Major Vascular and Thoracic Trauma in Nordic Populations

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Alvarlegir æða- og brjóstholsáverkar í norrænu sjúklingaþýði

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Ágrip

Áverkar á stærstu slagæðar líkamans og hjarta eru ein mikilvægasta orsök andláts og örkumlunar í heiminum. Rannsóknir á faraldsfræði æðaáverka eru af skornum skammti og ljóst að mikilvægt er að fyrirbyggja þá, t.d með betri akvegum og öruggari ökutækjum. Einnig er þörf á aukinni þekkingu um þá þætti sem valda andláti þeirra sem komast lifandi á sjúkrahús eftir slíka áverka, í þeim tilgangi að bæta árangur meðferðar og lifun. Markmið þessarar doktorsritgerðar, sem tekur til fimm vísindagreina, er að meta árangur meðferðar við þessum áverkum og skilgreina forspárþætti 30 daga- og langtímalifunar í vel skilgreindum norrænum þýðum sjúklinga, bæði á Íslandi og í Bergen.

Skráðar voru lýðfræðilegar upplýsingar um sjúklingana, orsök áverka og staðsetning þeirra, meðferð, heildarlifun og áverkaskor (Injury Severity Score [ISS], New ISS [NISS], og Trauma Score and Injury Severity Score [TRISS]). Notast var við gögn úr sjúkraskrám á landsvísu en einnig frá svæðissjúkrahúsum. Loks var reiknað út skor á samhliða sjúkdómum og lyfjanotkun (Comorbidity Polypharmacy Score) sem og marghliða fylgikvillastuðull (Comprehensive Complication Index) til að meta forspárþætti fyrir dánartíðni á sjúkrahúsi í kjölfar alvarlegra brjóstholsáverka.

Í **Grein I** voru með afturvirkum hætti rannsakaðir allir fullorðnir (aldur ≥ 18 ára) sem hlutu meiriháttar æðaáverka í umferðarslysum á Íslandi á árunum 2000-2011. Um var ræða 62 einstaklinga (meðalaldur 44 ár; 79% karlar) sem samtals hlutu 95 æðaáverka sem töldust alvarlegir. Fyrir innlögn létust 41 sjúklingar en 21 (34%) komst lifandi á sjúkrahús. Árleg nýgengi mældist 1,69/100 000 íbúa fyrir bæði kyn saman. Marktækt fleiri einstaklingar slösuðust í dreifbýli miðað við í þéttbýli (69% á móti 31%, p <0,01). Sjúklingarnir sem létust hlutu oftast æðaáverka í brjóstholi (76%) eða í kviðarholi (23%). Banvæna brjóstholsósæðaráverka mátti oftast rekja til áreksturs (77%) og 74% af þeim áttu sér stað í dreifbýli. Meðal NISS-skor fyrir þá 21 sjúklinga sem lögðust inn var 44. Æðaaðgerðir voru framkvæmdar á 18 sjúklingum, þ.m.t. þremur með innæðarstoðneti sem komið var fyrir með æðaþræðingu. Fimmtán sjúklingar af þeim 21 (71%) sjúklingum sem lagðir voru inn lifðu fram að útskrift og voru 86% þeirra á lífi fimm árum síðar.

Grein II kannaði afdrif 9 fullorðinna sem gengust undir bráða brjóstholsskurðgerð á Íslandi á árunum 2005-2010 þar sem við innlögn lá fyrir sterkur grunur um alvarlegan hjarta og/eða æðaskaða í brjóstholi. Miðgildi aldurs var 36 ár og allir sjúklingarnir karlkyns. Fimm þeirra hlutu sljóan og fjórir ífarandi áverka, og voru sex þeirra með áverka bundinn við brjósthol en þrír fjöláverka. Miðgildi áverkaskora ISS og NISS voru 29 og 50. Fjórir sjúklingar af 9 létust, þar af þrír sem aldrei mældust með lífsmarki eftir

komu á sjúkrahús. Af þeim fimm sem lifðu af áverkann náðu fjórir góðum bata en einn sjúklingur hlaut þverlömun vegna mænuskaða.

Grein III rannsakaði alla sjúklinga sem lagðir voru inn á sjúkrahús á Íslandi í kjölfar stunguáverka 2000-2015, samtals 73 einstaklinga (meðalaldur 32,6 ár, 90,4% karlar). Í flestum tilvikum var um líkamsárás (96%) að ræða og algengasta staðsetning áverka á brjóstholi (n = 32), kviði (n = 26) og efri útlimum (n = 26). Meðaltal ISS-skors var 9, og reyndust 14 sjúklingar (19,2%) með alvarlega áverka (skilgreint sem ISS-skor >15). Tuttugu og átta sjúklingar (37%) lögðust inn á gjörgæslu og 38 (51%) gengust undir skurðaðgerð. Aðeins þrír létust vegna áverkans (4,1%) innan 30 daga.

Í **Grein IV** voru rannsakaðir allir fullorðnir sem lagðir voru inn á Haukeland háskólasjúkrahúsið í Bergen á tímabilinu 2009—2018 sem reyndust hafa alvarlega brjóstholsáverka (skilgreind sem Abbreviated Injury Scale [AIS]-skor ≥ 3). Um var að ræða 514 sjúklinga með alvarlega brjóstholsáverka (meðalaldur 51 ár, 78% karlar). Meðaltal árlegs nýgengis reyndist 13,3/100.000 íbúa yfir 10 ára tímabil. Fjöláverkasjúklingar voru 61% og ISS-skor þeirra að meðaltali 21. Flestir áverkar hlutust í kjölfar umferðarslysa (49%) eða eftir fall (35%). Fjölþáttagreining sýndi að kvenkyn, og TRISS með lifurnarlíkur (probability of survival) ≤ 50%, fleiri en samtals 9 samhliða sjúkdóma og lyfjameðferðir vegna þeirra sem og marghliða fylgikvillastuðull ≥ 30 spáðu marktækt fyrir um dánartíðni á sjúkrahúsi. Algengasti alvarlegi fylgikvillinn reyndist öndunarbilun hjá 14% sjúklinga og var dánartíðni á fyrstu 24 klst. 5% og innan 30 daga 12%.

Grein V náði til 68 fullorðinna sjúklinga (miðgildi aldurs 44 ár, 76% karlkyns) sem lagðir voru inn vegna slagæða- eða bláæðaáverka á Haukeland háskólasjúkrahúsið í Bergen frá 2009-2018. Samtals var um 81 æðaáverka að ræða: 46 sljóa og 22 (32%) ífarandi. Árleg tíðni alvarlegra æðaáverka fyrir bæði kyn saman reyndist 1,45/100.000 íbúa. Staðsetning áverka var oftast í brjóstholi (n = 17), hálsi (n = 16) og kviðarholi (n = 15). Áverkana mátti oftast rekja til umferðarslysa (n = 31), stunguáverka (n = 17) eða falls (n = 10). Miðgildi ISS-skors var 22, og höfðu 50 sjúklingar (74%) alvarlega áverka (ISS-skor > 15). Tólf (18%) sjúklingar létust innan 24 klukkustunda og höfðu sex þeirra áverka á ósæð.

Ofangreindar fimm vísindagreinar sýna að alvarlegir æðaáverkar eru fátíð dánarorsök á Íslandi og í Vestur-Noregi. Árangur meðferðar og lifun virðist svipaður og á stærri sjúkrahúsum í N-Evrópu og N-Ameríku. Oftast hljótast áverkarnir af umferðarslysum, ólíkt því sem tíðkast í Bandaríkjunum og Bretlandi þar sem ífarandi áverkar eru langalgengasta orsök alvarlegra æðaáverka. Einnig staðfesta vísindagreinarnar fimm hversu há 30 daga dánartíðni er eftir áverka á ósæð, ekki síst þegar þeir verða í dreifbýli. Nýgengi stunguáverka sem kröfðust innlagnar á Íslandi hefur haldist nokkuð stöðug á þeim 16 árum sem rannsökuð voru, sem samrýmist erlendum rannsóknum. Bráða brjóstholsskurðaðgerðir á bráðamóttöku eru sjaldan framkvæmdar á Íslandi. Engu að síður virðist lifun í kjölfar aðgerðar síst verri á Íslandi en á stærri sjúkrahúsum erlendis, m.a. á hinum Norðurlöndunum, þrátt fyrir að um fáa sjúklinga sé að ræða. Bæði á Íslandi og í Noregi voru flestir æðaáverkar meðhöndlaðir með opinni skurðaðgerð en innæðaaðgerðum beitt í völdum tilvikum. Forspárþættir fyrir andláti sjúklinga á sjúkrahúsi með alvarlega brjóstholsskaða reyndust kvenkyn, samhliða sjúkdómar og lyfjameðferðir vegna þeirra, TRISS-skor með lifunarlíkur (probability of survival [Ps]) undir 50%, sem og ef upp koma alvarlegir fylgikvillar í sjúkrahúslegu. Fyrri sjúkrasaga, sem og orsök æðaáverka, eru því mikilvægar upplýsingar þegar metnir eru sjúklingar með æðaáverka á brjóstholi. Á Íslandi og í Noregi eru oft erfiðar aðstæður til sjúklingaflutninga vegna landfræðilegra aðstæðna og veðurs, auk þess sem um tiltölulega fáa sjúklinga er að ræða borið saman við stærri fyrsta stigs áverkamóttökur í Evrópu og N-Ameríku. Bæði á Íslandi og í Noregi eru hins vegar vel skipulagðar bráðamóttökur og fámennið virðist ekki koma niður á árangri meðferðar.

Vonandi munu niðurstöður þessara fimm vísindagreina stuðla að bættum árangri meðferðar sjúklinga með alvarlega áverka á æðar og líffæri í brjóstholi. Ljóst er að bæta þarf enn frekar skráningu þessara áverka og mikilvægt að starfsfólk fái þjálfun í að mehöndla þessa sjúklinga og þekki þá áhættuþætti sem draga úr lífslíkum sjúklinga.

Lykilorð:

æðaáverki, brjóstholsáverki, faraldsfræði, áverkaskor, lifun, forspárþáttur, meðferð.

Abstract

Injuries involving major arteries and the thorax are major causes of mortality and morbidity worldwide. Studies on the epidemiology of vascular trauma are scarce and preventive measures are of utmost importance, such as improved roads and safer vehicles. There is a need to better understand factors predictive of mortality in trauma patients who are admitted alive to hospitals, aiming to improve treatment outcomes and lower mortality rates. The aim of this doctoral thesis, which consists of a collection of five scientific articles, is to evaluate outcomes and prognostic factors associated with 30-day and long-term survival in patients with severe injuries to major arteries of the body in two well-defined Nordic patient cohorts, both in Iceland and Bergen.

Data regarding patient demographics, mechanism and location of vascular injury and treatment, incidence, overall survival, and injury scores (Injury Severity Score [ISS], New ISS [NISS], and Trauma Score and Injury Severity Score [TRISS]) were recorded. The data were extracted from national and local trauma registries and patient charts. We also calculated Comorbidity Polypharmacy Scores and Comprehensive Complication Indexes to evaluate predictive factors for in-hospital mortality after serious thoracic trauma.

In **Paper I**, adults (age ≥ 18 years) who sustained major vascular injuries in traffic accidents in Iceland in the years 2000–2011 were retrospectively studied. Sixty-two patients (mean age, 44 years; 79% males) sustained 95 major vascular injuries. Before admission, 41 patients died and 21 (34%) reached the hospital alive. The annual incidence for both sexes was 1.69/100 000 inhabitants. A significantly higher proportion of individuals sustained their injuries in rural vs. urban areas (69% vs. 31%, $p < 0.01$). Patients who died sustained thoracic (76%) or abdominal major vascular trauma (23%). Fatal cases of thoracic aortic injury were largely (77%) attributed to motor vehicle collisions and 74% occurred in rural areas. The average NISS for the 21 admitted patients was 44. Vascular surgery was performed on 18 patients, including three in which endovascular stents were placed. Fifteen of the 21 admitted patients (71%) survived until discharge, and their five-year survival rate was 86%.

Paper II included 9 adults who underwent emergency thoracotomy at the accident site, during transport, or just after admission, in Iceland from 2005 to 2010, due to severe chest trauma with a strong suspicion of severe cardiac and/or vascular injury. The median age was 36 years and all were males. Five sustained blunt trauma and four sustained penetrating injuries; six sustained typically isolated thoracic injury and three had polytrauma. The median ISS and NISS were 29 and 50, respectively. Four of the nine patients died and three of those had no sign of life at admission. Five patients

survived the injury and procedure and 4 of those made a good recovery. One patient had paraplegia related to spinal injury.

Paper III included all 73 patients (average age, 32.6 years; 90.4% males) who were admitted to a hospital in Iceland following penetrating injuries between 2000 and 2015. Most cases were due to assault (96%) and the most frequent locations of injury were the chest (n = 32), abdomen (n = 26), and upper limbs (n = 26). The average ISS was 9, and 14 patients (19%) sustained severe injuries (ISS > 15). Twenty-eight patients required admission to the intensive care unit and 38 patients (51%) needed surgery. Only three patients died within 30 days following the injury (4.1%).

In **Paper IV**, all adults who were admitted to Haukeland University Hospital in Bergen, in the period 2009–2018 with severe chest trauma (with AIS ≥ 3) were studied. There were 514 adults with severe chest trauma (mean age, 51 years; 78% males). The average annual incidence was 13.3/100 000 population over the 10-year study period. Polytrauma patients constituted 61% of patients with an average ISS of 21. Most injuries occurred as a result of traffic accidents (49%) and falls (35%). The multivariate analysis demonstrated that female sex, TRISS with a probability of survival (Ps) of ≤ 50%, having more than nine comorbidities and concurrent medications, and a Comprehensive Complication Index ≥ 30 were significant predictors of in-hospital mortality. The most common severe complication was respiratory failure in 14% of patients and these patients had a 5% 24 h mortality rate and a 30-day mortality rate of 12%.

Paper V included 68 adult patients (median age, 44 years; 76% male) who were admitted with vascular injuries to Haukeland University Hospital in Bergen, from 2009–2018. There were 81 vascular injuries: 46 blunt and 22 (32%) penetrating. The annual incidence of major vascular injuries was 1.45/100 000 inhabitants for both sexes. The most frequent locations of injury were the thorax (n = 17), neck (n = 16), and abdominal region (n = 15). The injuries were most often attributed to traffic accidents (n = 31), as well as stab injuries (n = 17) and falls (n = 10). The median ISS was 22 and 50 (74%) patients sustained severe injuries (ISS > 15). Twelve (18%) patients died within 24 h and 6 of those had aortic injuries.

These five scientific papers show that serious vascular injuries are an uncommon cause of death in Iceland and Western Norway. The results of treatment and survival are similar to those reported in larger hospitals in North Europe and North America. Most vascular injuries in both Iceland and Bergen were caused by traffic accidents, in contrast to the US and UK where penetrating injuries are much more common causes of vascular injury. The 30-day mortality rate is high after aortic injuries, particularly when they occur in rural areas. Contrary to the impressions of many, the incidence of trauma among patients who were admitted due to stab injuries remained relatively stable in Iceland over the 16-year study period, which is in line with other recent reports. Emergency thoracotomy is a rarely performed procedure in Iceland; however, the survival rate seems higher than reported in publications from Scandinavia. In both

Iceland and Norway, a majority of vascular trauma cases were treated via open surgery and endovascular treatment was applied in selected cases. Independent predictors of in-hospital mortality among patients with severe chest injuries were female sex, comorbidities and medications, TRISS with a Ps lower than 50%, as well as the occurrence of in-hospital complications. Previous medical history together with the cause of injury is therefore important information to consider when evaluating trauma patients. Although Iceland and Norway have level 1 trauma centres with low patient volumes and often difficult transport routes, the outcomes of treatment are similar to those reported from high volume centres in Europe and North America, and well-organised trauma centres established in both countries.

The findings of these five papers may help to improve the outcomes of seriously injured vascular and thoracic trauma patients and lower both mortality and morbidity. Further improvements in the registration of these injuries are needed in addition to improved training of trauma teams involved in the treatment of patients, to increase knowledge on risk factors related to inferior outcomes which is of vital importance.

Keywords:

vascular injury, thoracic injury, epidemiology, injury score, survival, predictive factor, treatment

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List of Abbreviations

ABR	All body regions
ACS	American College of Surgeons
AIS	Abbreviated Injury Score
ASA	American Society of Anesthesiologists
ASIA	American Spinal Injury Association
ATLS	Advanced Trauma Life Support
CCI	Charlson Comorbidity Index
CDS	Clavien–Dindo scale
CI	Comprehensive Complication Index
CPS	Comorbidity Polypharmacy Score
CTA	Computed tomography angiography
DGU	Deutsche Gesellschaft für Unfallchirurgie [German Society for Trauma Surgery]
DSATC	Definitive Surgery and Anaesthesia in Trauma Care
DSTC	Definitive Surgical Trauma Care
eFAST	Extended Focused Assessment with Sonography in Trauma
ETC	European Trauma Course
GCS	Glasgow Coma Scale
GOS	Glasgow Outcome Scale
ICD	International Classification of Diseases
ICU	Intensive care unit
IQR	Interquartile range
ISS	Injury Severity Score

IVT	Iatrogenic vascular trauma
KE	Kinetic energy
MRA	Magnetic resonance angiography
MRI	Magnetic resonance imaging
NISS	New Injury Severity Score
NKT	National Competence Service for Traumatology
NTDB	National Trauma Data Bank
NTR	Norwegian National Trauma Registry
PRBCs	Packed red blood cells
Ps	Probability of survival
REBOA	Resuscitative endovascular balloon occlusion of the aorta
ROSC	Return of spontaneous circulation
RR	Respiratory rate
RTA	Road traffic accident
RTS	Revised Trauma Score
SBP	Systolic blood pressure
SOL	Signs of life
TBI	Traumatic brain injury
TRISS	Trauma Score and Injury Severity Score
UK	United Kingdom
US	United States
WHO	World Health Organization

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List of Original Papers

This thesis is based on the following original publications, which are referred to in the text by their Roman numerals (I–V):

I. **Johannesdottir BK**, Johannesdottir U, Logason K, Jonsson Th, Lund SH, Mogensen B, Gudbjartsson T. High Mortality from Major Vascular Trauma in Traffic Accidents: A Population-Based Study. Scand J Surg. 2020 Dec;109(4):328-335. doi: 10.1177/1457496919863944. Epub 2019 Jul 29. PMID: 31354052.

II. **Johannesdottir BK**, Mogensen B, Gudbjartsson T. Emergency thoracotomy as a rescue treatment for trauma patients in Iceland. Injury. 2013 Sep;44(9):1186-90. doi: 10.1016/j.injury.2012.05.005. Epub 2012 May 24. PMID: 22633693.

III. Johannesdottir U, Jonsdottir GM, **Johannesdottir BK**, Heimisdottir A, Eythorsson E, Gudbjartsson T, Mogensen B. Penetrating stab injuries in Iceland: a whole-nation study on incidence and outcome in patients hospitalized for penetrating stab injuries. Scand J Trauma Resusc Emerg Med. 2019 Jan 23;27(1):7. doi: 10.1186/s13049-018-0582-2. PMID: 30674331; PMCID: PMC6343331.

