic-risk categories are modelled estimates and were not obtained from prospective clinical testing. Analysis of the data presented in Table 5 demonstrated a clear relationship between the duration of the pressure-relief phase and the predicted level of ischaemic load. Short relief intervals combined with longer reocclusion phases resulted in a lower frequency of recurrent bleeding and provided an optimal balance between maintaining stable haemostasis and preventing ischaemic injury. Extending the duration of the relief phase was accompanied by an increase in the predicted ischaemic effect, which necessitated more precise control of the restored compression pressure. The highest rebleeding rates were observed in modes with the longest relief intervals, limiting their suitability in situations involving uncontrolled massive bleeding. The generalised dataset highlighted the need to optimise the balance between ischaemia prevention and stable occlusion during prolonged transportation of the wounded.

The combined "tourniquet+deep haemostatic packing" protocol is considered a method of enhancing bleeding-control effectiveness in injuries where achieving complete mechanical occlusion is difficult. The summarised data showed that the use of haemostatic materials such as *Combat Gauze* or *ChitoGauze* in conjunction with a tourniquet reduced the frequency of rebleeding after the removal or partial relaxation of compression. The effectiveness of the combined approach depends on the depth of packing, the structure of the wound tract, and the mechanical characteristics of the tourniquet, which must ensure uniform pressure distribution along the proximal segment of the limb [38; 39]. The findings confirmed the appropriateness of the combined technique in cases where anatomical features or injury patterns diminish the effectiveness of standard occlusion.

Sensor-based pressure-control systems, presented as pressure-feedback devices, were evaluated in terms of their ability to provide automated monitoring of compression during evacuation delays exceeding 180 minutes. The use of such systems enables detection of pressure fluctuations caused by movement or tissue swelling and allows real-time adjustment of tension. The generalised results demonstrated a reduction in technical errors associated with gradual loss of compression force, which is critical in tactical environments with high levels of physical activity. The presented data illustrate the potential of sensor systems to enhance occlusion stability and compensate for the technical limitations of mechanical devices during prolonged transportation.

Evaluation of innovative techniques for controlling massive bleeding requires comparative analysis of their compression potential, acceptable duration of safe use, and ability to maintain stable occlusion under conditions of prolonged evacuation delays [40]. The comparative secondary data from Poland, Ukraine, the USA, the UK, and Lithuania made it possible to identify parameters characterising the functional suitability of each technology, and particularly the risk of recurrent bleeding and compliance with the logistical capabilities of field units. The presented indicators provide an informative basis for the development of technological and procedural solutions aimed at optimising the bleeding control in environments with limited opportunities for rapid medical evacuation and are summarised in Table 6.

Analysis of the data presented in Table 6 revealed significant differences between technologies in their ability to provide long-term and stable occlusion under conditions of delayed evacuation. The longest duration of safe occlusion was demonstrated by pressure-feedback devices; however, their compatibility with the logistical capabilities of Polish field units remains limited due to increased requirements for technical equipment and the need for specialised maintenance. The combined "tourniquet+deep packing" protocol and mechanically adjustable tension tourniquets were characterised by stable occlusion performance and a high level of practical applicability, defining them as the most balanced solutions for widespread use in tactical environments. Partial reperfusion and cyclic compression techniques demonstrated an acceptable balance between the risk of recurrent

bleeding and control of the ischaemic load, thus highlighting their potential suitability for scenarios involving prolonged evacuation intervals. The obtained results provide quantitative guidance necessary for determining the optimal strategies for integrating these technologies into tactical protocols while accounting for realistic operational constraints.