IV. Fokkema AT, **Johannesdottir BK**, Wendt K, Haaverstad R, Reininga IHF, Geisner T. Comorbidities, injury severity and complications predict mortality in thoracic trauma. Eur J Trauma Emerg Surg. 2022 Dec 17. doi: 10.1007/s00068-022-02177-6. Epub ahead of print. PMID: 36527498.

V. **Johannesdottir BK**, Geisner T, Gubberud ET, Gudbjartsson T. Civilian vascular trauma, treatment and outcome at a level 1-trauma centre. Scand J Trauma Resusc Emerg Med. 2022 Dec 21;30(1):74. doi: 10.1186/s13049-022-01059-5. PMID: 36544205; PMCID: PMC9773450.

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Declaration of Contribution

My contributions to the individual papers were as follows:

Paper I. I planned this study with my supervisors Tomas Gudbjartsson, MD, PhD and Brynjolfur Mogensen, MD, PhD. I applied for the appropriate ethical and research approvals. To identify patients, I searched and reviewed electronic medical records as specified in the methods section. I manually reviewed 2 859 autopsy records to identify patients who died in traffic accidents due to major vascular trauma. I further analysed data from the National Blood Bank for the prior identified patients. I calculated injury scores, NISS, ISS, RTS, TRISS, and Ps. Furthermore, I performed the statistical analysis with the help of Sigrun Helga Lund. I discussed the results with Tomas Gudbjartsson and Brynjolfur Mogensen. I wrote the manuscript under the supervision of Tomas Gudbjartsson and Brynjolfur Mogensen. Una Johannesdottir, MD; Karl Logason, MD, PhD; Thorbjorn Jonsson, MD; and Sigrun Helga Lund, PhD participated in writing the manuscript and all revisions of the paper.

Paper II. I planned this study with Tomas Gudbjartsson, MD, PhD. I applied for the appropriate ethical and research approvals. To identify patients, I searched and reviewed electronic medical records as specified in the methods section. I further analysed data from the National Blood Bank for the prior identified patients. I performed the statistical analysis with help from Martin Ingi Sigurdsson, MD, PhD. I discussed the results with Tomas Gudbjartsson and Brynjolfur Mogensen. I wrote the manuscript under the supervision of Tomas Gudbjartsson and Brynjolfur Mogensen.

Paper III. Una Johannesdottir, MD planned this study with Brynjolfur Mogensen, MD, PhD; Gudrun Maria Jonsdottir, MD; Tomas Gudbjartsson, MD, PhD; and myself. Una Johannesdottir, MD applied for the appropriate ethical and research approvals. To identify patients, Una Johannesdottir, MD searched and reviewed electronic medical records as specified in the methods section. A medical student, Alexandra Heimisdottir, collected the data along with Una Johannesdottir, MD and used data from my prior established database on vascular trauma in Iceland. Una Johannesdottir, MD; Gudrun Maria Jonsdottir, MD; and Elias Eythorssonan, MD, PhD performed the statistical analyses. Una Johannesdottir, Gudrun Maria Jonsdottir, Brynjolfur Mogensen, Tomas Gudbjartsson, and I wrote the manuscript, with Una Johannesdottir as the major contributor. All of the co-authors read the manuscript and participated in all revisions of the paper.

Paper IV. In the beginning, I planned this study with Tomas Gudbjartsson, MD, PhD; Thomas Geisner, MD; and Gustav Pedersen, MD, PhD. The plan was to analyse all cases of thoracic injury in the local trauma database in Western Norway with a focus on incidence and outcome. I applied for the appropriate ethical and research approvals. We were then approached with an interesting idea by a medical student, Anne Fokkema, and his supervisors at the University of Groningen in the Netherlands, Klaus Wendt, MD, PhD and Inge H. F. Reininga, MD, PhD. They suggested that we analyse the data further to identify risk factors of mortality using the Comorbidity Polypharmacy Score and complications measured using the Comprehensive Complication Index. Anne Fokkema performed the literature research and set up the study design. Anne Fokkema and I identified patients in the trauma database as specified in the methods section. Anne Fokkema and I searched and reviewed electronic medical records and collected the data. Anne Fokkema performed the statistical analysis with the help of Geir Egil Eide, PhD; Thomas Geisner; and myself. Anne Fokkema was the major contributor and wrote the manuscript with my assistance. All of the co-authors read and participated in all revisions of the paper.

Paper V. I planned this study with Tomas Gudbjartsson, MD, PhD; Thomas Geisner, MD; and Gustav Pedersen, MD, PhD. I applied for the appropriate ethical and research approvals. To identify patients, I searched and reviewed electronic medical records in the local trauma database as specified in the methods section. I reviewed autopsy records and analysed data from the National Blood Bank for the previously identified patients. I performed the statistical analysis with the help of Fatemeh Zamanzad Ghavidel. I discussed the results with Thomas Geisner, Espen Gubberud, and Tomas Gudbjartsson. I wrote the manuscript under the supervision of Tomas Gudbjartsson. All of the co-authors read the manuscript and participated in all revisions of the paper.

1 Introduction

Severe or major trauma is a leading cause of death and disability worldwide and therefore a major global public health issue (**Figure 1**). Civilian and war-related injuries result in more than 4.4 million annual deaths worldwide, constituting approximately 8% of all deaths according to a report from the World Health Organization (WHO) published in 2021. The main causes are road traffic accidents, suicide, and homicides among people aged 5–29 years (10). These patients can impose a significant amount of burden on hospital resources in terms of blood transfusion requirements, critical care requirements, and hospital length of stay, particularly following blunt trauma (11-14).

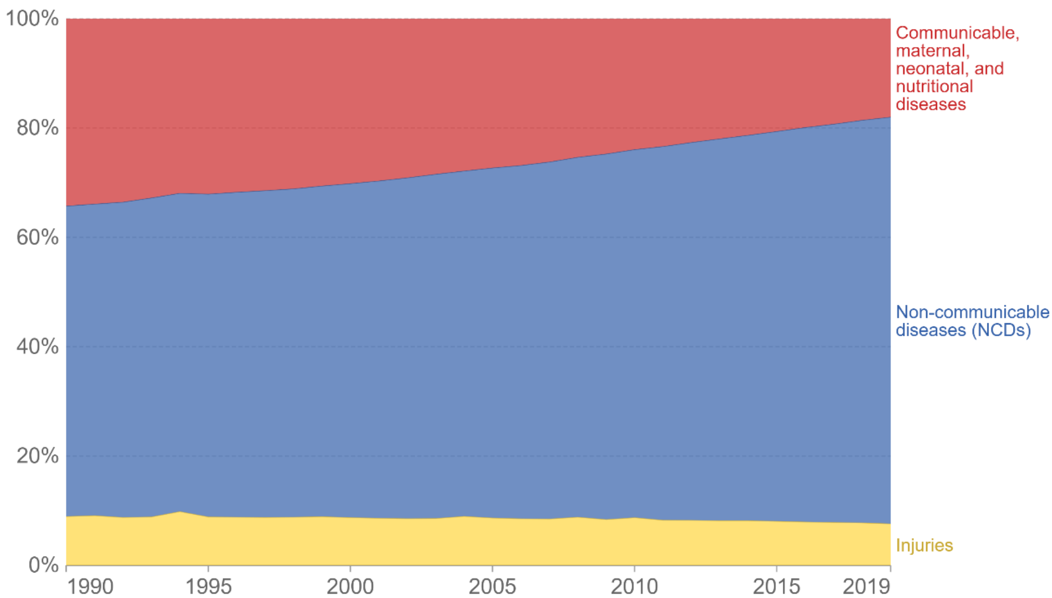

Figure 1. Global deaths by cause, 1990–2019 according to the Global Burden of Disease Study. Non-communicable diseases include cardiovascular disease, cancers, diabetes, and respiratory diseases. Injuries include road accidents, homicides, conflict deaths, drowning, fire-related accidents, natural disasters, and suicides. Adapted and used with permission (5)

The burden and impact of trauma as a cause of mortality and morbidity have been increasingly well characterised. The prevalence and incidence of individual cases of vascular trauma in local settings have been well documented, particularly during wartime. With rising incidences of crime and high-energy trauma in urban areas, reports suggest a rising incidence of major vascular trauma in civil settings (15);

however, there are few epidemiological studies in civilian practice (16). This is true for both blunt and penetrating vascular injuries (15, 17, 18).

Most trauma-related deaths are due to blunt injuries related to motor vehicle accidents. However, in countries such as the United States (US), the United Kingdom (UK), and South Africa, penetrating trauma is the predominant form of injury and a major health care problem (19-23). There is a paucity of European studies on penetrating trauma, particularly in urban areas (21, 24-26).

Thoracic injuries have quickly risen to be the second most common form of severe traumatic injury resulting from non-intentional trauma (27). Although their frequency and associated mortality rate are high, few epidemiological studies have been conducted in Scandinavian countries to evaluate risk factors for mortality (28) following thoracic trauma (29-41). Further, many studies have focused on risk factors for mortality after trauma in general, and little has been published on posttraumatic complications and mortality interactions in thoracic trauma (29).

Risk factors for trauma are associated with cultural variables, human behaviour, and the political and economic situation in each country (42, 43). To prevent morbidity and mortality, and reduce possible complications, an effective and multidisciplinary approach with an accurate diagnosis and effective surgical intervention is essential when treating thoracic and vascular trauma (44). Establishing a well-organized trauma centre has proven to be an important element in the treatment outcome and survival of trauma patients (28, 45-47). Trauma centres are often classified into five categories that refer to the kinds of treatment resources available (see *Appendix A. Trauma Centre Designations and Levels*). A level 1 Trauma Centre is a highly specialised medical care facility that can provide total care for polytrauma patients (48).

While management strategies have evolved over the last decade, the indications for some high-risk life-saving procedures, such as emergency thoracotomy, remain controversial. This is particularly true in cases of blunt trauma wherein less than 2% of patients survive after emergency thoracotomy (49, 50). Furthermore, in small trauma centres in Europe where blunt trauma is relatively more common, there has been a lack of studies on emergency thoracotomy (51).

Effective measures of prevention and treatment can reduce trauma-related injuries and decrease their burden (52, 53). Therefore, it is important that each country registers and analyses data to provide a satisfactory overview of the impact of injuries, compare these with other countries, and outline strategies on how to improve outcomes.

1.1 Epidemiology of thoracic trauma

The prevalence of chest injuries has increased rapidly, and currently constitutes 5—10% of all admitted cases of trauma injury, often following road traffic accidents (54, 55). Trauma to the thoracic region is the second most common cause of death after head trauma in polytrauma patients (27). More than 50% of all severely injured patients (Injury Severity Score [ISS] > 15) sustain thoracic trauma (56, 57). Approximately two-thirds of severe trauma patients have thoracic injuries and 25–60% of deaths worldwide following accidents can be attributed to thoracic injuries (27, 58, 59).

Table 1. Overview of selected published studies on thoracic trauma

Country	Study period	Inclusion criteria	Proportion of all trauma admissions (%)	No. of patients with chest trauma	Blunt (%)	Mortality (%)	RTA (%)	Authors
US	1987–1992	Hosp., rib fracture	10%	7147	NR	12%	NR	Zieglar et al. (55)
Norway	2003–2004	Hosp.	NR	436	96%	5%	46%	Kjøs et al. (60)
Trauma Register DGU®	2005–2014	Hosp., AIS≥3	NR	16773	95%	5%	65%	Horst et al. (61)
US	2013	Hosp., AIS≥3	14%	118334	NR	NR	NR	*National Trauma Data Bank Annual Report* (62)
US	2016	Hosp., AIS≥3	15%	129338	NR	10%	NR	*National Trauma Data Bank Annual Report* (63)
Saudi Arabia	2013–2019	Hosp., all chest trauma	NR	236	95%	NR	87%	Hajjar et al. (64)

Hosp., hospitalised; AIS, abbreviated injury score; NR, not recorded; Trauma Register DGU®, Deutsche Gesellschaft für Unfallchirurgie [German Society for Trauma Surgery].

Blunt injuries represent 70–95% of all cases of chest trauma and account for more than 15% of all trauma admissions to emergency departments worldwide (61, 65, 66). The associated mortality rate can sometimes be difficult to evaluate as the resulting deaths may be due to pulmonary and non-pulmonary complications (67). In a study of hospitalised blunt chest trauma victims conducted in the UK, 5% of the admitted trauma patients had a blunt chest injury and 57% were due to road traffic accidents, with a mortality rate of 19% (54). An analysis of data from the German trauma registry over the period 2003–2012 revealed that chest trauma, both blunt and penetrating, constituted 56% of all trauma admissions, resulting in a mortality rate of 52%, 57% of which were related to road traffic accidents (68). Horst et al. (2017) analysed the data of 16 773 patients with severe chest trauma (Abbreviated Injury Score [AIS] ≥3) from the Trauma Register DGU® (Deutsche Gesellschaft für Unfallchirurgie [German Society for Trauma Surgery]) from 2005– 2014. This registry is voluntary and admitted trauma patients were mainly registered from Germany (90%), as well as Austria, Belgium, China, Finland, Luxembourg, Slovenia, Switzerland, The Netherlands, and United Arab Emirates. The in-hospital mortality rate was 4.8%, and 95.4% experienced blunt injuries while 4.6% experienced penetrating injuries (61). In the 2016 Annual Report of the National Trauma Data Bank (NTDB), which is a US trauma registry, the total incidence rate of thoracic trauma was 23%, with 15% of all admitted trauma patients having thoracic trauma with AIS ≥ 3 and a 10% mortality rate (63) (**Table 1**).

1.1.1 Predictive risk factors for mortality in thoracic trauma

In patients with multiple injuries, the evaluation of the severity of thoracic trauma influences decision making as well as the subsequent clinical course. Injury severity is a risk factor for mortality in thoracic trauma. It can, however, be difficult to estimate due to a wide variety of scoring systems that implicate different parameters (35). Each scoring system usually combines anatomical and physiological parameters that are most suitable for severity assessment (35).

Several other risk factors are thought to influence the clinical course of patients with thoracic trauma, such as older age, female sex, anticoagulant use, accompanying injuries, comorbidities, and complications. With the increasing number of elderly patients with multiple trauma, it has been observed that the age of 65 years and older is a negative predictive factor in patients with thoracic trauma (60, 69, 70). Furthermore, comorbidities of patients have been shown to influence mortality (34, 41, 71).

Thoracic trauma, regardless of its severity, is associated with worse outcomes when accompanied by traumatic brain injury (72). Up to 30% of patients with traumatic brain injury have coexisting thoracic injuries, and these patients have a mortality rate of up to 80% (73). Leone et al. (2003) found that almost 30% of patients with head trauma have pulmonary contusion as an accompanying injury (74). This emphasises the importance of early management of associated injuries, especially traumatic brain injury (75).

Complications may significantly alter the clinical course of patients with thoracic trauma. Common complications, such as pneumonia and adult respiratory distress syndrome, are known causes of mortality following thoracic trauma (76). However, no systematic review is available on the influence of comorbidities on mortality.

1.2 Epidemiology of major vascular trauma

Studies on the epidemiology of major vascular injury are difficult to compare due to a lack of uniformity in injury descriptors, comparable outcome metrics, and follow-up periods (16). In epidemiological research on trauma, it is important to identify risk factors for injury and death, in addition to defining which individuals are at the most risk and determining where the public health problem is greatest. There is a need to monitor the incidence over time as well as the effectiveness of injury prevention and management. Such information can help in decision making to create better health programmes with suitable priorities and hopefully, lower the incidence of injuries and improve patient outcomes (77).

Although serious vascular injuries are not a common cause of death, many patients die from such injuries in motor vehicle accidents and a majority of deaths occur on-site. The proportion of deaths occurring immediately after trauma has remained at 50–60% over time, despite advancements in prehospital care, injury prevention, automotive safety, emergency medical services, and transportation (78). Among those who reach the hospital alive, the mortality rate is also high (up to 30%) (11, 12, 79, 80).

Table 2 presents an overview of selected published studies on vascular injuries, mechanisms of injury, and mortality in Europe, Australia, and North America. Most studies on vascular trauma emanate from countries with well-organised and specialised trauma centres. Barmparas et al. (2010) examined the national US trauma database and found that approximately 1.6% of injuries occurring among US civilians were vascular injuries (79). Similar findings have been reported in Australia, where 1–4% of admitted trauma patients had vascular injuries. The highest mortality rate was recorded among persons with thoracic and abdominal injuries (11, 81, 82). However, the incidence is often not registered in studies when analysing vascular trauma data.

Table 2. Overview of selected published studies on vascular injuries, mechanisms of injury, and mortality from Europe, Australia, and North America

Country	Study period	Inclusion criteria	Proportion of all trauma admissions (%)	No. Patients with vascular trauma	Blunt (%)	Mortality rate (%)	RTA (%)	Surgical repair (%)	Endovascular treatment (%)	Amputation	Authors
Sweden	1987–2005	Hosp., non IVT	NR	965	45%	3%	NR	93%	3%	NR	Rudström et al. (83)
Australia	1995–1999	Hosp., non IVT	1.8%	169	58%	26%	43%	NR	NR	NR	Sugrue et al. (11)
Australia	1994–2000	Hosp., non IVT	1%	153	56%	30%	72%	NR	NR	NR	Gupta et al. (81)
US	2002–2006	Hosp., adults, non IVT	1.6%	20951	48%	23%	32%	NR	NR	12%	Barmparas et al. (79)
UK	2005–2010	Hosp., ≥14 years, non IVT	4%	256	47%	18%	31%	93%	21%	12%	Perkins et al. (12)
Finland	2006–2010	Hosp., non IVT	NR	143	38%	0%	NR	94%	11%	2%	Poyhonen et al. (84)
Canada	2011–2015	Hosp., adults, non IVT	NR	1330	63%	24%	36%	68%	10%	2%	Smith et al. (85)
US	2013–2014	Hosp., non IVT	NR	542	47%	13%	34%	49%	7%	8%	Dubose et al. (86)
Australia	2014–2019	Hosp., ≥14 years, non IVT	3.9%	213	69%	8.5%	44%	NR	NR	4.7%	Weller et al. (82)

Hosp., hospitalised; IVT, iatrogenic vascular trauma; NR, not recorded; RTA, road traffic accident

1.2.1 Vascular trauma and motor vehicle accidents

Road traffic accidents, suicides, and homicides are the three leading causes of injury and violence-related deaths according to the World Health Organization (87). More than 1.2 million people die each year worldwide in road traffic accidents (**Figure 2**). Furthermore, it is estimated that approximately 50 million people worldwide are seriously injured each year (5, 88) and about 30% of these victims die at the scene (89).

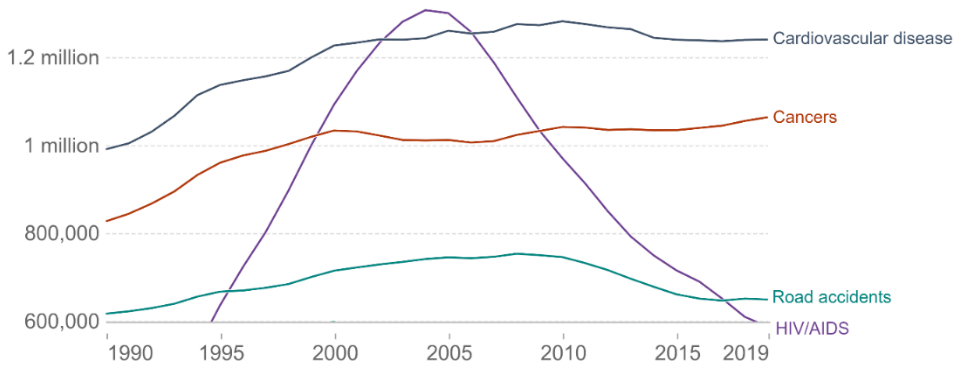

Figure 2. Annual number of deaths by cause among people aged 15–49 years worldwide, between 1990–2019, according to the Global Burden of Disease Study. Adapted and used with permission (5)

Across Western Europe and Japan, annual death rates due to road traffic accidents are typically lower than 5 per 100 000 individuals, which is the lowest worldwide. In North America, these rates are typically higher, or around 5–20 per 100 000. In contrast, in Sub-Saharan Africa, these rates are usually much higher at over 25 per 100 000 (5) (**Figure 3**). In Iceland, a country with a population of 370 000, about 35–40 individuals die every year due to trauma and about 50% of these occur following motor vehicle accidents (90).

In 2019, Iceland recorded one of the lowest age-standardised injury-related death rates worldwide, at 2.9 deaths per 100 000 people (5). In Norway, approximately 2500 individuals die due to trauma every year, accounting for about 6% of all deaths in the country (91). In 2019, the incidence rate of motor vehicle-related deaths in Norway was 3.15 per 100 000 people (5) (**Figure 4**).

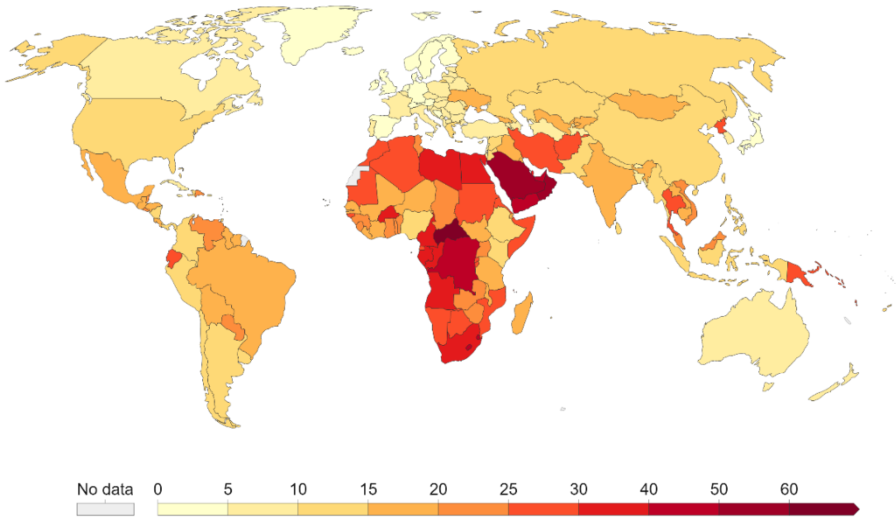

Figure 3. Annual number of deaths in 2019 from road traffic accidents per 100 000 people. Deaths include those occurring among drivers, passengers, motorcyclists, cyclists, and pedestrians according to the Global Burden of Disease Study. Adapted and used with permission (5)

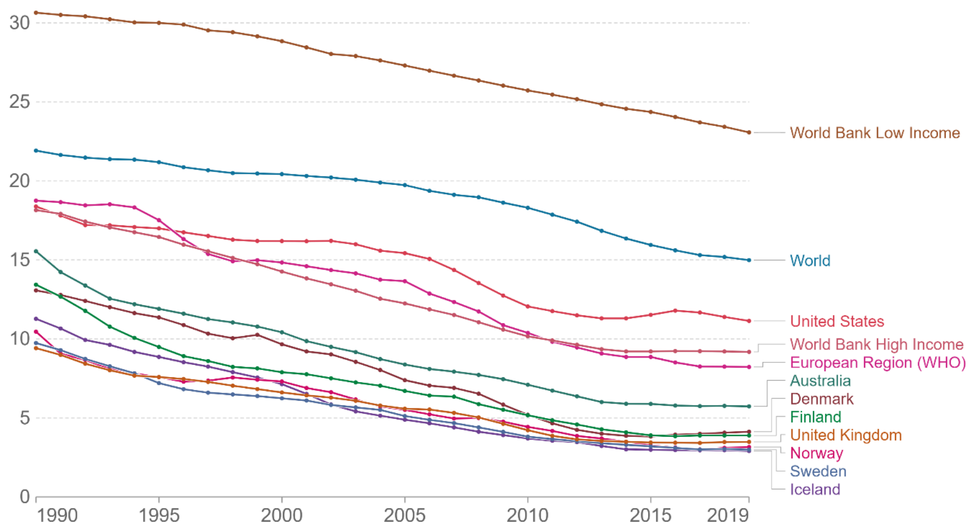

Figure 4. Annual number of deaths (from 1990– 2019) due to road traffic accidents per 100 000 people according to the Global Burden of Disease Study. Adapted and used with permission (5)

Traffic accidents are the main cause of serious vascular injuries among civilians and one of the main causes of death among people aged 15–29 years (88, 92). Many people die or sustain permanent serious injuries related to severe vascular injuries, and about 18–24% of these people die after arriving at the hospital (12, 79, 80, 88, 93). The introduction of security and restrain systems for passengers in automobiles has resulted in more survivors of traffic accidents. Simultaneously, the incidence of blunt cerebrovascular and thoracic arterial injuries has increased (94).

The high mortality rate among patients who sustained vascular trauma in traffic is due to transections of the thoracic aorta and major injuries to the abdominal veins (95). Up to 80% of these injuries result from high-speed road traffic accidents, in which injury occurs after rapid deceleration following head-on or side-impact collisions (96). Head-on collisions are frequent when traffic streams are not separated using barriers and they are the most likely type of collision to cause fatality and severe injury (93).

Traumatic aortic injury accounts for 16–29% of motor vehicle-related deaths, and this has not changed during the past decade (97, 98). Newman et al. (1983) studied all individuals injured in car accidents in the UK, including those who died before admission. The researchers found that aortic injury was responsible for 17% of traffic fatalities (99). Sturm et al. (1988) examined the on-scene death rate among patients with traumatic aortic rupture in the US and found that 68% died before hospital admission (100). In addition, Hunt et al. (1996) analysed data from the North Carolina Trauma Registry from 1988–1994 and reported that 44% of patients with aortic rupture that made it to the emergency department died due to the injury (101).

1.3 Pathophysiology and clinical signs of thoracic injury and major vascular injury

1.3.1 Thoracic injury

Chest injuries can interfere with respiration and/or blood circulation. Contusions of the chest wall in the pattern of seatbelts, pain over the ribs, decreased breath sounds, tachypnoea, and hypoxia, are all symptoms suggestive of thoracic trauma (102). The most important and severe forms of thoracic trauma include injury to the aorta, blunt cardiac injury and cardiac tamponade, flail chest, haemothorax, pneumothorax, and pulmonary contusion (103)

Thoracic injuries are associated with an increased risk of serious intrathoracic and abdominal injuries, including flail chest, sternal fracture, posterior sternoclavicular dislocation, scapula fracture, and multiple rib fractures, as well as displaced rib fractures (104). Almost two-thirds of patients admitted following a motor vehicle collision with thoracic injuries sustain rib fractures (105).

Sternal fractures are mainly caused by a high-energy blow from the steering wheel. About 18% of multiple trauma patients with thoracic injuries have a fractured sternum. Seat belts that are positioned over the shoulder, as well as missing or failing airbags, can also contribute to such injuries (106).

Direct damage to the lungs or airways, as well as altered mechanics of breathing, compromise respiration. Pulmonary contusion and tracheobronchial disruption can result from direct damage to the lungs or airways and can manifest clinically as subcutaneous emphysema and pneumo-mediastinum. Haemothorax, pneumothorax, and flail chest can alter the mechanics of breathing. Tension pneumothorax refers to the accumulation of air in the pleural space under pressure and can swiftly impair respiration and circulation. Furthermore, bleeding, decreased venous return, and direct cardiac injury can impair blood circulation, and massive bleeding can cause shock and decreased venous return with impaired cardiac filling (27).

Symptoms of thoracic injury include pain related to breathing and sometimes shortness of breath. Common findings include chest tenderness, ecchymosis, and respiratory distress; hypotension or shock may also be present. Patients with acute cardiac tamponade can present with a collection of three clinical signs associated with low arterial blood pressure, distended neck veins, and distant, muffled heart sounds, which are often referred to as Beck’s triad (107). Patients with tension pneumothorax may also have arterial hypotension, tracheal deviation, and neck vein distention (103).

1.3.2 Major vascular trauma

Vascular traumatic injury is mainly characterised by damage to the veins and arteries. Haemorrhage and ischaemia are clinical manifestations of vascular trauma and can be life-threatening and usually require emergency care (108). The leading cause of potentially preventable deaths among injured patients is uncontrolled bleeding from trauma to the major arteries (95, 109). Transection of the thoracic aorta and major injuries to the abdominal veins are associated with the highest mortality rate (95).

Vascular trauma can result in an extremely high rate of mortality and morbidity, particularly if its diagnosis or treatment is delayed (98). Early diagnosis of significant vascular injury is crucial and relies almost entirely on physical examination. If a major vascular injury is present, immediate intervention is usually required in the form of open surgery or endovascular repair (108). The two main consequences of vascular trauma are haemorrhage and ischaemia. If unrecognised and uncontrolled, it can quickly lead to limb loss, stroke, bowel necrosis, multiorgan failure, or rapid blood loss with shock and death (108, 110).

The signs of vascular injury are usually classified into hard and soft signs. Hard signs include arterial bleeding, expanding or pulsatile haematoma, and lack of distal pulse, bruit, thrill, and shock with no other explanation. Neurological defect is a soft sign of vascular injury along with non-expanding, non-pulsatile haematoma and a history of profuse or pulsatile bleeding (98). In 97% of patients, hard signs are predictive of significant vascular injury (111).

In ischaemia, there is an acute interruption of blood flow to an organ or limb with an interruption of delivery of oxygen and an accumulation of toxic metabolites. Anaerobic metabolism takes over if there is insufficient oxygen to meet demand. Skeletal muscles can recover function if arterial supply is re-established within 3–6 h. Peripheral nerves, on the other hand, are much more sensitive to ischaemia, such that even a short period of tissue ischaemia can lead to prolonged neurological deficit (112).

The most common form of vascular trauma is laceration with complete or incomplete transection. Compared to complete transection which leads to retraction and vasoconstriction of a vessel with limited bleeding, partial transection tends to result in more severe bleeding (108, 112).

1.3.3 Blunt and penetrating injury

$$KE = \frac{1}{2}MV^2$$

Equation 1. The kinetic energy (KE) transferred to the tissues is a function of mass (M) and velocity (V)

Trauma is frequently categorised based on location and mechanism of injury. The most common mechanisms of injury are blunt and penetrating injuries. The severity of vascular trauma is proportional to the amount of kinetic energy transferred to the tissues (**Equation 1**). This is true for both blunt and penetrating injuries (111).

Studies of hospitalised trauma patients show that blunt trauma patients often have higher ISS compared to those with penetrating trauma as well as a higher mortality rate and risk for limb amputation. They are also twice as likely to require massive blood transfusions and have longer hospital stays (113). Blunt force trauma can lead to vessel wall injury. Shearing and compressive forces can lead to vascular contusion, laceration, transection, and dissection (114), and usually result from high-impact trauma with rapid deceleration forces (115). The most frequently injured blood vessels in blunt trauma are the iliac vessels, internal carotids, brachial arteries, and the thoracic aorta (114).

Penetrating injuries can be serious and result in infection, shock, exsanguination, and death (23). Penetrating vascular injury often leads to partial and total transection of an artery or vein (116). Full transection of a vessel can lead to spasms and the formation of blood clots; thus, massive bleeding is more common following vessel laceration (117). The most frequently injured vessels in penetrating trauma are the brachial artery and superficial femoral artery; however, penetrating trauma to the aorta most often occurs secondary to gunshot and stab injury (118). Although such injuries are fortunately uncommon, they are highly lethal, with a mortality rate of up to 90% and most patients dying before reaching the hospital (115).

Table 3. Overview of selected published studies on penetrating stab injuries from Europe and Australia (7)

Country	Study period	Inclusion criteria	No. of stab injuries	Mortality rate (%)	Authors
Belgium	2000–2007	Hosp./ABR	170	0%	El-Abdellati et al. (119)
Australia	1998–2005	Hosp./ABR	1550	0.2%/2.3%	Jacob et al. (120)
Australia	1991–2001	ISS >15/ABR	98	15%	Wong et at. (25)
Sweden	1987–1994	Hosp./ABR	1315	3.4%	Bostrom et al. (121)
Sweden	2000–2009	Hosp./Abd	6	0%	Pekkari et al. (122)
Finland	1997–2011	Hosp./Thx and Abd	130	5%	Inkinen et al. (123)
Norway	1980–1987	Hosp./Abd	111	2%	Nesbakken et al. (124)
UK	1997–2005	Hosp./ABR	33903	0.45%	Maxwell et al. (22)
UK	2012–2014	Hosp./Abd	111	NR	Fisher et al. (26)
UK	1978–1983	Hosp./ABR	201	0.5%	Stebbings et al. (125)

Hosp., hospitalised; ABR, all body regions; NR, not recorded; Thx, thorax; Abd, abdomen

In some parts of the world such as the US, South Africa, and Australia, penetrating trauma, either from gunshot wounds or stab injuries, is a major public health problem (19, 21, 23). In Northern Europe, however, penetrating injuries are a less frequent cause of mortality and morbidity (24, 122-124). Furthermore, in the Nordic countries, the US, and Australia, stab injuries are more common than gunshot wounds (122, 123); this is in contrast to South Africa where gunshot-related injuries are far more common (21, 23, 126). The associated mortality rates are often in the range of 2–15% and the variation can to a certain degree depend on the cohort of patients studied, such as if they are from a low or high-volume centre, as well as differences in inclusion criteria (25, 124) (**Table 3**).

1.3.4 Vascular neck injury

Vascular injury may be present in 3–20% of patients admitted with craniocervical injury and can be present in approximately 1% of all trauma patients admitted due to blunt force trauma (127-129). Due to their anatomical location, such injuries can be difficult to manage. Injury to the vascular structures in the cervical region can cause haemorrhage, vessel occlusion, and thromboembolic stroke (128). Vascular trauma to the neck and thoracic outlet can be highly lethal and cause serious neurological deficits.

Approximately 5% of traumatic injuries to the cervical region are due to blunt force trauma and are rarely isolated injuries (130). Blunt cervical trauma is seen in about 1% of patients who sustain significant blunt trauma. These patients have a poor prognosis with a mortality rate of 31–59% and a stroke rate of 25–58% (111). Fabian et al. (1996)

analysed data regarding blunt carotid artery injuries over an 11-year period at a level 1 trauma centre and reported stroke and mortality rates of 43% and 31%, respectively (131). In another study conducted in North America, Biffl et al. (1998) found that 0.86% of all trauma admissions had a blunt carotid arterial injury that resulted in 32% of the patients succumbing and 15% of the survivors sustaining a stroke (94). Motor vehicle accidents are the leading cause of blunt vascular injury in the neck. Other causes include assault with a direct blow or strangulation and falls (129). Patients with multiple injuries can have few signs of blunt cervical trauma and timely imaging is therefore crucial.

Penetrating trauma to the vessels in the neck comprises as much as 5–10% of all admitted cases of injury, and results in a mortality rate as high as 10% (130). Furthermore, vascular injuries are present in up to 40% of patients with penetrating neck injuries (130). Carotid artery injuries constitute approximately 22% of all cervical vascular injuries and most often involve the common carotid artery (75%) with associated mortality and stroke rates of about 31% and 23%, respectively (132-134). Penetrating cervical trauma is less common in Western Europe than in South Africa and the US (135). In the US, most penetrating neck injuries in the adult population occur secondary to assault and contribute to less than 2% of all reported injuries (62).

1.3.5 Vascular injury to the torso

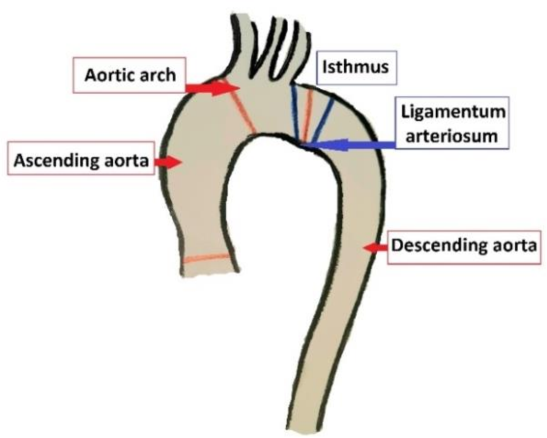

Figure 5. The anatomy of the aorta, demonstrating the location of the isthmus

Injury to thoracoabdominal vessels can lead to significant but sometimes occult haemorrhage into the thorax, abdomen, or retroperitoneum. Clinical signs can be unreliable, and delays in recognition and management increase the risk of death (98, 135). Thoraco-abdominal vascular trauma is reported to constitute 0.01–2% of all trauma admissions (136-138). In 70–95% of cases, the injury is due to penetrating trauma (136, 138-140). Road traffic accidents are the most common cause of blunt thoracoabdominal trauma followed by falls from heights (141-145).

The mechanism of injury in blunt aortic injury is usually high-energy trauma, such as those resulting from a road traffic accident or a fall from a height. Blunt thoracic injury is the second leading cause of death, after head injury, in polytrauma patients (144, 146). Thoracic aortic injury accounts for 16–29% of motor vehicle fatalities (142, 144, 147, 148). Following blunt thoracic trauma, injury can occur along the entire length of the aorta, primarily from the ascending aorta to the iliac bifurcation, although the injury typically occurs at the aortic isthmus or in about 90% of cases (149-151). The isthmus refers to the portion of the proximal descending thoracic aorta between the origin of the left subclavian artery and the ligamentum arteriosum (152) (**Figure 5**). The injury is believed to result from a combination of sudden deceleration associated with torsion, stretching, and shearing forces, in addition to thoracic compression. The ascending aorta is the most often affected part, in approximately 10–25% of cases (115, 151). Blunt traumatic aortic injury is uncommon. In a study conducted by Ungar et al. (2006), 2% of patients admitted in Colorado, US, with blunt chest injury after motor vehicle collision sustained an injury to the thoracic aorta (153). Approximately 80% of patients die before reaching the hospital and around 19% die during triage after being admitted to the hospital (154, 155).