Table 6. Comparative parameters of innovative haemostasis methods in conditions of prolonged evacuation

Method	Permissible duration of safe occlusion over 3 hours (min)	Mean occlusive pressure (mmHg)	Rebleeding rate (%)	Compatibility with Poland's logistical capabilities
Partial limb reperfusion protocol	180-240	170-200	4-10	Average
Tourniquet pressure cycling	200-260	160-190	5-12	High
Combined protocol "tourniquet+deep packing"	150-210	180-220	3-7	High
Pressure feedback devices	240-300	150-180	2-6	Low
Mechanical adjustable tension harnesses	210-270	180-210	4-8	High

Note: Pressure feedback devices – sensor systems for automated compression pressure control; partial limb reperfusion protocol – partial limb reperfusion; the 'compatibility' indicator is presented as an integral assessment taking into account the existing infrastructure, equipment availability of units, and requirements for personnel training.
Source: compiled by the author based on NATO Standard AMedP-7.1 [13], NATO Centre of Excellence for Military Medicine [15], Joint Trauma System [16], S. Olsen [20], International Committee of Military Medicine [21], N. J. Scallan et al. [22], D. O. Samofalov et al. [23], M. Latos et al. [24], C. U. Kharod et al. [25], C. A. B. Mclaren et al. [26], Deployed Medicine [27], Tactical Combat Casualty Care [28], European Civil Protection and Humanitarian Aid Operations [29], World Health Organization [30], MEDEVAC – keeping the wounded alive [31].

The systematised presentation of the characteristics of innovative technologies formed a structural basis for further development of protocols capable of ensuring predictable effectiveness of haemostatic interventions in complex tactical conditions. Generalisation of the data on compression mechanisms, combined techniques, and pressure-monitoring systems enables progression towards modelling algorithms for tourniquet application that are aligned with realistic temporal and resource parameters of the operational environment. This analytical framework establishes a logical foundation for further determination of parameters required to adapt technologies to field conditions and creates prerequisites for the development of practical solutions capable of ensuring stable control of massive bleeding in settings with prolonged evacuation delays. These findings address the second research task by comparing innovative haemostatic techniques and technical solutions in terms of the occlusion duration, pressure, rebleeding risk, and logistical applicability.

Formation of an applied model for the modernisation of tourniquet application protocols in Polish military units

Determination of normative occlusion parameters represents a key stage in the development of a modernised model for tourniquet application in field units operating under conditions of prolonged evacuation delays. Generalisation of comparative secondary data from Poland, Ukraine, the USA, the United Kingdom, and Lithuania, together with structural-functional modelling, yielded ranges of compression pressure and occlusion duration used in the proposed model to balance the haemostatic effectiveness and ischaemic risk. These parameters were used to define the limits within which the compressive effect remains safe during extended time intervals characteristic of delayed evacuation. Alignment of these limits with real operational capabilities provides a basis for adapting tacti-

cal protocols to scenarios in which occlusion must be maintained for substantially longer periods than those prescribed by doctrinal guidance.

For structured presentation of the key regulatory values, comparative indicators of the minimum and maximum occlusive pressure, permissible safe occlusion duration, the expected level of the ischaemic load, and thresholds for transition to a partial limb reperfusion protocol are presented. This format of generalisation enables direct integration of quantitative guidelines into the modernised protocol model and supports the formulation of regulated decisions regarding pressure control during stabilisation phases. The presented values form the basis for further adaptation of recommendations according to the operational context and resource capabilities of units functioning in environments with prolonged evacuation delays. These parameters are summarised and presented in Table 7.

Table 7. Recommended standard occlusion parameters for long evacuation delay conditions

Parameter	Recommended value	Operational purpose
Minimum occlusive pressure (mmHg)	170-190	Ensuring complete mechanical arrest of arterial bleeding in most anatomical segments of the limb
Maximum occlusive pressure (mmHg)	220-240	Limiting compression load to reduce the risk of ischemic injury during prolonged transportation
Allowable duration of occlusion without reperfusion (min)	120-180	A guideline for maintaining occlusion in delayed evacuation situations with minimal risk of critical ischemia
Expected level of ischemia (integrated assessment)	Moderate	Characteristics of the total tissue load provided that the pressure is maintained within the regulatory limits
Reperfusion decision threshold (min)	150-180	Interval after which it is appropriate to consider the use of a partial limb reperfusion protocol to reduce ischemic stress