Clinical diagnosis of thoracic aortic injury can be difficult because of non-specific and distracting injuries that are often present. Blunt thoracic aortic injury rarely occurs in isolation and the patient can present with chest or mid-scapular back pain, signs of external chest trauma, or haemodynamic instability. Trauma to the aorta may result in minimal aortic injury, laceration, transection, pseudoaneurysm, and intramural haematoma (148). An aortic dissection, however, is rarely a sequela of trauma (146).

Abdominal aortic injuries are a rare form of traumatic aortic injury. Less than 1% of admitted blunt trauma patients sustain aortic injury, and only 5% of injuries are located in the abdominal aorta (156). The most common cause is deceleration in motor vehicle accidents, and the trauma can cause intimal tears, pseudoaneurysm, and aortic transection (157). The most common location of injury is at the level of the inferior mesenteric artery (≈ 33%) and renal arteries (≈ 25%) as well as inferior to the inferior mesenteric artery (20%) (157). Following blunt abdominal aortic trauma, about 50% of patients also have retroperitoneal haematoma, and up to 40% have bowel and mesenteric injuries (158).

Subclavian artery injuries are uncommon, constituting less than 3% of all penetrating trauma cases and only 0.4% of blunt trauma cases. These injuries are associated with a high mortality rate, and up to 42% of trauma patients die before hospital admission or upon presentation to the hospital (159, 160). In a study conducted in California, Demetriades et al. (1999) reported an overall mortality rate of 34.2% among patients admitted with subclavian and axillary vascular injuries. Furthermore, the mortality rates for isolated arterial and venous injuries were 20.5% and 50%, respectively, and 45.0% for both vessels (159).

Injuries to the abdominal visceral vessels are uncommon but linked to a high rate of mortality due to exsanguinating haemorrhage (137, 161). The subsequent vascular repair can be complex and often unsuccessful. The reason for delayed death in those who survive the primary surgical procedure is usually sepsis or multiple organ system failure following intestinal ischaemia (141, 162). Penetrating abdominal injuries account for 90–95% of these injuries, including injuries to the visceral blood vessels, and are usually the result of missile injuries and stab wounds. Visceral vascular injuries caused by blunt trauma, however, most commonly occur in the superior mesenteric artery (137, 163).

Traumatic venous injury of the abdomen is associated with a high mortality rate of 50–70%, particularly for injuries to the superior mesenteric vein, the portal vein, and the inferior vena cava (137, 164, 165). In addition, up to 50% of trauma patients with injury to the inferior vena cava die before reaching the hospital (166).

Abdominal and pelvic vascular trauma account for approximately 30% of all cases of vascular trauma. They can be difficult to manage due to concomitant injuries. In 90% of cases, they are associated with penetrating injuries (135, 136).

Injuries to the iliac arteries and veins account for 11% of all vascular injuries, making them some of the most common injuries to truncal vascular structures. However, the survival rate is only about 50%. When the injury follows blunt trauma, which rarely is the case, it is associated with significant morbidity (15, 98, 167, 168). Iliac artery injury most often occurs due to penetrating trauma, and only 3.5% of all cases of severe pelvic fracture occur with a blunt force trauma mechanism. Pelvic injury is associated with a high morbidity rate (167, 169).

1.3.6 Peripheral vascular injury

Peripheral vascular injuries are defined as those affecting the axillo-brachial vessels and branches in the upper extremity and the femoropopliteal or more distal branches in the lower extremity. Due to the anatomical location of these arteries and veins in the limbs, they are vulnerable to penetrating and blunt trauma (170). Peripheral vascular injuries account for 40–75% of all admitted cases of vascular injury among civilians (18, 170). They are present in less than 5% of admitted cases in rural centres and 1% of admissions in urban trauma centres (18, 140). Nevertheless, these injuries are associated with significant morbidity and loss of function in young patients (135). The primary goal should therefore be to prevent amputation of the injured extremity.

Vascular injuries of the lower extremity are more common than those of the upper extremity and a majority are due to penetrating trauma (171). Injury to vessels in the limbs generally results in haemorrhage or haematoma formation that is visible on clinical exam. Usually, the injuries can also be easily controlled in the field by direct pressure or tourniquet application which increases the likelihood that the patient would present to the hospital in a stable condition (98). Lower limb arterial injury is associated with a high amputation rate of up to 12% (12, 79). The likelihood of subsequent amputation is increased after blunt trauma and in the presence of extensive soft tissue injury or fracture (135).

Penetrating injury accounts for up to 80% of cases of peripheral vascular trauma in the US. Approximately every other injury results from bullets from handguns and one in three are stab wounds (170). In European countries where firearms are less available, gunshot wounds cause peripheral vascular injuries in only 5% of cases (171, 172).

One of the worst early complications of peripheral vascular injury is compartment syndrome. It results from swelling of muscle in a confined space limited by fascia, causing intracompartmental hypertension and potentially leading to muscle necrosis. The causes are decreased perfusion and ischaemia, intracompartmental haemorrhage, or reperfusion oedema after revascularisation. The compartments most likely to develop acute compartment syndrome are below the knee, although it can occur in any area of the body with closed compartments (173, 174).

1.4 Diagnostic imaging in thoracic and vascular injury

When treating a bleeding trauma patient, early diagnosis of significant vascular injury is crucial for improving the likelihood of a favourable outcome. This is also true after admission to the hospital (108, 175). Adequate availability of imaging technology can help in planning incisions and the operative strategy. It can also aid in evaluating if the patient should undergo endovascular therapy.

Stable patients with suspected vascular injury have multiple screening options available that can significantly influence the course of care (98). Imaging options include magnetic resonance imaging, magnetic resonance angiography (MRA), ultrasound, traditional angiography, and computed tomography angiography (CTA) (98). Blunt cerebrovascular and thoracic arterial injuries can be difficult to detect early without the assistance of imaging studies (176).

A chest x-ray is the standard when evaluating severely injured trauma patients with chest injuries. It is a widely available and quick imaging procedure that can diagnose injuries such as pneumothorax, haemothorax, clavicular fractures, and most rib fractures, as well as moderate or severe pulmonary contusions. A conventional x-ray can detect aortic injury with widening of the mediastinum (often over 8 cm) when taken in the supine position. The sensitivity for detecting aortic injury is high; however, it has a low specificity due to other causes of mediastinal haematoma, such as tearing of the mediastinal vessels, sternal injury, or thoracic spine injury (177). Among patients with blunt aortic injury, 7—44% of cases may present a normal mediastinum on conventional chest x-ray, for which reason CT is the diagnostic test of choice (178-180).

CTA has become the main screening tool for traumatic aortic injury and is increasingly more commonly used in diagnosing vascular injury in the upper and lower extremities. It is fast, easy, has a low complication rate, and can be performed with significantly less contrast and radiation exposure compared to traditional angiography. CTA also gives information on non-vascular structures. Its accuracy has improved over time with improved CT scanners and increased expertise in the interpretation of the images. On the other hand, the limitations of CTA include patient transportation and exposure to contrast and ionising radiation (98, 135, 181). Today, CTA is considered the first-line investigation for all patients with suspected vascular trauma, except when there is an indication for immediate operative intervention (135).

Ultrasound in trauma settings, or eFAST (extended focused assessment with sonography in trauma), has the benefit of being portable and non-invasive and the physician can obtain information rapidly. The examination is usually done during the resuscitation phase. The procedure is, however, highly operator-dependent and the results are limited in the presence of soft tissue injuries. The reported sensitivity of eFAST ranges from 50–100% (98).

Although MRA in non-traumatic vascular lesions can provide accurate images, the study can take a long time and is susceptible to motion artefacts. It is therefore not advised in unstable patients or patients with metallic fragments (98, 182).

Traditional angiography as a screening tool in trauma has a reported sensitivity of 95–100% and a specificity in the range of 90–98% (183). However, similar to MRA studies, it can be time-consuming and also requires the administration of an iodinated contrast medium. Furthermore, it requires an advanced imaging team with specialised training and is therefore not always available in acute circumstances in most trauma centres (98).

1.5 Management of thoracic trauma

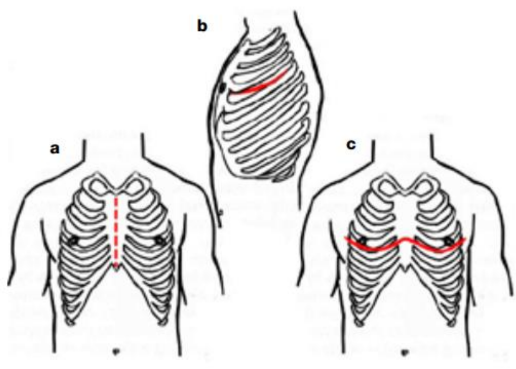

Figure 6. Different types of chest cavity openings when treating traumatic injury to the thorax. a. Sternotomy. b. Left anterolateral thoracotomy. c. Clam-shell thoracotomy (9)

Individuals who sustain chest trauma may initially have mild symptoms that do not necessarily reflect the severity of internal injuries, and can lead to rapid death in trauma patients (184). In most cases, however, chest injuries are minor, such as rib fractures, and most patients with chest injuries do not require emergency surgery. Actually, only about 10–15% of such patients require treatment in the form of open surgery or endovascular treatment (185, 186). In major penetrating thoracic vascular injury, the need for early surgery is determined solely based on clinical assessment (98, 135).

A chest drain is often inserted in patients with thoracic injury, for instance, if there is bleeding in the pleural cavity or lung collapse due to pneumothorax. In the presence of more severe damage to the chest cavity and severe intrathoracic bleeding, it is sometimes necessary to perform an emergency thoracotomy, even on the scene, during transport, or when the patient arrives in the emergency department (187). The chest cavity is then opened via thoracotomy between the ribs or with a sternal incision so that the heart, lungs, and large vessels in the chest cavity can be accessed **(Figure 6)**. These procedures allow for life-saving procedures such as direct cardiac massage, evacuation of blood from the pericardium, and control of bleeding.

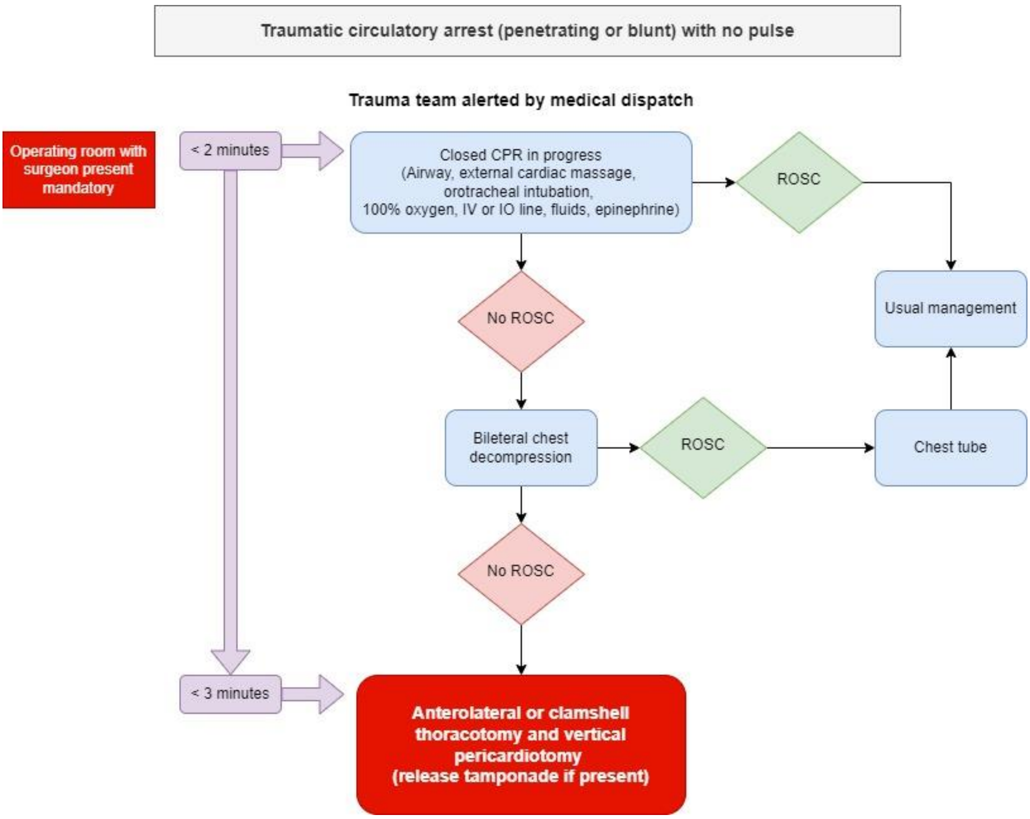

Figure 7. Adjusted algorithm for the management of traumatic circulatory arrest according to the ATLS, 10th edition. ROSC, return of spontaneous circulation (6)

According to the 9th edition of the Advanced Trauma Life Support (ATLS) guidelines, emergency thoracotomy is rarely indicated (188). Furthermore, it is recommended that only qualified surgeons perform this procedure for patients that arrive pulseless after penetrating thoracic injuries, but have myocardial electrical activity. If there are no signs of life, no further resuscitative efforts should be made. If the procedure is performed for the correct indication, in a highly selected patient group and by an experienced surgeon, it appears to save lives (6) (**Figure 10**). Its drawbacks include high costs and the risks of blood-borne infections to the operating team (189-191).

In a review conducted by Cothren et al. (2006), patients with penetrating cardiac wounds who presented with hypovolemic shock in the emergency department and underwent treatment via emergency thoracotomy showed an approximate survival rate of 35%, as compared to 15% among all patients with penetrating injury. The worst outcome following emergency thoracotomy was documented after blunt trauma, with only a 2% survival rate for patients with shock and a survival rate of less than 1% if the patient had no sign of life (49). In a meta-analysis conducted by Rhee et al. (2000), the mean survival rate after penetrating thoracic trauma was reported as 19% (range, 5.1–72.2%) (192). It is therefore important to analyse the outcome of this procedure at both large and small trauma units. Large trauma centres in the US and South Africa have mostly gained experience with emergency thoracotomy. In those countries, penetrating chest trauma is far more common than in Europe (51, 187). However, in small trauma centres in Europe, where blunt trauma is much more common than penetrating injuries, there has been a lack of studies on emergency thoracotomy and its outcomes (51). To date, two Norwegian reports have been published on emergency thoracotomy, one from a trauma unit in Stavanger with no survivors out of 10 patients (51) and another from Oslo with a survival rate of 18% among 105 emergency thoracotomies performed (193). The indications for the procedure are constantly debated, particularly in patients with blunt trauma, among whom less than 2% of patients survive the procedure (ranging from 0–2%) (49, 50). For penetrating trauma, particularly if the heart is the only structure affected, the survival outcomes have been more encouraging at up to 35%, according to a literature review (49).

1.6 Management of vascular trauma

Vascular injuries (to both arteries and veins) most often require immediate treatment. Bleeding and ischaemia are the primary manifestations of vascular injury, and delay in instituting appropriate treatment can lead to amputation or even death (108). Management strategies have evolved over the last decade, as speed in diagnosis and treatment is vital for favourable outcomes (95). Although open procedures, often involving vascular prostheses, have been the mainstay of treatment for decades, invasive endovascular techniques are increasingly being applied in the management of vascular injuries (98). In the past decade, the use of endovascular techniques to treat vascular trauma has increased; however, few trauma surgeons possess an advanced catheter-based skill set (95, 194). A study of data from the NTDB from 1997 to 2003 showed a significant increase in the number of endovascular treatment procedures, particularly from 2000–2003 when the rate increased from 2.4% to 8.1% (98).

The benefits of a hybrid approach in trauma and resuscitative endovascular balloon occlusion of the aorta (REBOA) have in previous research been well-established in the management of haemodynamically unstable trauma patients (195). Endovascular techniques offer the ability to treat injuries in anatomically difficult areas such as the suprarenal aorta, retro-hepatic inferior vena cava, and high cervical carotid vessels and are more frequently applied in the treatment of acute vascular trauma (80, 98). Endovascular treatment has some advantages over open surgery, including decreased ischaemic time since there is no need for cross-clamping of the vessel. Pain related to the incisions is also less, complications related to laparotomy and thoracotomy are

Figure 8. A hybrid operating theatre at Haukeland University Hospital (4)

avoided, and recovery time and length of hospital stay are shortened (98). Endovascular procedures, however, must be performed in specially equipped operating theatres with specialised staff and facilities that are not available in all hospitals, not even some tertiary trauma care centres. Tertiary care centre is defined as facility that can give highly specialised medical treatment (48). Currently, there is a shortage of endovascular physicians involved in trauma care in many countries (196). In Iceland, these skills are only in the hands of 2–3 radiologists and vascular surgeons and therefore have not become the standard.

Although endovascular therapy is constantly evolving and moving forward, there are still concerns regarding long-term patency, device failure, migration, leakage, and deformation over time (98).

When normal blood flow is re-established, reperfusion injury to the tissue can occur alongside endothelial damage, which can lead to oedema, microvascular thrombosis, and tissue necrosis. The use of shunts and thus early restoration of perfusion reduces circulating markers of tissue injury (197).

In patients with haemorrhagic shock, transfusion support is vital in addition to choosing the right component. Early and increased use of packed red blood cells, thawed plasma, and platelets, while limiting the use of crystalloid fluids have been established as an effective strategy in the treatment of haemorrhagic shock (198-200). It moderates the ischaemic reperfusion response and extends the ischaemic threshold (201). Transfusing fresh red blood cells increases oxygen delivery and freshly thawed plasma can reduce the incidence of reperfusion injury (202, 203). In addition, numerous studies have suggested that crystalloid resuscitation leads to some harmful effects (204, 205).

1.7 Evaluating trauma with injury scores

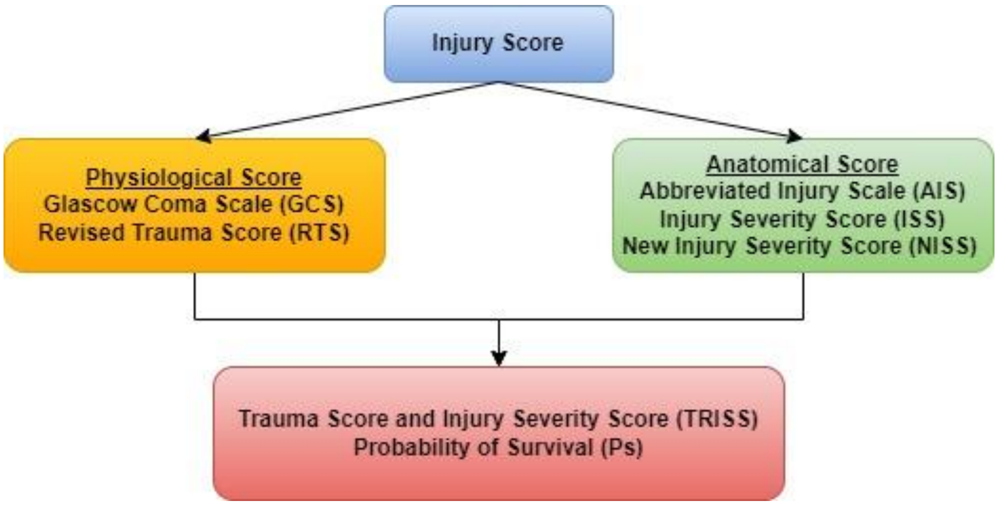

Figure 9. Flowchart showing the use of injury scores in trauma evaluation

The severity of injuries can be considered from two concepts: anatomical severity and physiological severity. Mortality and the probability of survival can be assessed by assessing the severity of the injury. When evaluating injury severity, injury scoring systems such as the ISS and New ISS (NISS) can be used. The ISS and NISS are anatomical scoring systems based on the AIS, which provides a reasonably accurate ranking of the severity of injury with a score from 1–6 (206). The ISS and NISS yield scores ranging from 0 to 75 and a score higher than 15 is considered representative of severe injury. However, studies have shown that the NISS statistically outperforms the ISS when analysing the data of patients with multiple injuries within the same body region (172, 206-208). The Revised Trauma Score (RTS) incorporates physiological status on first medical contact (Glasgow coma scale, respiratory rate, and systolic blood pressure). The parameters are converted to coded values that are assigned by specified ranges 0-4 (**Table 5**). It can be used for field triage and helps in evaluating which patients should undergo treatment at a specialised trauma unit (RTS <4) (151, 209, 210). The RTS makes it possible to calculate the probability of survival (P_S) using the TRISS (Trauma Injury Severity Score) methodology (211, 212) (**Figure 9**).

Table 4. Scoring systems most often used in the evaluation of the severity of injury, probability of death, and the likelihood of survival after trauma (103, 207, 209, 210)

Score	Function	Calculation	Variables and methods	Score interpretation
GCS	Physiological scoring system Brain function Patient survival	Eye opening (1–4) + Best verbal response (1–5) + Best motor response (1–6)	Based on the cerebral response to stimulation	Ranges from 3–15
AIS	Anatomical scoring system Patient survival		The scoring system classifies each injury by body region on a 6-point scale.	Ranges from 1–6
ISS	Anatomical scoring system Patient survival	$A^2+B^2+C^2$	The body is divided into six anatomical regions. A, B, and C are the highest AIS grade of the three most injured body regions.	Ranges from 0–75 ISS > 15 with major trauma
NISS	Anatomical scoring system Patient survival	$1X^2+2X^2+3X^2$	The body is divided into six anatomical regions. 1–3X are the three highest AIS grades regardless of the body region.	Ranges from 0–75 NISS > 15 with major trauma
RTS	Physiological scoring system Patient survival	(0.9368 × GCS value) + (0.7326 × SBP value) + (0.2908 × RR value)	Respiratory rate (RR), systolic blood pressure (SBP), Glasgow Coma Scale (GCS)	Ranges from 0–7.84
TRISS	Combination scoring system Patient survival	$\frac{1}{1+e^{-b}}$ ¥	RTS, ISS, age, blunt or penetrating mechanism of injury	Ranges from 0 (unsurvivable)–1 (high likelihood of survival)

¥ *bBlunt = –0.4499 + 0.8085 × RTS–0.0835 × ISS–1.7430 × Age Index / bPenetrating = – 2.5355 + 0.9934 × RTS –0.0651 × ISS–1.1360 × Age Index / Age Index.* In the formula, patients younger than 55 years are scored 0 and patients aged 55 years and older are scored *1.*

Table 5. The Revised Trauma Score coding (210)

CODED VALUE	*GCS*	*SBP*	*RR*
4	*13-15*	*>89*	*10-29*
3	*9-12*	*76-89*	*>29*
2	*6-8*	*50-75*	*6-9*
1	*4-5*	*1-49*	*1-5*
0	*3*	*0*	*0*

The ISS, RTS, and TRISS are considered traditional trauma scoring systems. They were designed to predict mortality based on the entire spectrum of trauma patients. These scoring systems, however, often underestimate the risk of mortality when vascular trauma is present in multi-trauma patients. The TRISS scoring system is the most accurate in predicting mortality in vascular trauma because it combines anatomic and physiologic parameters. However, the TRISS does not weight factors specific to vascular injuries and is therefore considered to underestimate actual mortality (80). In a recent study, Höke et al. (2021) compared trauma severity scores and the TRISS score was shown to be the most successful score in predicting mortality among trauma patients. On the other hand, the NISS was the most successful in predicting intensive care unit (ICU) admission. In the same study, the most sensitive scoring system was the ISS, whereas the RTS was shown to be the most specific scoring system (213).

1.8 Evaluating comorbidities, complications, and outcomes

The effect of comorbidities on the clinical course of a patient can be assessed with different scoring systems, such as the American Society of Anesthesiologists (ASA) score, Charlson Comorbidity Index (CCI), and Comorbidity Polypharmacy Score (CPS).

Table 6. The ASA classification modified from the American Society of Anesthesiologists guidelines (214)

Classification	**Definition**
ASA I	A normal healthy patient
ASA II	A patient with mild systemic disease
ASA III	A patient with severe systemic disease
ASA IV	A patient with severe systemic disease that is a constant threat to life
ASA V	A moribund patient who is not expected to survive without the operation
ASA VI	A patient declared brain dead, and whose organs are to be removed for donor purposes

The ASA classification is well known and has been widely used in the health care system for more than 60 years. The classification system is based on morbidity and comorbidity, and is used to estimate the operative risk of a patient based on six categories **(Table 6)** (214, 215).

The CCI can be used to predict 10-year survival in patients with multiple comorbidities by allocating points for comorbidities and age. The index consists of 17 variables and yields a total score ranging from 0 to 33 points (8). The CCI is calculated according to the formula shown in **Equation 2.** The possible points given for each morbidity factor are shown in **Table 7.**

Table 7. Allocation of points in the Charlson Comorbidity Index (216)

Variable	Points
Myocardial infarction	1
Congestive heart failure	1
Peripheral vascular disease	1
Cerebrovascular accident or transient ischaemic attack	1
Dementia	1
Chronic obstructive pulmonary disease	1
Connective tissue disease	1
Peptic ulcer disease	1
Mild liver disease	1
Uncomplicated diabetes	1
Hemiplegia	2
Moderate to severe chronic kidney disease	2
Diabetes with end-organ damage	2
Localised solid tumour	2
Leukaemia	2
Lymphoma	2
Moderate to severe liver disease	3
Metastatic solid tumour	6
Acquired immunodeficiency syndrome	6

Plus 1 point for each decade for ages 50 years and over, with a maximum of 4 points

$$\text{10-year survival probability} = 0.983^{e^{0.9\times CCI}}$$

where CCI is the Charlson Comorbidity Index adjusted for age and e represents Euler's number, a mathematical constant approximately equal to 2.71828

Equation 2. Formula for 10-year survival probability based on Charlson Comorbidity Index (8)

The CPS combines the number of comorbidities in a patient with the number of regular medications the patient is taking, thereby estimating the severity of comorbidities. The score quantifies the overall severity of comorbidities using the concept of polypharmacy to evaluate the treatment needed to sufficiently control chronic medical conditions. The CPS has a minimum score of 0 and no maximum (217). Patients with a CPS score of 15 and higher are at greater risk of poor clinical outcomes (218). Retrospective studies have shown that the CPS may help identify older trauma patients who are at risk of poor outcomes as well as those who may need additional resources at discharge (218-220).

Table 8. Clavien–Dindo classification (221)

Grade	**Definition**
Grade I	Any deviation from the normal postoperative course without a need for pharmacological treatment or surgical, endoscopic, and radiological interventions. Allowed therapeutic regimens are drugs such as antiemetics, antipyretics, analgesics, diuretics; electrolytes; and physiotherapy. This grade also includes infected wounds opened at the bedside.
Grade II	Requiring pharmacological treatment with drugs other than those allowed for grade I complications. Blood transfusions and total parenteral nutrition are also included.
Grade III	Requiring surgical, endoscopic, or radiological intervention
Grade IIIa	Intervention not under general anaesthesia
Grade IIIb	Intervention under general anaesthesia
Grade IV	Life-threatening complications (including complications of the central nervous system) requiring IC/ICU-management
Grade IVa	Single organ dysfunction (including dialysis)
Grade IVb	Multiorgan dysfunction
Grade V	Death of a patient

The Clavien–Dindo classification is based on treatments needed for complications and is used to classify their severity (215, 222). It was developed as a tool for quality assessment in surgery. Its categories are shown in **Table 8**. The Comprehensive Complication Index was then developed to summarise complications classified according to the Clavien–Dindo system (223). The index is calculated by multiplying all the different grades of complications with a weighted factor; the weighted value is then calculated as a sum of scores for all complications and ranges from 0 for a mild complication to 75 for a lethal complication (2) (**Equation 3**).

When assessing the neurological outcome of trauma patients, the Glasgow Outcome Scale (GOS) and the American Spinal Injury Association (ASIA) scale are most often used. The GOS is a global scoring system for assessing the functional outcome of

$$\text{Comprehensive complication index} = \sqrt{\left(\sum MRV_{phys} \times MRV_{pat}\right)}\,/2$$

Equation 3. Formula for the Comprehensive Complication Index. MRV_{phys} is the median reference value for physicians and MRV_{pat} is the median reference value for patients (2, 3)

patients with traumatic brain injuries. It rates patient status into five categories as seen in **Table 9** (224). The ASIA impairment scale describes a patient's functional impairment as a result of a spinal cord injury. The scale has five classification levels as shown in **Table 10** (225).

Table 9. Glasgow Outcome Scale (226)

1	Dead
2	Vegetative state, unable to interact with the environment; unresponsive
3	Severe disability, able to follow commands/unable to live independently
4	Moderate disability, able to live independently; unable to return to work or school
5	Good recovery, able to return to work or school

Table 10. The ASIA (American Spinal Injury Association) Impairment Scale is an international standard scale used for the neurological classification of spinal cord injury (225)

ASIA Grade	Clinical state (below level of injury)
A	***Complete:*** No sensory or motor function is preserved in the sacral segments S1 to S5
B	***Sensory incomplete:*** Sensory, but not motor function, is preserved below the neurological level and includes the sacral segments S4 to S5.
C	***Motor incomplete:*** Motor function is preserved below the neurological level, and more than half of key muscles below the neurological level have a muscle grade of less than 3.
D	***Motor incomplete:*** Motor function is preserved below the neurological level, and at least half of key muscles below the neurological level have a muscle grade of 3 or more.
E	***Normal:*** Motor and sensory functions are normal and the patient had prior deficits.

1.9 Trauma care in Europe and Scandinavia

The acute and complex nature of severely injured trauma patients calls for broad knowledge of physiology and anatomy, as well as leadership and organisational skills (227). Trauma is a surgical disease in which surgeons play an important role in the optimal treatment of patients. Severely injured trauma patients need surgeons with broad technical competence to provide care that is complete and of a wide range (228).

Trauma management systems have been developed and are based on the trauma population in each country, geographical conditions, as well as the available provisions of healthcare. To improve patient outcomes, National trauma registries are being established in many countries (229). Information gathered in trauma registries is valuable for the evaluation of the quality of care and injury prevention. These registries can further be used in clinical and epidemiologic research (230).

Implementation of a complete trauma system results in a reduced mortality rate among severely injured patients, improves the quality of life, and reduces cost (45, 46). Trauma care has evolved in different ways within Europe due to the variable ongoing efforts aimed at improving care in each country (228). Europe covers less than a tenth of the Earth’s land surface with a population of 748 million people in 44 countries. However, Europe has some of the most developed health care systems in the world and a strong foundation in vascular surgery (231).

While organising the structure of a trauma system, some major factors to consider are geographic and demographic circumstances. In countries with a widespread population, long transport distances, and extreme weather conditions, the transport time is longer and prehospital treatment is even more important (232). Under these circumstances, it may also be difficult to centralise all major trauma care and patients need to be stabilised at lower-level trauma hospitals (233).

Scandinavia most commonly refers to Denmark, Norway, and Sweden, and is part of the Nordic region that consists of Denmark, Norway, and Sweden together with Finland and Iceland (234). Together, these five countries cover an area of 1.35 million km^2 with a total population of about 27 million inhabitants (234, 235). Parts of some of these countries are sparsely populated with long prehospital distances; the mean population density is 18 per km^2, ranging from 2.8 per km^2 in Iceland to 125 per km^2 in Denmark (236). More than 200 Scandinavian hospitals receive injured patients and there is increasing emphasis on multidisciplinary trauma teams (234).

In the US, general surgeons lead the care of severely injured patients and trauma surgery is combined with acute care surgery and/or intensive care medicine (237). In most European countries, however, where most surgeons are not trained specifically in intensive care medicine, general or orthopaedic surgeons lead the work-up of trauma patients (228, 238).

The training of the trauma team is an important part of the process of establishing an organised and well-functioning trauma centre and prehospital care. Multiple courses have been designed to improve the management of multiple trauma patients, such as the ATLS®, European Trauma Course (ETC®), Definitive Surgical Trauma Care (DSTC®) programme, Definitive Surgery and Anaesthesia in Trauma Care (DSATC®) programme, and the Advanced Trauma Operative Management programme. Most of these are available for entire trauma teams and not only for surgeons or vascular surgeons (228).

1.9.1 Trauma care in Iceland

In Iceland, primary trauma care is provided in relatively small hospitals in each quarter of the country (239). Two hospitals in Iceland are capable of receiving seriously injured patients with vascular surgeons on call and available ICU care. The first is Landspitali University Hospital in Reykjavik and the second is Akureyri Hospital (SAK) in Akureyri, an area with 19 000 inhabitants, and which serves a population of about 20 000 to 25 000 in the Northern and Eastern parts of Iceland. Landspitali Hospital is the only tertiary trauma hospital and is located in the capital, with about 232 280 out of a population of 369 000 living within 7 minutes of ambulance transport to the hospital (240, 241). All medical specialities are represented at Landspitali Hospital and it is the only centre that has surgeons that perform cardiothoracic surgery in Iceland. Almost all major vascular trauma patients are referred to Landspitali Hospital in Reykjavik for further treatment. Patients are transported to the hospital either in an ambulance or airlifted in a helicopter/plane or transported while being escorted by a physician.

Many areas outside Reykjavik are sparsely populated, such that transport can be difficult due to the harsh terrain and unpredictable weather. Response time and transfer capabilities are therefore often much longer than in Reykjavik or its surroundings. Each year, more than 25 000 trauma patients are treated at Landspitali and more than half of them have an ISS > 15 (242). The hospital offers all forms of major trauma care with an ATLS-certified trauma team that includes a senior emergency doctor, an anaesthetist, and a general surgeon with immediate consultations available from all other specialities.

1.9.2 Trauma care in Norway

The mainland of Norway covers an area of 385 178 km^2 and had 5 455 582 inhabitants in 2022 (243). It is estimated that approximately 10% of the inhabitants are injured every year and about 300 000 individuals need hospital care due to severe injury, with around 2 500 fatalities (244, 245). In Norway, long distances separate urban and rural areas, and in winter there are often extreme weather conditions.

Norway has 34 hospitals around the country with acute trauma functions and 4 classified level 1 trauma centres, including Haukeland University Hospital in Bergen, the second largest city in Norway. Acute care hospitals offer 24 h general surgical services and have the competences to stabilise trauma patients before transfer to the trauma centre if needed (246). Almost half of the smaller hospitals with acute trauma functions treat fewer than 100 trauma cases each year (247).

In 2007, the National Competence Service for Traumatology (NKT-Trauma) published an official trauma system for the organisation of treatments for seriously injured patients, which has been updated regularly over the last two decades (244). The national trauma system defines criteria for trauma team activation, as well as a minimum level of competency for the trauma team members. According to a recent Norwegian study conducted by Bredin et al. (2022), 95% of Norwegian hospitals performed systematic trauma team training (248). In Norway, there is a centralised nationwide trauma registry, the Norwegian Trauma Registry (NTR), that contains data on all potentially seriously injured patients treated by the specialist health service in Norway (249).

2 Aims

2.1 General aims

The main aim of this PhD thesis is to accumulate data on major vascular and thoracic trauma in Iceland and Bergen, representing Nordic populations where studies on these injuries are scarce. This includes data on the severity of injury, management, and outcomes, to serve as bases for improving the management and outcomes of this patient group and international comparison.

2.2 Specific aims

2.2.1 Paper I

This paper aimed to study major vascular injuries following road traffic accidents in Iceland, determine their incidence, and identify risk factors for 30-day mortality and long-term survival.

2.2.2 Paper II

This paper aimed to collect data on emergency thoracotomy in a tertiary care hospital in Iceland, to study its incidence, and more importantly to investigate short- and long-term complications and survival.

2.2.3 Paper III

This study aimed to investigate the incidence, demographic features, and outcomes of penetrating stab injuries in a whole population and to evaluate any changes in annual incidence, as well as the management and outcomes of this patient group.

2.2.4 Paper IV

The primary aim of this paper was to describe in a level 1 North European trauma centre the epidemiology and predictive factors for mortality following severe thoracic trauma in a well-defined geographical region. Ultimately, it aimed to recognise patients at risk of an adverse outcome and to reduce the incidence of complications.

2.2.5 Paper V

This paper aimed to assess in a level 1 North European trauma centre the incidence, treatment, and outcomes of admitted patients with vascular trauma in a well-defined geographical region. Ultimately, it aimed to improve the management and outcomes of this patient group.

3 Materials and Methods

In all five papers, the incidence, outcomes, and demographic features of non-iatrogenic vascular or thoracic trauma in adults were studied in a well-defined Nordic population.

3.1 Ethical considerations

The study protocols were approved by the Icelandic National Bioethics Committee, the Data Protection Authority, and the Regional Medical Ethics Committee in Norway. Individual patients were not identified. The need for individual consent was waived in the Icelandic aspect of the study. As requested by the Regional Medical Ethics Committee in Norway, informed consent forms were sent to all patients who fulfilled the study criteria of the Norwegian aspect of the study.

3.2 Study population/cohort and data collection

All studies were retrospective in design and all medical data were individually reviewed. Baseline demographic information and clinical data were collected for all patients from pre-hospital reports, patient charts, surgical reports, and autopsy reports, using a standardised data sheet. Among all patients, data collected included information on age, sex, location of trauma site, mechanism of injury, location of major injury, surgeries performed, and length of hospital stay.

3.2.1 Paper I

In this study, the data of 62 patients aged ≥ 18 years who sustained major vascular trauma in traffic accidents in Iceland between January 1, 2000 and December 31, 2011 were retrospectively reviewed. Traffic accident trauma was defined as an injury sustained due to a motor vehicle accident, a motorcycle accident, or a bicycle accident and pedestrians were included.