Note: partial limb reperfusion protocol is a partial reperfusion technology that involves a short-term controlled reduction in pressure followed by reocclusion; 'integrated assessment of ischemia' characterises the total tissue load generated by the magnitude of pressure and the duration of occlusion.
Source: compiled by the author based on S. Olsen [20], M. Latos et al. [24], C. U. Kharod et al. [25], C. A. B. Mclaren et al. [26], Deployed Medicine [27], Tactical Combat Casualty Care [28], European Civil Protection and Humanitarian Aid Operations [29], World Health Organization [30], MEDEVAC – keeping the wounded alive [31].

The values presented in Table 7 represent model-based recommendations derived from secondary evidence rather than prospectively validated clinical thresholds. Analysis of the data presented in Table 7 demonstrated the presence of a clearly defined range of occlusive pressure that provides a balanced relationship between haemostatic effectiveness and a controlled level of ischaemic load. The minimum pressure values defined the threshold necessary to achieve complete mechanical occlusion of most major vessels, which is critical in situations of massive bleeding. At the same time, the upper limit of occlusive pressure constrained the compressive load, making it possible to reduce the risk of developing severe ischaemic complications during prolonged evacuation delays. The permissible duration of occlusion established a guideline within which tissue condition remained relatively stable, allowing haemostatic effectiveness to be maintained during transportation. The threshold for transition to reperfusion formed the structural basis for applying ischaemia-reduction techniques during prolonged stabilisation, providing algorithmic logic for clinical decision-making. The integration of these parameters created a comprehensive regulatory framework suitable for inclusion in a modernised Polish haemostatic care protocol.

Optimisation of equipment configuration to ensure stable occlusion under conditions of prolonged evacuation delays requires identification of the minimum yet sufficient set of tools capable

of maintaining haemostatic effectiveness regardless of tactical dynamics. Generalisation of the field data from Poland, Ukraine, the USA, the United Kingdom, and Lithuania demonstrated a strong dependence of tourniquet effectiveness on the availability of redundant compression devices that compensate for gradual tension loss or mechanical deformation of straps during movement and transport. The presented parameters form the basis for standardising equipment in accordance with the real operational requirements of units operating in environments characterised by extended evacuation intervals. These characteristics are summarised and presented in Table 8.

Table 8. Optimal equipment configuration to ensure stable occlusion during prolonged evacuation delays

Equipment component	Recommended indicator	Operational justification
Number of tourniquets per serviceman	2-3 serial harnesses (CAT, SOF-T, mechanical adjustable tension harnesses)	Providing the possibility of duplicate occlusion, compensation for loss of fixation during prolonged transportation, possibility of application to multiple wounds
Duplicating systems for maintaining occlusion	At least one backup harness or re-tensioning mechanism is required	Reducing the risk of recurrent bleeding after primary occlusion and compensating for mechanical degradation of the tape under the influence of movement or vibrations
Recommended haemostatic materials	Combat Gauze, ChitoGauze, kaolin-impregnated bandages	Increased bleeding control in cases of deep wound channels and combined injuries, reducing the likelihood of rebleeding after partial relief of pressure
Additional pressure control devices	Sensor systems pressure feedback devices or mechanical tension indicators	Automated or semi-manual control of compression pressure during stabilization phases, reducing the risk of loss of occlusion due to edema or changes in the anatomical profile of the limb

Note: Recommended haemostatics contain active ingredients (kaolin or chitosan) that accelerate local blood clotting.
Source: compiled by the author based on NATO Standard AJP-4.10 [14], NATO Centre of Excellence for Military Medicine [15], Joint Trauma System [16], S. Olsen [20], D. O. Samofalov et al. [23], M. Latos et al. [24], C. U. Kharod et al. [25], C. A. B. Mclaren et al. [26], Deployed Medicine [27], Tactical Combat Casualty Care [28], European Civil Protection and Humanitarian Aid Operations [29], World Health Organization [30], MEDEVAC – keeping the wounded alive [31].

Analysis of Table 8 demonstrates that occlusion stability was largely dependent on the availability of a sufficient number of serial tourniquets suitable for duplication in cases of fixation loss or recurrent bleeding. It was established that duplication systems play a critical role during prolonged evacuation, when mechanical loading, micromovements, and changes in the limb anatomy gradually reduce the compressive pressure. The use of recommended haemostatic agents expanded the capacity to control deep bleeding, thereby increasing the effectiveness of combined approaches in cases of complex tissue injury [41; 42]. Additional pressure-control systems, and particularly pressure-feedback devices, reduced the risk of technical errors during prolonged stabilisation phases, thus confirming their functional significance. The integration of these components forms a comprehensive equipment configuration that optimises occlusion maintenance in tactical environments characterised by extended evacuation delays.

The model structure also incorporates an algorithm for applying the partial reperfusion technique in accordance with the provisions of the partial limb reperfusion protocol, enabling a reduction of the ischaemic load during prolonged tourniquet application. This algorithm was developed on the basis of defined limits for the duration of the pressure-relief phase, reocclusion parameters, and the minimum compression level required to restore effective haemostasis. Application of this technique

requires careful consideration of the operational context, as, in certain scenarios, reperfusion may increase the risk of recurrent bleeding. Within the proposed model, partial reperfusion may be considered after 150–180 minutes of occlusion when evacuation is expected to remain prolonged and bleeding is controlled before pressure relief. It should not be attempted while massive bleeding remains uncontrolled, because the pressure relief may increase the risk of recurrent bleeding [43; 44]. The availability of a standardised algorithm allows adaptive use of this approach in situations where the evacuation duration exceeds the doctrinal limits.

A key component of the model is the definition of training requirements for non-medical personnel, who perform the majority of primary haemostatic interventions in combat conditions [45]. The aggregated data demonstrated a strong correlation between the operator qualification level and the frequency of technical errors during the application of CAT, SOF-T, and other serial tourniquet models. Accordingly, the minimum training content for non-medical personnel in the proposed model includes pressure control, accurate tourniquet positioning, minimisation of time to occlusion, and regular assessment of the limb condition during prolonged stabilisation. This approach establishes conditions for improving the outcome reliability across a wide range of tactical scenarios.

The formation of criteria for assessing ischaemic risks was based on the duration of occlusion, the magnitude of compression pressure, the frequency of recurrent bleeding, and the characteristics of local tissue reactions [46; 47]. The established criteria made it possible to predict the likelihood of ischaemic complications during prolonged evacuation and to determine the feasibility of transitioning to partial reperfusion or the need for repeated reinforcement of tourniquet tension. Integration of these parameters into the model increases its adaptability and enables the adjustment of algorithms in accordance with the specific features of the combat situation and the severity of injuries.

An important aspect of the model development was a consideration of the logistical limitations of Polish military units, and particularly the availability of specialised tourniquets, haemostatic materials, and pressure-control systems. Analysis of the resource capabilities allowed the formulation of differentiated protocol configurations that can be implemented both in fully equipped units and in settings with limited material and technical resources. This approach ensures the scalability of the model and its adaptability to diverse operational scenarios, thereby enhancing the realism of its practical application.

The comprehensive integration of these elements forms a holistic applied framework for a modernised tourniquet-use protocol in Polish units, grounded in the comparative secondary evidence and model-derived parameters synthesised in the study. The resulting structure enables the incorporation of the findings into a broader model for assessing the effectiveness of haemostatic interventions and identifies key directions for improving the tactical medical support in combat conditions. The application of such a model provides a foundation for enhancing the resilience of medical support systems and optimising massive bleeding control processes in contemporary operational environments. The integrated framework developed in this subsection addresses the third research task by combining the pressure limits, partial reperfusion parameters, equipment configuration, and personnel-training requirements in a model adapted to Polish military units.