Major vascular trauma was defined as vascular trauma on a named vessel in patients admitted to the ICU for longer than 24 h or who died within 24 h of injury. Using a centralised database at Landspitali and Akureyri Hospital, we identified all patients with the following ICD-10 trauma codes: S15-18, S25-28, S35-38, S45-48, S75-78, and S85-88.

To identify individuals who died on-scene or during transport to the hospital, we reviewed the forensic autopsy databases of the Medical Examiner Office of Iceland and the Department of Pathology at Landspitali Reykjavik and Akureyri Hospital. These databases list all autopsies conducted in Iceland and autopsy records for all individuals who underwent autopsy during the study period (2,859) were manually reviewed to identify vascular trauma. In Iceland, autopsies are performed on all individuals who die from trauma. For the same period, The Cause of Death Registry at Statistics Iceland was queried. Information on packed red cell transfusion and plasma and blood platelet transfusion was obtained from the National Blood Bank in Iceland.

Data on the vessel injured and associated injuries were also collected. Massive transfusion was defined as a transfusion requirement of ≥ 10 units of packed red blood cells (PRBCs) in 24 h. The presence of signs of life (SOL) was identified and registered during the pre-hospital phase, during transportation, and on arrival at the emergency department. SOL was defined as the presence of at least one of the following: spontaneous respiratory effort, pupillary response, movement of an extremity, measurable blood pressure or palpable pulse, or cardiac electrical activity.

Vascular injuries to the head or solid organs in the abdomen or thorax (i.e., involving the cerebral or coronary arteries) were excluded. Furthermore, all iatrogenic vascular injuries were excluded, as were vascular injuries below the knee and elbow.

Information on the survival of all patients was available from Statistics Iceland and was 100% complete. We excluded individuals who died before arrival at the hospital from the survival calculations.

3.2.2 Paper II

Paper II included 9 patients who underwent emergency thoracotomy for major thoracic trauma in Iceland between January 1, 2005 and December 31, 2010. All of them had penetrating and/or blunt trauma and the patients could be identified using a centralised, computerised trauma database as well as the operation registry at Landspitali University Hospital. Furthermore, surgeons from other hospitals in Iceland were queried if they had performed emergency thoracotomy during the study period, but none of them had. Non-traumatic indications for emergency thoracotomy, such as cardiac arrest or iatrogenic cardiac tamponade, were excluded.

Data on the vessel injured, associated injuries, and the need for blood transfusion (PRBCs, plasma, and platelets) were collected. Massive transfusion was defined as a transfusion requirement of ≥ 10 units of PRBCs in 24 h. The presence of SOL was identified and registered during the pre-hospital phase, during transportation, and on arrival at the emergency department. The reason for death was obtained from autopsy reports.

The clinical indication for emergency thoracotomy was evaluated as well as the surgical technique. Emergency thoracotomies were usually performed in the emergency department or an operating theatre next to the emergency department. All cases were true emergencies and were usually performed within half an hour of arrival at the hospital. The decision to perform an emergency thoracotomy was clinically based on the discretion of the attending cardiothoracic or trauma surgeon.

3.2.3 Paper III

In this paper, 88 patients aged ≥ 18 years were included who sustained a penetrating stab injury (with a knife or machete) in Iceland, including 73 patients who were admitted to the hospital between January 1st 2000 and December 31st 2015. Patients who died on-site or at the emergency department before admission to the hospital (n = 15) were also included in calculations of total mortality. Patients' data were obtained from the National Cause of Death Registry in Iceland and compared to those in the autopsy databases of the Medical Examiner Office of Iceland and the Department of Pathology at Landspitali Hospital.

We excluded patients who were treated at the emergency department and discharged without hospital admission.

In addition, we collected data on the type of injury (assault, self-inflicted injury, or accident) and whether the patient was intoxicated with alcohol when injured. The reason for death was registered from autopsy reports.

3.2.4 Paper IV

This study included 514 patients aged ≥ 18 years who sustained thoracic trauma with an Abbreviated Injury Scale (AIS) chest score of ≥ 3 admitted to Haukeland University Hospital, a level 1 trauma centre, between January 2009 and December 2018. The patients were registered in the local hospital trauma registry until December 2014 and in the Norwegian National Trauma Registry (NTR) thereafter.

We excluded patients who were not admitted directly to Haukeland and patients who were dead on arrival. The patients were classified into three subgroups: 1. isolated thoracic injury with ISS < 16; 2. polytrauma without traumatic brain injury (TBI, defined as a head injury with AIS ≥ 3); and 3. polytrauma with ISS > 16 and head injury with AIS ≥ 3.

Information regarding comorbidities, medication use, and complications was also registered. In addition, causes of death from discharge notes were categorised into: thoracic bleeding, abdominal bleeding, pelvic bleeding, bleeding in several anatomical regions, other forms of bleeding, asphyxia, primary brain damage, pulmonary embolism, and organ failure.

3.2.5 Paper V

This study included 68 patients aged ≥ 18 years who sustained vascular trauma on a named vessel and were admitted alive to the hospital and registered in the Trauma

Registry at Haukeland University Hospital in Bergen between 1st January 2009 and 31st December 2018. We excluded patients who died before admission. Patients were identified based on the AIS for non-iatrogenic vascular trauma registered in The Local Trauma Registry at Haukeland University Hospital and the NTR.

Data on the vessel injured, associated injuries, and the need for blood transfusion (PRBCs, plasma, and platelets) were registered. Massive transfusion was defined as a transfusion requirement of ≥ 10 units PRBCs in 24 h. The reason for death was registered from autopsy reports.

We excluded iatrogenic injuries as well as isolated vascular injuries to the head and solid organs in the abdomen.

3.3 Classification of injuries and injury score

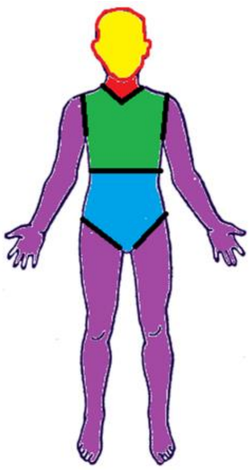

Figure 10. Anatomical zones

In Papers I–V, the ISS and NISS were calculated for all patients at admission based on the AIS code calculated at admission (208). An ISS and NISS score higher than 15 were considered to represent severe injury.

Vascular injuries were classified into five anatomical zones based on the injury location (**Figure 10**). (i) Neck, which included injuries to the external and internal jugular veins; internal, external, and common carotid arteries; and the vertebral arteries. (ii) Thorax, which included injuries to the thoracic aorta, superior and inferior venae cavae, and the subclavian and pulmonary vessels. (iii) Abdomen, which included injuries to the abdominal aorta; iliac, mesenteric, renal, and splenic vessels; hepatic portal veins; and inferior vena cava. (iv) Upper limb, which included injuries to the subclavian, axillary, and brachial vessels. (v) Lower limb, which included injuries to the femoral and popliteal vessels.

The revised trauma score (RTS) and the chance of survival (Ps) were calculated using the trauma-injury severity score (TRISS) methodology based on the physiological status on first medical contact (Glasgow Coma Scale [GCS], respiratory rate, and systolic blood pressure) (211, 212).

3.3.1 Paper IV

In this paper, ISS ≥ 16 was applied as a cut-off for polytrauma patients. In the analysis of comorbidity data, it was scored according to the American Society of Anesthesiologists (ASA) score, Charlson Comorbidity Index (CCI), and Comorbidity Polypharmacy Score (CPS) (8, 215, 250). Complications were scored using the

Clavien–Dindo scale (CDS), which classifies complications based on the most intensive therapy required to treat complications, and the complication index was calculated and analysed (222, 223).

3.3.2 Paper V

Polytrauma was defined as an AIS of ≥ 3 in two or more body regions. Hypovolemic shock was defined as systolic blood pressure (SBP) < 90 mmHg or a base deficit > 6, or a blood transfusion requirement of > 4 units in the first 24 h. The following operative techniques were registered: primary repair on an artery or vein, including patch angioplasty, direct suture repair, or end-to-end anastomosis.

3.4 Outcome parameters and follow-up

In Papers I–V, the primary outcome was 30-day mortality. In **Paper I,** the follow-up ended on December 31st, 2015. The mean and median follow-up durations of patients who arrived at the hospital alive were 6.1 and 6.5 years, respectively (range, 9.4–11.8). The follow-up was 100% complete. Two foreign visitors were excluded from the long-term survival analysis but included in the short-term analysis. In **Paper II**, the follow-up was 100% complete with a median survival duration of 12 months (range, 12–24) among 5 survivors and the follow-up ended on December 31st, 2010. In **Papers III** and **IV**, follow-up ended at in-hospital death or discharge. In **Paper V** follow-up ended on 31st December 2019 and was 96% complete. Three patients were transported or moved out of Norway and therefore could not complete a one-year follow-up.

3.5 Statistical analysis

In **Papers I**, **II**, and **V**, Microsoft Excel (versions 2010 and 2016; Microsoft Corporation, Redmond, WA, USA) was used for descriptive statistical analyses of both continuous and categorical variables.

In **Papers I–III**, the incidence was calculated according to the age and sex distribution of the population as derived from National Statistics Iceland, standardised to the World Health Organization European Standard Population.

In **Papers I** and **V**, annual percentage changes and differences in incidence according to residency were estimated via Poisson regression. Continuous variables were expressed as the mean ± standard deviation and categorical variables as percentages. The Student *t*-test was used to analyse continuous variables and the chi-squared test or Fisher's exact test was used to analyse categorical variables, as appropriate. Odds ratios for predictors of short-term mortality (< 24 h or 30-day mortality) were estimated via logistic regression. Long-term survival was estimated using Kaplan–Meier analyses and differences in survival according to sex were estimated via log-rank tests.

Further analyses were performed using R version 3.3.2 (The R Development Core Team, Vienna, Austria) for Paper I, R version 3.4.4 (The R Development Core Team) for Paper III, RStudio 4.0.2 (RStudio Team, Boston, MA, USA) for Paper V, and Stata 15 (Stata Corp. LLC, College Station, TX, USA) for Paper IV.

In **Papers I, II, III,** and **V**, analysis items with $p < 0.05$ were considered statistically significant.

In **Paper III**, variables with skewed distributions were summarised with their medians and interquartile ranges (IQRs) and compared using the Wilcoxon rank-sum test. Age standardisation was accomplished using the direct method and confidence intervals were calculated assuming a gamma distribution. Rates were compared using median unbiased estimation.

In **Paper V**, categorical data are presented as counts and percentages and continuous data as medians and IQRs.

3.5.1 Paper IV

Risk factors for in-hospital mortality among trauma victims and related variables were analysed with several factors. Age was categorised into four groups: 0–39, 40–59, 60–74, and ≥ 75 years. Comorbidities were scored using the Charlson Comorbidity Index and categorised into 0, 1, and ≥ 2. Comorbidity Polypharmacy score was described as 0–9 and > 9. The ISS was categorised into minor (0–9), moderate (10–15), and severe (≥ 16). RTS was classified into the following categories: low risk of death (< 5%, RTS > 7.2), intermediate risk of death (5–50%, RTS 3.4–7.2), and high risk of death (> 50%, RTS < 3.4). TRISS was classified into three categories based on the Ps 0–50, 51–75, and 76–100 and was analysed as a categorical variable. The Clavien–Dindo score was categorised into two groups: no or minor complications and severe (Clavien–Dindo score > 3). Complications were scored using the complication index and categorised into: no or minor complications (complication index < 30) and severe complications (complication index ≥ 30).

Categorical variables are presented as frequencies and percentages and were analysed using Pearson’s chi-squared test or Fisher’s exact test, as appropriate. Variables with normal distributions are presented as means and standard deviations and analysed using *t*-tests and repeated measures analysis of variance. Variables with non-Gaussian distributions are presented as medians and IQRs and were analysed using the Kruskal–Wallis test.

Logistic regression with stepwise backward selection was used to identify risk factors for mortality following thoracic trauma. The p-value for the inclusion of variables in the logistic regression models was set at 0.157. A subgroup analysis was performed on cases of isolated thoracic trauma and polytrauma with and without TBI. Hosmer–Lemeshow goodness of fit tests and areas under the receiver operating characteristic curve were computed for each model and the best model was selected.

4 Results

The main findings of the five studies are summarised below. Further details can be found in the original publications and manuscripts (**Papers I–V**).

4.1 Paper I

There were 62 patients with 95 injuries: 77 to arteries and 18 to veins. During the 12-year study period, Iceland had a mean population of 303,383 and 319,575 inhabitants at the end of December 2011 (251). The incidence of severe vascular injury was 1.69 per 100 000 inhabitants (95% confidence interval [CI], 1.27–2.21): 2.70/100 000/year (95% CI, 1.96–3.64) for males and 0.65/100 000/year (95% CI, 0.32–1.20) for females. The mean age was 44 ± 18 years: 43 ± 17 years for the 49 males and 49 ± 20 years for the 13 females. Over time, there was a significant decline in the incidence rate, from 2.9/100 000 in 2000 to 0.94/100 000 in 2011, with an annual mean percentage change (APC) of 0.92 (p = 0.0272). Forty-one (66%) individuals died before admission: 33 at the scene and 8 during transportation. The other 21 patients (34%) reached the hospital alive.

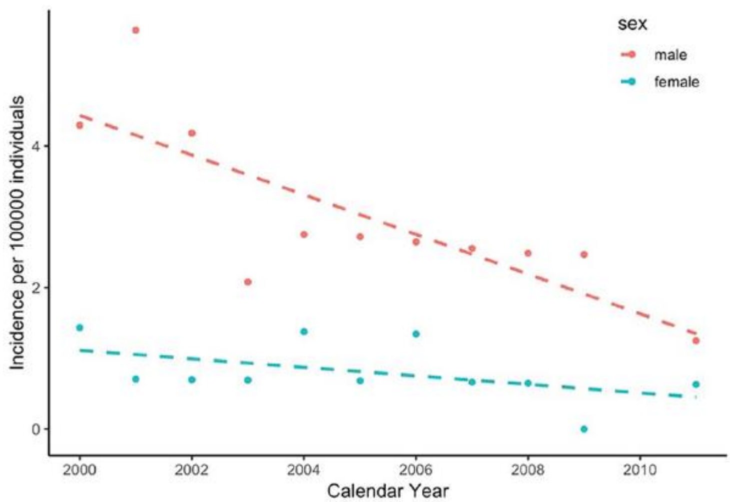

Figure 11. Incidence of major vascular trauma following traffic accidents in males (red) and females (blue) in Iceland over the study period 2000–2011 (1)

The causes of injury were motor vehicle accidents (n = 52), motorcycle accidents (n = 6), bicycle accident (n = 1), and pedestrian accidents (n = 3). Most of the patients (n = 47, 76%) had thoracic vascular injuries and 19 (31%) had abdominal vascular injuries. Almost 80% (32/41) of those who did not reach the hospital alive had thoracic aortic injuries, compared to 48% (10/48) among those admitted to the hospital alive ($p = 0.015$). Vascular trauma in the abdominal area accounted for 32% (13/41) of all injuries among patients who died before admission and 29% (6/21) among those who reached the hospital alive ($p = 0.803$). All 9 patients who had combined thoracic and abdominal major vascular trauma died before reaching the hospital.

A significantly higher proportion of individuals sustained injuries in rural areas (69% vs. 31%, $p < 0.01$) and the mortality rates before hospital admission were 67% (29/43) and 63% (12/19), for rural and urban areas, respectively. Seventy-seven percent of fatal thoracic aortic trauma cases (26/34) had been characterised by frontal collisions and 74% of accidents occurred in rural settings.

Eighteen of the admitted patients underwent operative procedures, 16 via open vascular repair. These included 16 patients who underwent operative procedures within the first 24 h of admission and 3 of whom underwent acute endovascular stent graft insertion. The mean length of hospital stay was 34 ± 21 days among the 15 patients who were discharged (median, 35 days; range, 6–62).

Forty-seven of the 62 patients (67%) died within 30 days of injury. Four (19%) of the 21 patients admitted died within 30 days, all within 24 h due to severe haemorrhagic shock.

The mean ISS and NISS values for patients who were admitted were 36 ± 18 and 44 ± 17, respectively. All but one patient had ISS and NISS scores above 15, and the mean estimated Ps was 66%.

The long-term survival probability among the 21 individuals who were admitted to the hospital with major vascular trauma was 86% at both 1 year and 5 years, and comparable for males and females (log-rank test, $p = 0.31$).

Neurological outcomes among the 15 patients who survived the injury and were discharged from the hospital included one case of mild brain damage (GOS = 5), two cases of spinal cord injury (both ASIA grade A), two cases of limb amputation, and one case of spinal cord injury (ASIA grade E) that also required amputation.

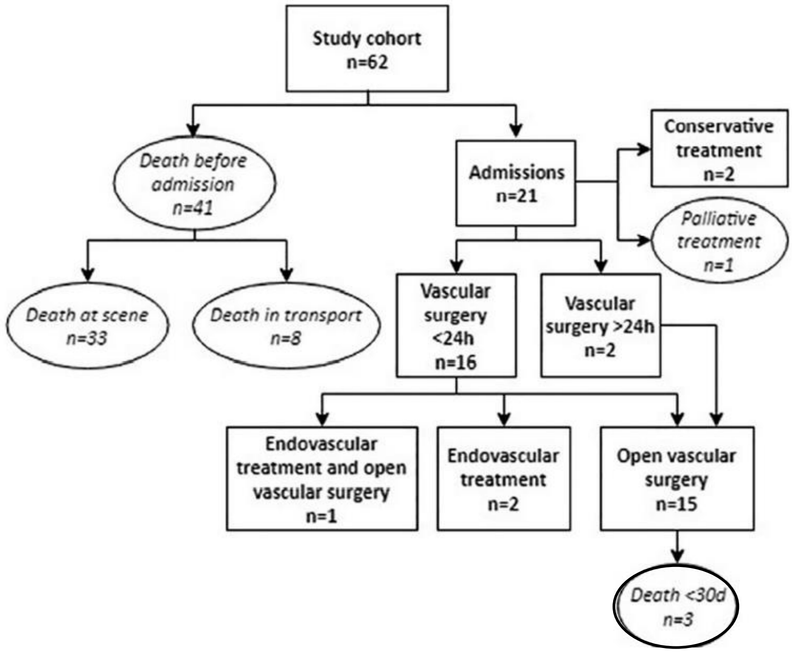

Figure 12. Flow chart showing the management of, and outcomes among 62 patients with major vascular trauma following traffic accidents in Iceland during the study period (1)

4.2 Paper II

Nine patients underwent emergency thoracotomy on account of trauma during the six-year study period, resulting in an incidence of 1.3 per 100 000 inhabitants per year (95% CI, 0.61–2.62). All the patients were males and had a median age of 36 years (range, 20–76). There were five cases of blunt trauma and four cases of penetrating injuries. Four of the injuries were due to motor vehicle accidents, two of the patients sustained gunshot wounds, and two sustained knife injuries. The most frequent location of major injury was the thorax (isolated thoracic injuries, n = 6) and three patients sustained polytrauma.