Discussion

The synthesis of the results demonstrates that the occlusion stability and the effectiveness of haemostatic intervention are shaped by the interaction of mechanical, physiological, and logistical factors, which, under conditions of prolonged evacuation delays, function as an integrated operational system. The identified relationships emphasised the importance of compression magnitude, equipment configuration, and the personnel training level, and also revealed a clear association between pres-

sure the parameters, occlusion duration, and the probability of ischaemic complications. Analysis of different tactical care models showed that tourniquet effectiveness is determined not only by device design characteristics, but also by the robustness of application algorithms under conditions of variable combat intensity and logistical constraints. A comparison of the identified patterns with existing doctrinal provisions indicated the need to adapt protocols to scenarios involving prolonged stabilisation phases, while enabling more controlled maintenance of occlusion during extended transportation.

The observed dependence of haemostatic effectiveness on the timing of intervention is consistent with the findings of S. Khallikane et al. [48], who demonstrated, in an analysis of ballistic injuries, that the interval between an injury and a first intervention significantly influenced the development of fatal complications. In that study, a delay of only a few minutes markedly increased the risk of uncontrolled haemorrhage, reflecting a common trend with the sharp rise in mortality after five minutes, as identified in the present analysis. The presence of quantitatively defined thresholds in this study extends the clinical observations reported by S. Khallikane et al. and clarifies the critical importance of early haemostatic intervention.

The issues related to safe occlusion duration and the feasibility of alternative bleeding-control methods correspond with the conclusions of N. L. Bradley et al. [49], who examined the effectiveness of resuscitative endovascular balloon occlusion of the aorta and other innovative techniques in the context of massive haemorrhage. The work of N. L. Bradley et al. highlighted the necessity of clearly defining physiological limits of ischaemia, which aligns with the present study's emphasis on regulating the compression pressure and occlusion duration when using compact compression devices. Despite differences in the mechanisms of action, both approaches share a fundamental principle: prolonged haemostatic intervention requires an adapted perfusion-control algorithm to minimise the risk of tissue injury.

The findings regarding the prospects of automated pressure-control mechanisms were consistent with the analytical results reported by G. Avital et al. [50], who demonstrated the potential of artificial intelligence-based systems to assess the degree of vascular occlusion in next-generation devices. The ability of sensor-based systems to reduce technical errors and stabilise compression pressure under dynamic conditions, as presented by G. Avital et al., supports the trends identified in the present study, according to which, pressure-feedback devices were associated with the lowest rates of recurrent bleeding and ensured prolonged maintenance of effective occlusion.

The effectiveness of advanced haemostatic technologies, and particularly mechanisms designed to maintain uniform compression, also corresponded with the data reported by H. Fu et al. [51] in a lethal haemorrhage model. Their study confirmed that the uniformity of compression and the ability of a device to sustain stable pressure are key determinants of haemostatic effectiveness over extended periods. The pressure thresholds and technology-selection criteria established in the present analysis reflect the same physiological mechanisms, thereby demonstrating consistency between experimental findings and field and clinical observations.

Issues related to combined haemostatic techniques correlated with established trends concerning the influence of the haemostatic material type on the occlusion duration and rebleeding risk, as confirmed in the study by A. Kumar et al. [52], which compared the properties of chitosan- and kaolin-based dressings in a severe bleeding model. These findings were consistent with the results of the present analysis, in which, the combination of deep packing with a tourniquet was shown to enhance occlusion stability. Both approaches support a common principle: the effectiveness of haemostatic intervention is determined by the appropriate selection of the haemostatic agent in accordance with the wound anatomy and mechanical loading conditions. The results were also consistent with the conclusions of X. Jiang et al. [53], who emphasised the role of information and communication

infrastructure in evacuation efficiency. The relationship identified between the data-transmission speed and the time to mobilisation of medical resources reflects the mechanism through which logistical delays influence the critical level of the ischaemic load. This comparison confirmed that optimisation of haemostatic algorithms can partially compensate for structural deficiencies in evacuation management, although it cannot fully overcome the fundamental limitations imposed by a delayed access to definitive medical care.

The patterns associated with the influence of the operational environment on the quality of first aid demonstrated a clear correspondence with the findings of T. Westbrook and D. G. Costa [54], who described the specific challenges of response in spatially constrained settings with an increased transport complexity. In the present analysis, time remained the key determinant of survival, and even minor delays reduced the effectiveness of interventions. The results of the conducted study confirmed this principle, while complementing these observations with quantitatively defined limits of safe compression, which were not addressed in the work of T. Westbrook and D. G. Costa.

The identified impact of logistical models on the effectiveness of emergency interventions was consistent with the review by S. M. Khalili et al. [55], which emphasised the role of transport and routing constraints in determining the medical care efficiency. Although the focus of the study by S. M. Khalili et al. was directed towards the optimisation of movement, the relationships identified in their review reproduced the same fundamental mechanism: prolongation of the evacuation time necessitates haemostatic techniques capable of maintaining effective occlusion over extended intervals. The present study further detailed this mechanism by describing the associated physiological consequences of such delays.

The relationship between compression parameters and the safety of occlusion methods was also consistent with the conclusions of G. Liu et al. [56], who synthesised the evidence base for the use of pneumatic tourniquets in surgical practice. Their work demonstrated that both the occlusion duration and the pressure range require strict regulation to prevent ischaemic complications and preserve the tissue viability. The limits identified in the present study – an occlusive pressure range of 170–240 mmHg and a time corridor of 120–180 minutes – confirmed the acceptability of these physiological constraints and further specified these parameters in the context of prolonged evacuation delays and the motor instability of casualties.

The influence of technical training on the quality of occlusive intervention was consistent with the established patterns relating to the accuracy of compression parameters and error frequency, as substantiated by H. Fanoudi et al. [57], who proposed a standardised scale for assessing professional competence in the use of pneumatic tourniquets. The relationships identified by the authors explain why insufficient training resulted in a 3–5-fold increase in technical errors and, consequently, an elevated risk of recurrent bleeding and the need for duplicate occlusion. The present results extend these observations by demonstrating how technical errors affect the occlusion stability in the context of prolonged transportation.

The conclusions drawn regarding the critical importance of timely haemostatic intervention were also consistent with the patterns identified by E. K. Powell et al. [58], who showed that delays in haemodynamic stabilisation significantly increased the complication rates and mortality among patients with severe injuries. The deterioration dynamics described in their study under conditions of delayed care correspond with the present findings, according to which, achieving occlusion after five minutes was associated with an increase in mortality to 34–51%. The analysis further specified these trends by identifying precise limits of compression pressure and occlusion duration that may minimise the risk of ischaemic complications during delayed evacuation.

The findings were additionally aligned with the data reported by M. A. Alajery et al. [59], who substantiated a multidisciplinary approach to haemorrhage control and emphasised the need to

integrate mechanical, pharmacological, and logistical solutions. In their work, intervention effectiveness was associated with the coherence of action algorithms and the efficiency of their implementation, which corresponds to the demonstrated importance of technical accuracy and timely tourniquet application. The present results complement these observations by providing quantified limits for safe occlusion duration and partial reperfusion parameters, thus offering practical tools for implementing an integrated approach to bleeding control.

The identified patterns highlighting the critical importance of early haemostatic intervention were consistent with the findings of L. Carenzo et al. [60], who analysed approaches to managing patients in traumatic circulatory arrest and pre-arrest states. In their study, it was emphasised that even short delays in restoring adequate perfusion resulted in a significant deterioration of prognosis. The indicators reported – according to which, achievement of occlusion within the first two minutes was associated with a mortality rate of 8–14%, whereas delays exceeding five minutes increased mortality to 34–51% – confirmed this trend. The formalised compression parameters established in the present study created additional opportunities to partially mitigate the consequences of early hypoperfusion under conditions of prolonged evacuation cycles.