Suspected pericardial tamponade was the most common (n = 2) indication for emergency thoracotomy; however, this was only confirmed intraoperatively in one case. Thoracotomy was performed in five patients and sternotomy in two, and two patients underwent both procedures. Furthermore, one patient underwent emergency thoracotomy in the ambulance before arrival at the hospital, and the other eight patients were operated on after arrival at the hospital. All emergency thoracotomies, except one performed by a junior trauma fellow in the ambulance, were performed by two cardiothoracic surgeons and one general surgeon.

All 9 patients had indications of severe injury based on median ISS and NISS values of 29 (range, 16–54) and 50 (range, 25–75), respectively. The median RTS was 7 (range, 0–8) with an estimated Ps of 85% (range, 1–96). All five survivors had GCS ≥ 10 and SBP ≥ 100 mmHg at first medical contact. Three of the patients did not have any SOL at first medical contact, and all of them died.

There were five long-term survivors, three of whom made a good recovery. One of the patients sustained mild anoxic brain injury and another sustained paraplegia related to spinal injury. Autopsy revealed severe injuries and major bleeding as the causes of death in all four cases with fatal outcomes. The mean ISS and NISS values for survivors were 41 and 66, respectively, as opposed to 23 and 30 for non-survivors.

4.3 Paper III

During the 16-year study period, 88 patients had penetrating stab wounds, 15 of whom died before reaching the hospital. Out of the 73 admitted patients, 70 were treated at Landspitali and three at Akureyri Hospital (the regional hospital of North Iceland). Sixty-six of the patients (90.4%) were males and seven (9.6%) females, with a mean age of 32.6 years. Eighty-one per cent of the patients were younger than 45 years.

The average population in Iceland during the study period was 309 360 and at the end

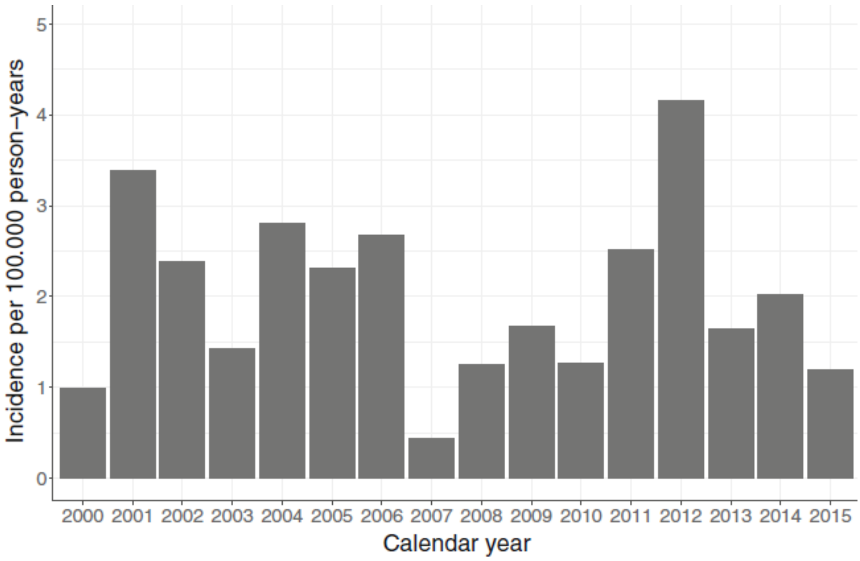

Figure 13. Incidence of penetrating stab injuries during the study period (7)

of December 2015, the population was 332 529 (252). The age-standardised incidence was 1.54 per 100 000 inhabitants (95% CI, 1.21–1.94) for both males and females together. The incidence did not change significantly during the study period, with an incidence ratio of 1.00 (95% CI, 0.58—1.73, p = 0.826).

The most common locations of injury were the chest (26.4%), abdomen (21.5%), and upper limbs (21.5%), and 38.4% of the patients sustained injuries in more than one region. The most common cause of injury was assault (in 96% of cases), with a majority of cases occurring at home (54.8%) or on public streets (31.5%).

Out of 73 patients, 47 (64%) underwent a total of 60 surgical procedures, with soft tissue repairs (n = 23) and chest tube insertion (n = 19) being the most common. Twenty-six of the patients (35.6%) required ICU admission with a median length of stay of 1 day (mean, 4 days; IQR, 1–1.75; range, 1–38) in the ICU. Overall, the median length of stay in the hospital was 2 days (mean, 5.5 days; IQR, 1–4; range, 0–53). The median ISS and NISS values of all patients admitted were 9 (IQR, 2–11) and 9 (IQR, 3–11), respectively, with 14 patients (19.2%) presenting with an ISS > 15.

Three patients died within 30 days of admission, yielding a 30-day mortality rate of 4.1%. All three patients that succumbed had severe injuries with ISS values of 17, 25, and 75.

4.4 Paper IV

In total, 4 042 trauma patients were admitted during the study period, out of which 514 patients who sustained thoracic injuries were included in the study, with 78% being males and a mean age of 51 ± 18 years. The mean annual incidence rate per 100 000 inhabitants remained the same during the study period, with a 10-year average of 13.3 cases per year. The most frequent mechanism of injury was road traffic accident (49%), followed by falls (35%). The median ISS was 17 (IQR, 13—27) and the median revised trauma score was 7.8 (IQR, 7.1–7.8).

The most common injuries were costal fractures, which occurred in 426 (83%) patients, with head and abdominal injuries being the most common co-occurring injuries. A majority of patients (61%) were polytrauma casualties, 19 (4%) of whom underwent emergency thoracotomy and 126 (25%) of whom underwent chest tube insertion.

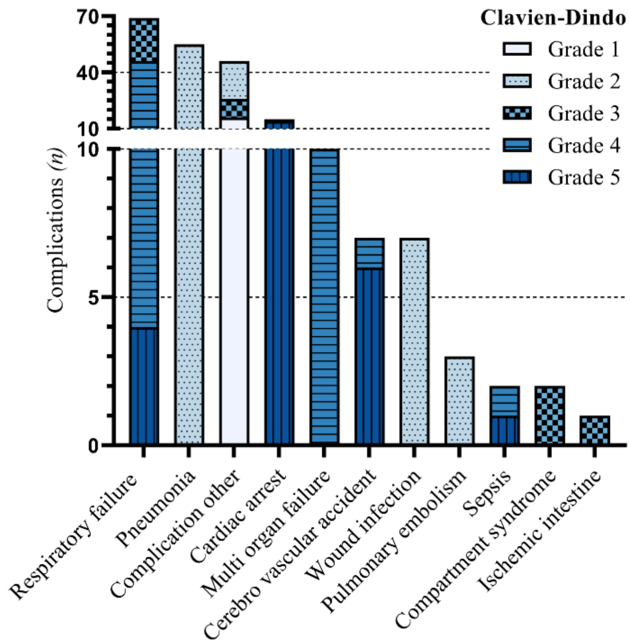

Figure 14. Frequencies and nature of severe complications. CDS grade 1, requires no treatment; CDS grade 2, requires pharmacological treatment; CDS grade 3, requires surgical treatment; CDS grade 4, requires intensive care; CDS grade 5, death (293)

Complications occurred in 189 patients (37%), among whom the most common severe complication (Clavien—Dindo score ≥ 3) was respiratory failure in 70 (14%) patients. Furthermore, severe comorbidities according to Charlson Comorbidity Index were present in 190 (40%) patients. The median Comorbidity Polypharmacy Score was 0 (IQR, 0–4) and according to the ASA classification, most patients had normal health status (55%). Anticoagulants had been used by 85 (17%) patients before trauma.

According to the subgroup analysis, 201 (39%) patients had isolated thoracic trauma, 215 (42%) had polytrauma without traumatic brain injury, and 98 (19%) had polytrauma with traumatic brain injury. Polytrauma patients with traumatic brain injury were significantly younger (mean age, 47 years) compared to the other subgroups (polytrauma without traumatic brain injury: mean age, 52 years and isolated thoracic injury: mean age, 53 years). Sex ratio was equally distributed among the subgroups with no differences observed in the rate of comorbidities between the sexes. High-energy falls (from a height > 3 m) were more often the causative mechanism in both polytrauma subgroups compared to low-energy falls (from a height < 3 m) in the isolated thoracic trauma subgroup. The median ISS was significantly higher in both polytrauma groups (without traumatic brain injury: n = 22 and with traumatic brain injury: n = 29) compared to the isolated thoracic injury group (n = 11) ($p < 0.001$). The mortality rate was highest in the polytrauma with traumatic brain injury group, in which 25 deaths (25%) occurred within 30 days. Among polytrauma cases without traumatic brain injury, the highest number of fatalities occurred within 24 h after trauma, and 18 patients (58%) succumbed. A majority of deaths (n = 11, 45%) in the subgroup of patients with polytrauma with traumatic brain injury occurred on the second day after trauma. Among polytrauma patients, the main causes of death among those with and without traumatic brain injury were brain injury and exsanguination, respectively. Female sex was not a risk factor for mortality in the subgroup of patients with polytrauma without traumatic brain injury. Multivariate analysis of risk factors for mortality in the subgroups did not reveal any potential risk factors.

Data on 463 patients with complete data were included in the multivariate analysis. The analysis showed that female sex, a combination of more than nine comorbidities and medications, TRISS with a Ps lower than 50%, and a complication index ≥ 30 were associated with death after trauma. Anticoagulants taken before trauma, however, did not predict mortality.

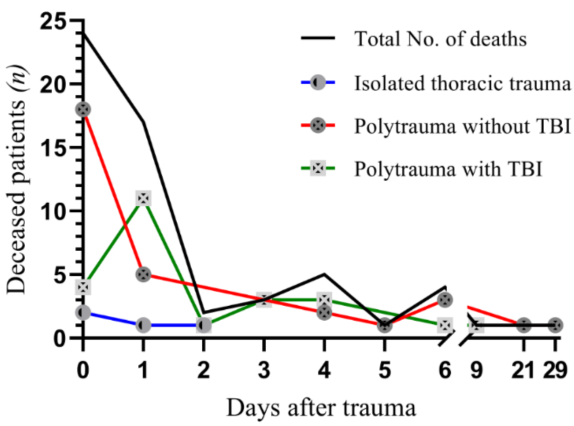

Figure 15. Temporal distribution of deaths after trauma. Abbreviation: TBI, traumatic brain injury (293)

4.5 Paper V

A total of 4 042 patients were admitted as trauma patients to our level 1 centre and evaluated by the Haukeland Trauma Team. Sixty-eight of them met the criteria for vascular trauma, including 8 patients who were transported to our centre from another regional hospital. There were 52 males and 16 females, with a median age of 44 years (IQR, 31–60) for all patients, distributed as 42 years (IQR, 31–60) for males and 50 years (IQR, 40–63) for females. The overall incidence over the 10-year study period was 1.45 per 100 000 inhabitants (95% CI, 1.13–1.82). No significant changes in incidence were observed over the 10-year study period ($p = 0.48$).

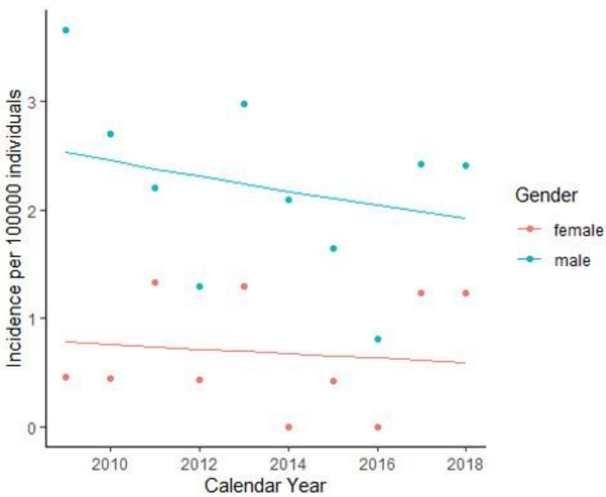

Figure 16. The incidence of cases of vascular trauma admitted to Haukeland Hospital and evaluated and treated by the trauma team was 2.2 per 100 000 inhabitants (95% CI, 1.7–2.9) among males (blue) and 0.7 per 100 000 inhabitants (95% CI, 0.4–1.1) among females (red) during 2009–2018. The overall incidence was 1.5 per 100 000 inhabitants with no significant change over the 10-year study period (294)

The 68 admitted patients had a total of 81 vascular injuries, including 69 and 12 arterial and venous injuries, respectively. Most patients sustained vascular injuries located in the chest ($n = 17$, 25%) or neck ($n = 16$, 24%). The most commonly injured vessel was the thoracic aorta ($n = 11$), followed by the abdominal aorta ($n = 4$).

Blunt injury was significantly more common than penetrating trauma (68% vs. 32%, $p < 0.05$) and most were due to traffic accidents (n = 31). Seventeen out of 22 penetrating injuries were knife injuries. There were no shotgun injuries. Most of the patients (32%) sustained aortic injuries following road traffic accidents (involving the thoracic aorta, 22.6% and abdominal aorta, 9.7%). The median ISS and NISS values of the 68 patients admitted were 22 (IQR, 14–36) and 33 (IQR 17–46), respectively, and 50 (74%) and 55 (81%) of the patients had ISS and NISS scores above 15. ISS and NISS scores were significantly higher for blunt trauma compared to penetrating trauma [32 (IQR, 20–38) and 34 (IQR, 27–48) vs. 14 (IQR, 8–17) and 17 (IQR, 10–27), respectively, ($p < 0.05$)]. The median estimated TRISS was 91%, distributed as 93% and 90% ($p = 0.90$) for penetrating vs. blunt trauma, respectively.

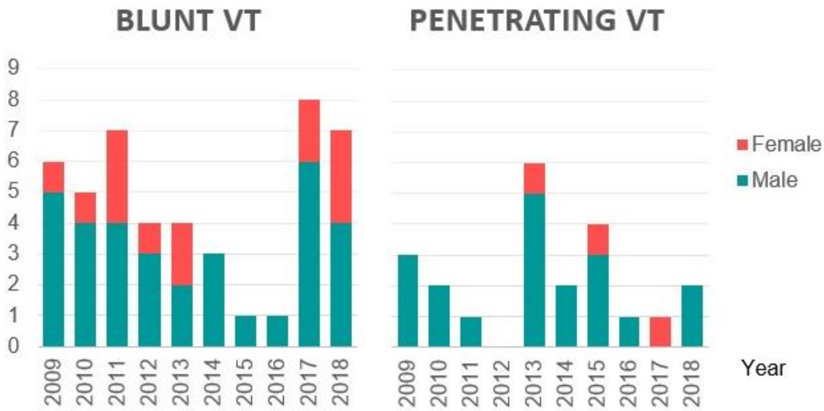

Figure 17. Distributions of blunt (green) and penetrating injuries (red) recorded during the study period. Abbreviation: VT, vascular trauma (294)

Haemorrhagic shock was registered for 50% of the patients, with no significant differences for penetrating (59%) compared to blunt (46%) vascular trauma ($p = 0.44$). The same was true for the number of blood transfusions administered to 45 of the patients. Patients who underwent transfusions received a median of 5 units (IQR, 2.5–10.5; range, 1–82), distributed as 6.5 (IQR, 3–10.5) and 4 (IQR, 2–9) units for blunt (n = 28) and penetrating (n = 17) trauma, respectively ($p = 0.56$). Twelve of the patients required massive PRBC transfusion (PRBCs ≥ 10 units within 24 h).

The median duration of hospital stay was 4.5 days (IQR, 2–16) with no significant difference between patients admitted with penetrating trauma and blunt trauma [3.5 days (IQR, 1–6) vs. 10 days (IQR, 3–21), $p = 0.08$].

Forty-three of the 68 patients (63%) were treated surgically, distributed as 19 (86%) for penetrating trauma and 24 (52%) for blunt injury. Primary repair (n = 17) was the most common surgical procedure, and 8 patients (12%) underwent endovascular repair.

Although no patients required limb amputation, four patients (6%) died before surgical treatment. Only conservative treatment was advocated in 16 cases and palliative treatment was chosen for five patients, most often due to severe brain injury.

Most often, surgical operations were performed by vascular surgeons (n = 17), including two cases that also involved an endovascular radiologist, 6 cases that involved a thoracic surgeon, and 6 cases involving surgeons from other surgical specialities. Finally, vascular reconstruction was performed solely by a general surgeon in 6 of the cases.

Autopsy was performed in 17 (77%) of the 22 patients who died within one year following trauma. Vascular trauma was the major reason for death in 15 of these patients and haemorrhagic shock was the reason for death in all but one (11/12) of the patients who died within 12 h.

There were no significant differences in 24 h (overall, 18%; 23% vs. 15%; log-rank test, $p = 0.45$) or 30-day mortality (overall, 31%; 27% vs. 33%; log-rank test, $p = 0.71$) between the penetrating and blunt injury groups. There was no significant difference in the 30-day mortality rate between males and females (29% vs. 38%; log-rank test, $p = 0.50$). Forty per cent of deaths occurred among patients with injuries to the aorta (thoracic aorta, n = 4/11 and abdominal aorta, n = 2/4). All deaths due to aortic trauma occurred within 24 h of admission.

Emergency thoracotomy was performed in 9 patients, five and four of whom had sustained penetrating and blunt trauma, respectively. Two patients with penetrating trauma underwent emergency thoracotomies in the emergency department, while the other 7 underwent surgery in an operation room close to the emergency department. Seventy-eight per cent of patients who underwent emergency thoracotomy died, all within 24 h.

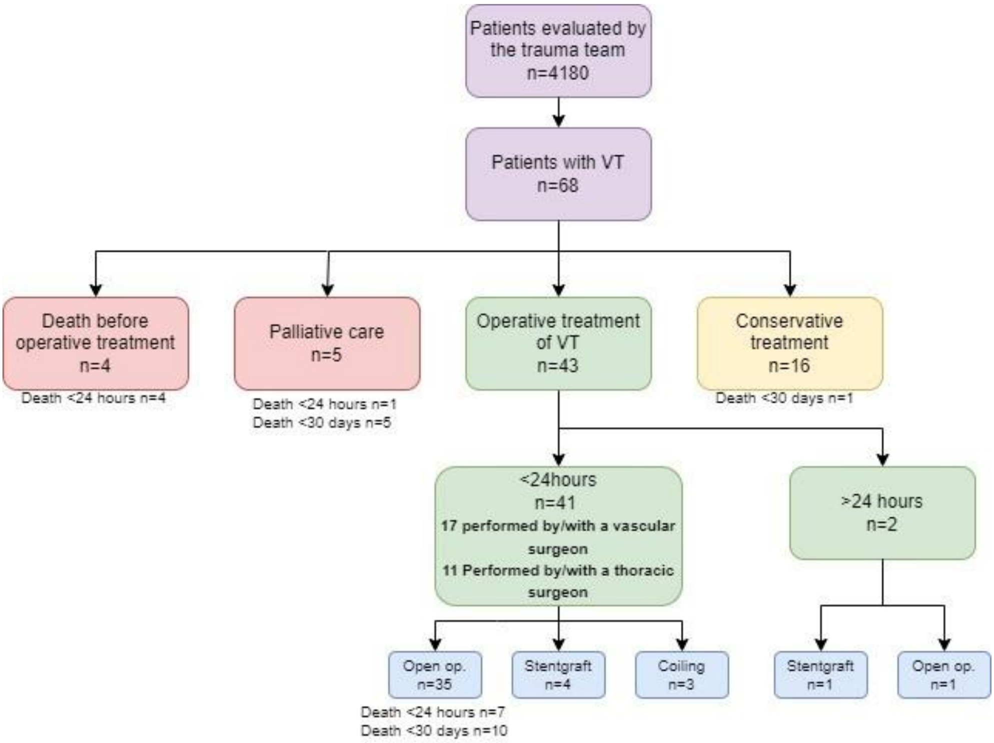

Figure 18. Flow chart showing the management and outcomes (survival) of 68 patients with vascular trauma in Western Norway during the study period (294)

5 Discussion

This thesis presents data on the incidence, mechanisms of injury, management, and outcomes of major vascular and thoracic trauma in two well-defined Nordic populations. Furthermore, it provides insight into treatment outcomes of vascular and thoracic trauma at low-volume level 1 trauma centres, including the indications for and outcomes of emergency thoracotomy. Importantly, in terms of demographics, socioeconomic status, and geographical challenges, Iceland and Bergen share many characteristics. This is probably also the case for most other Nordic trauma centres.