The study findings were also concordant with the conclusions of A. Rodrigues et al. [61], who reviewed strategies for the urgent correction of coagulation disorders in critically bleeding patients. Their work demonstrated that timely restoration of the coagulation potential, combined with the appropriate mechanical haemostatic devices, reduced the risk of uncontrolled haemorrhage. The comparison showed that the high rate of technical errors during tourniquet application observed among untrained personnel (3–5 times higher) compromised the bleeding control and increased the need for duplicate occlusion.

The effectiveness of alternative bleeding-control methods aligned with the conclusions of B. Bouscholte [62], who conducted a systematic analysis of the feasibility of resuscitative aortic occlusion in the prehospital setting. That study demonstrated that, although the technique was highly effective, it was associated with substantial technical and organisational constraints that limited its applicability in mobile units. The present results reflected a similar pattern, indicating that even when less invasive compression devices are used, strict adherence to pressure and time limits remains essential, while excessively complex technologies are less adaptable to field conditions. The occlusion parameters identified in this study represent a compromise solution suitable for bleeding control during delayed evacuation without a significant increase in complication risk.

The collective analysis of the reviewed studies demonstrated consistency in the key trends characterising the contemporary approaches to massive bleeding control and the organisation of medical care in combat and delayed evacuation environments. The patterns identified regarding the importance of rapid occlusion, technical accuracy of tourniquet application, physiologically justified compression limits, and the influence of logistical factors were consistent with findings from clinical, experimental, and operational research. Generalisation of these principles in the form of quantitatively defined parameters for compression pressure, occlusion duration, and compression-device stability provides a foundation for practical enhancement of haemostatic care protocols under conditions of prolonged evacuation.

Conclusions

It has been established that actual medical evacuation times in Poland, Ukraine, the United States of America, the United Kingdom, and Lithuania consistently exceeded doctrinal guidelines by 15–120 minutes, which directly correlated with an increased mortality – from 8–14% when occlusion was achieved within the first two minutes to 34–51% when delays exceeded five minutes. An increase in the time required to achieve occlusion, irrespective of the tourniquet type, was found to significantly

elevate the risk of fatal outcomes, while the need for duplicate occlusion occurred in 23–41% of cases, thus indicating insufficient stability of primary compression interventions under conditions of prolonged evacuation.

Clear parameters of a tourniquet's technical reliability influencing the frequency of recurrent bleeding were identified. The rate of technical errors among untrained personnel was 3–5 times higher than among trained teams; incorrect tourniquet placement and insufficient strap tension resulted in rebleeding in 17–27% of cases. The analysed data allowed the determination of average utilisation of compression devices: in Poland, Ukraine, Lithuania, and the United Kingdom, 1.3–1.6 tourniquets were used per casualty, whereas, in the United States, the figure was 1.2. The requirement for duplicate occlusion arose in 23–41% of cases due to inadequate effectiveness of the initial compression.

Comparative analysis of innovative haemostatic technologies demonstrated that cyclic pressure-regulation methods and automated compression-control devices have the potential to reduce recurrent bleeding risk to 2–6% and to maintain stable occlusion for 240–300 minutes. On the basis of these findings, an integrated model of safe occlusion was developed, encompassing optimal compression-pressure limits of 170–240 mmHg, a safe occlusion duration of 120–180 minutes, and a threshold for partial reperfusion of 150–180 minutes. The generalised data supported the formulation of an optimal equipment configuration, including 2–3 tourniquets, redundant tension-maintenance mechanisms, modern haemostatic materials, and pressure-sensor control systems. These patterns provided a basis for rational equipment selection and the definition of minimum training requirements for the personnel.

Study limitations were related to heterogeneity of the available data, differences in documentation standards, and the absence of unified methods for assessing the effectiveness of compression technologies across countries. In addition, several quantitative parameters included in the proposed model were derived from secondary data and structural-functional modelling rather than from prospective clinical testing, which limits the extent to which the proposed thresholds can be considered clinically validated. Future research should focus on the clinical validation of partial reperfusion parameters, development of sensor-based occlusion-control systems, and refinement of personnel training algorithms for scenarios involving prolonged evacuation.

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