5.1 Incidence of serious vascular and thoracic trauma

The true incidence of vascular trauma in Iceland could not be evaluated in **Paper I**. In **Papers IV** and **V**, major vascular trauma was present in 1.7% of patients admitted and evaluated by the trauma team at Haukeland University Hospital, and serious thoracic injury was present in 13% of cases. Importantly, the incidence of major vascular trauma (overall incidence: 1.45/100 000) and serious thoracic trauma (mean annual incidence: 13.3/100 000) did not change over the 10-year study period. Previously, the actual incidence of major vascular and thoracic trauma in most European countries had not been well reported. However, **Paper V** showed that the incidence of vascular injuries at Haukeland was in accordance with those reported by recent larger studies conducted in Australia, the US, and the UK with organised trauma systems, in which vascular injury was responsible for 1–4% of general trauma admissions (11, 12, 79, 81, 82). Furthermore, the incidence rate of polytrauma with severe thoracic trauma among patients admitted at Haukeland University hospital was 8/100 000 inhabitants, which is comparable to that reported in the Netherlands, where it was 9/100 000 inhabitants in a recent study including 14,850 patients (253). The findings of **Paper I** are also in line with those reported by studies of data from the US National Trauma Data Bank (2013 and 2016), with 14–15% of trauma admissions being attributable to serious thoracic injuries (AIS ≥ 3) (62, 63).

As Nordic countries have many similarities in terms of geographical challenges, socioeconomic structure, and the structure and function of the health care system, we believe the incidence rates of vascular trauma we report from the Haukeland trauma team provide a realistic estimate of the true incidence in Western Norway even though a few cases may have gone unreported.

5.2 Penetrating injuries

In **Paper III**, the incidence of penetrating injuries, with or without vascular trauma, in a nationwide cohort in Iceland was reported as 1.54/100 000 inhabitants. This is in line with recent studies, including that from Finland, another Nordic country (0.9/100 000 inhabitants) (123), but much lower than reported in Australia (390/100 000 inhabitants) (120).

Almost all of these cases of penetrating injury reported in **Paper III** were assaults on young adult men. This is in line with previous studies, in which penetrating stab injuries were predominantly observed in men in the second and third decades of life (20, 25, 119, 121, 254-256). In Iceland, a noticeable majority of cases were due to domestic violence, in contrast to several other reports from Australia (25) and Iran (255), where a majority of cases occurred outdoors in a public location. The chest and abdomen were the most commonly affected body regions, which is also comparable to other overseas reports (25, 254, 257).

Patient care has evolved in recent years with most high-volume trauma centres favouring a more conservative and non-operative approach (119, 126, 257, 258). A high percentage of patients in our study underwent surgical intervention, which is in line with reports from other low-volume trauma centres in Norway and the UK (25, 125, 259, 260). Choosing a selective non-operative approach requires experience due to the dangers of delayed diagnosis of organ injuries (258). Only three of the 73 patients in **Paper III** died within 30 days of admission, yielding a mortality rate of 4%, in line with other similar reports from Europe (0.5—5%). In Australia, where penetrating injury is more frequent, the mortality rate was up to 15% (25). It is worth noting that our cohort was small compared to previously reported series (21, 119, 121, 254, 255).

5.3 Blunt and penetrating vascular trauma

In our analysis of patients admitted with major vascular injuries to Haukeland University Hospital in **Paper V**, the incidence of blunt vascular trauma (67.6%) was much higher compared to penetrating vascular injuries (67.6% vs. 32.4%). As expected, most (67.4%) cases that occurred secondary to the blunt injury mechanism were related to traffic accidents. This is in line with studies from countries with similar demographics, such as Canada and Australia, where 63–68% of cases of vascular trauma resulted from blunt force trauma (82, 85). However, in reports from Finland, Sweden, and the UK, the blunt mechanism was the cause of vascular trauma in 38–48% of cases (79, 84, 261). In contrast, in the US, firearm injury was a leading cause of trauma-related deaths (262, 263), whereas none of the penetrating injuries in our cohort was firearm related.

Vascular trauma due to blunt force indicates a significant transmission of force and often more severe injury with more extensive damage to associated soft tissue, bones, and nerves (12, 82, 264, 265). Approximately 80% of patients with vascular trauma reported in **Paper V** had a severe or life-threatening injury with an ISS or NISS > 15.

Patients with blunt vascular trauma had significantly higher ISS values compared to those with penetrating injuries and more frequently presented with polytrauma and hypovolemic shock at admission. These findings are in line with similar studies, including the study conducted by Weller et al. (2021) (12, 82). However, there were no significant differences in 24 h or 30-day mortality rate (overall, 31%; 27% vs. 33%; log-rank test, p = 0.71) between the penetrating and blunt injury groups, which most likely can be attributed to the low numbers of patients, with a potential risk of type II error in the statistical comparison of groups.

5.3 Thoracic and vascular injuries in road traffic accidents

According to the literature, road traffic accidents are the most common cause of blunt thoracic and abdominal trauma, followed by falls from heights (141-145). In **Paper I**, 76% of the 62 patients who experienced major vascular trauma following road traffic accidents in Iceland sustained thoracic injuries. In **Paper IV**, 49% of cases of serious chest trauma were due to road traffic accidents, which is lower than those reported in neighbouring countries such as Finland (58%) and Germany (64%) (266).

High-energy trauma to the thoracic region can lead to serious vascular injury, particularly to the aorta; however, traffic accidents are the main cause of serious vascular injuries among civilians (88, 92, 144, 146). In **Paper V**, 46% of blunt vascular injuries in Norway occurred following road traffic accidents, which is in accordance with those reported in countries such as Australia (44%) and Canada (36%) (82, 85). Aortic injury was the most common form of major vascular trauma among the admitted patients following road traffic accidents in both **Paper I** from Iceland and **Paper V** from Norway (48% and 32%, respectively). Nonetheless, Norway and Iceland are among the safest countries in terms of traffic safety and have traffic accident mortality rates among the lowest worldwide (death rates following road traffic accidents in 2019 were 2.9/100 000 in Iceland and 3.15/100 000 in Norway) (5, 267).

5.4 Treatment and utilisation of hospital resources

In **Paper I**, a total of 18 patients with major vascular trauma following road traffic accidents in Iceland underwent operative vascular repair, 16 cases within 24 h of admission, with laparotomy and thoracotomy being the most common surgical procedures. Three of the patients underwent endovascular stent graft insertion, all performed within 24 h of arrival, and all three patients survived at 30 days. In our analysis of operative approaches at Haukeland Hospital in **Paper V**, open surgery was also the main form of treatment, especially for cases of penetrating vascular injury (86%). There, surgeries were most often performed by vascular (n = 17) or thoracic (n = 11) surgeons. As expected, primary repair was the most commonly used operative technique, with simple suturing or ligation of the injury, which is also in line with reports from other similar studies (84).

Open surgery has been the golden standard for the management of all vascular trauma over the past 50 years (98). However, with rapid developments in the fields of imaging technology and endovascular treatment, this has been changing. Still, although in a modern setting, vascular trauma can be treated with both open and endovascular technologies, patients with haemorrhagic shock and classical signs of arterial injury should be taken immediately to the operating theatre for open surgery. For endovascular treatment, a hybrid operation theatre is preferred (98, 171).

In **Paper I,** three of the patients admitted following road traffic accidents in Iceland were treated via endovascular stent graft insertion in the aorta and all within 24 h. In **Paper V,** 8 (12%) of the cases (all blunt vascular injuries), bleeding could be stopped with an endovascular repair, and all cases except one underwent the procedure within 24 h. All of the patients treated via endovascular stent grafting at Haukeland Hospital survived after 30 days, as well as the first year, after sustaining vascular trauma. At Haukeland Hospital, a senior radiologist is always available 24/7; thus, endovascular procedures were performed together with a surgeon. Patients admitted and surgically treated at Landspitali and Haukeland each year were too few to statistically evaluate a trend in treatment choices for vascular injury.

Recent studies have indicated that treatment with thoracic endovascular aortic repair yields a lower mortality rate compared to open surgery, particularly for blunt thoracic aortic injury; thus, its usage is increasing (132, 268-270). However, some international society guidelines still only recommend such therapy in blunt thoracic injury, including the Society for Vascular Surgery (grade 2, level C) and the European Society for Vascular Surgery (class 1, level C) (268, 269, 271). This has led to challenges in most countries related to endovascular treatment, including a shortage of trained endovascular physicians involved in trauma care (196).

In **Paper V**, there was no significant difference in length of stay, ICU stay, or the need for blood transfusion between patients who sustained blunt and penetrating injuries. This could be due to the insufficient number of patients and therefore low statistical power when comparing the groups (type II error). In trauma, massive blood transfusion should be initiated if there is clinical suspicion of ongoing bleeding combined with physiological impact (109). In **Paper V**, PRBCs were transfused in 45 patients (17/22 patients with penetrating injury and 28/46 patients with blunt trauma). Altogether, 17% of patients with blunt vascular injury and 18% of patients with penetrating vascular injury underwent massive PRBC transfusion. In **Paper I**, only 15% of patients who sustained blunt injuries required massive PRBC transfusion. However, in a study conducted by Perkins et al. (2012), representing the situation at a British trauma centre, 48% of all admitted cases of blunt vascular trauma required massive blood transfusion compared to 25% of patients with penetrating vascular injury (12). To an extent, this difference can be explained by differences in approaches and definitions between the institutions in terms of massive transfusions. In addition, injury severities among the patients are not always comparable and trauma team leaders have varying levels of experience in evaluating patients at admission.

5.5 Indications for and outcomes of emergency thoracotomy

In **Paper II**, more than half of the small group of patients (5/9) survived the emergency thoracotomy and three of the survivors sustained blunt traumatic injuries. All the patients sustained serious injuries and an emergency thoracotomy was performed as a life-saving procedure. The favourable outcomes could be related to the short transportation time in Reykjavik and the availability of cardiothoracic services 24 h a day at Landspitali. Furthermore, the trauma teams at Landspitali have been trained according to the ATLS protocol (240).

The indications for emergency thoracotomy are still under debate, particularly after blunt traumatic injury, following which less than 2% of patients survive the procedure (49). The procedure is only indicated in selected cases as stated in the eighth edition of the ATLS guidelines (188). In Norway, Soreide et al. (2007) reported a similar annual incidence of the emergency thoracotomy procedure as our study (0.7 per 100 000 vs. 1.4 per 100 000 inhabitants) in a similarly relatively small trauma centre of Stavanger in Norway over a five-year period during which none of the 10 patients survived. The authors questioned whether the procedure was justified in a small trauma centre and some have used the word "futile" (51). More promising results were published after a study conducted by Pahle et al. (2010), representing a larger trauma centre in Oslo with a cardiothoracic surgeon on call, where there was a survival rate of 18% and a majority (75%) of the patients sustained blunt injury (193).

Three of the patients in **Paper II** presented without SOL before the procedure and all of them died. This is in line with several studies that reported emergency thoracotomy as contraindicated in injuries in the absence of witnessed cardiac activity (191, 272, 273). Of the five long-term survivors of the emergency thoracotomy procedure, three had good neurological recovery. Although the survival rate of patients who undergo emergency thoracotomy is often low, the survivors most often have a good neurological outcome, ranging from 50—100% in different studies (274, 275).

5.6 Short-term mortality and long-term survival following major vascular and thoracic trauma

In **Paper I,** two-thirds of the patients who were injured in road traffic accidents in Iceland died before hospital admission, either on the scene or during transport. Furthermore, 29% of the patients who reached the hospital alive did not survive to discharge. This mortality rate is slightly higher than reported in similar studies on patients with major vascular trauma who survived until hospital admission, among whom the mortality rates typically ranged from 18 to 24% (12, 79, 93).

In addition, in **Paper I**, a significantly higher proportion of individuals (69%) sustained major vascular injuries in the rural parts of Iceland. In Australia and the US, compared to those in urban areas, patients in rural areas showed higher mortality rates following vascular trauma (18, 81). This was, however, not the case in **Paper I**, in that the mortality rates due to major vascular trauma after road traffic accidents in Iceland before admission for both groups were 67% and 63% for rural and urban areas, respectively. Importantly, the 30-day survival rates following admission were 93% and 57% for patients from rural and urban areas. One reason for this difference could be that more severely injured patients do not reach the hospital alive and die on the scene or during transport.

In **Paper V**, both the 24-h and 30-day mortality rates among patients with major vascular trauma at Haukeland Hospital were high (18% and 30%, respectively). Furthermore, the in-hospital mortality rate was 29%. The mortality rates observed by other major trauma centres varied from 0–30% and our results were therefore at the higher end of the reported mortality range (11, 12, 79, 81-85, 261). This difference could to some extent be explained by the fact that at Haukeland Hospital, less severe cases of vascular trauma were not evaluated by the trauma team, and were therefore not included in **Paper V**.

In our analysis of serious thoracic trauma cases in **Paper IV,** a total of 12% of the admitted patients died within 30 days, whereas 5% of the patients died within 24 h. These mortality figures are in line with studies conducted in Germany (13%), the US, and Canada (10–12%) (55, 62, 66). Three hundred and thirteen (61%) chest trauma patients were polytrauma casualties, which could explain the relatively high overall mortality rate of 18%. Mortality rates after severe thoracic trauma in polytrauma vary in the literature, ranging from 10–18%, and are mostly explained by variations in the selection criteria of patients among studies (31, 60, 71, 253, 276). Mortality rates among patients who sustained polytrauma, except those with traumatic brain injury, were highest during the first 24 h, mainly due to exsanguination. Polytrauma patients with traumatic brain injury, however, most often died on the second day due to brain injury, the findings of which are in line with other studies on the subject (277, 278).

In **Paper V**, reviews of autopsy reports showed that vascular trauma was the direct cause of death in 68% of patients who succumbed after admission to Haukeland University Hospital. Exsanguination has been shown to be the most significant cause of potentially preventable death after injury (279), and in this study, haemorrhagic shock was the dominant cause of death in 12 out of 22 (55%) patients.

The long-term survival rate of the 21 individuals in **Paper I** who were admitted in Iceland with major vascular trauma following a road traffic accident was 86% at 1 year. In **Paper V**, the long-term survival rate among all cases of major vascular trauma at Haukeland Hospital was lower (67%) at 1 year.

5.6.1 Aortic injury and associated mortality

In **Paper V**, aortic injury (22%) was the most common major vascular injury at Haukeland Hospital during the study period. The thoracic aorta was injured in 75% of cases of aortic injury, usually following a blunt injury (87%). The death rate due to aortic injury was high (40%) and all the patients died within 24 h of arrival at the emergency department. This is in line with published reports in which only half of patients admitted with thoracic aortic injury survived the first 24 h (280).

Williams et al. (1994) reported that the incidence rate of trauma to the aorta following a fatal road traffic accident was 17%, death occurring before hospital admission in 44% of cases. Furthermore, 94% of the victims died within one hour of injury (96). These results are similar to those reported in the Icelandic study (**Paper I**) in which a majority of patients who died due to major vascular trauma following road traffic accidents sustained fatal aortic injuries. In the rural setting, the mortality rate was high (74%). Furthermore, almost 80% (32/41) of those who did not reach the hospital alive had a thoracic aortic injury, as compared to 48% (10/48) of those who were admitted alive ($p = 0.015$). This underscores the high mortality rate following aortic injury and how mortality increases with increased transport time.

5.6.2 Risk factors for mortality in thoracic trauma

As shown in **Paper IV**, patients with more than nine comorbidities and concurrent medications assessed by the Comorbidity Polypharmacy Score had a considerably higher mortality risk compared to patients with relatively few or no comorbidities (OR, 4.77; $p = 0.011$). Advancing age was also associated with a higher mortality risk (31, 40, 60, 281-285). In **Paper IV**, it is suggested that comorbidities accompanying advanced age contribute to mortality and not age alone. This should not come as a surprise and the study demonstrates that comorbid conditions independently predict mortality, findings that are in line with other reports (286, 287). Both Comorbidity Polypharmacy Score and Charlson Comorbidity Index have previously been shown to predict mortality in trauma (218, 288). However, in **Paper IV**, those factors turned out to be the strongest predictors of mortality.

Paper IV also emphasises the high risk of pulmonary complications after thoracic trauma, and the higher mortality rate in this patient group. Furthermore, patients with a Complication Index ≥ 30, which represent severe complications of Clavien–Dindo scale grade 3 and higher, were more likely to die.

Paper IV also shows that injury severity in thoracic trauma is best measured by the TRISS. It is well known that the anatomical severity of an injury, combined with the physiological burden on the body, is the best measure of injury severity, and therefore the strongest predictor of mortality after trauma (289, 290).

5.7 Strengths and limitations

The main strength of the studies conducted in Iceland lay in their use of a nationwide design. In Iceland, patients were treated at a single tertiary referral trauma centre and communication among the smaller trauma hospitals around the country was efficient. Furthermore, accessing both centralised nationwide hospital and autopsy databases, together with detailed patient records, strengthened the finding of the studies, with the follow-up of survival being almost 100% complete.

The main strength of the studies conducted at Haukeland University Hospital lay in their well-defined geographical cohort design. A further strength was the access to both a national and local trauma registry with nearly complete follow-up as well as the prospective enrolment in the trauma registries.

Furthermore, all studies were conducted over a relatively long period from 5 up to 16 years which is an important strength.

The limitations in all five studies were the relatively limited number of patients and the fact that they only covered trauma in adult patients. Therefore, the age-standardised incidence does not represent all age groups. Another limitation was the retrospective design which could lead to potential bias. Retrospective cohort studies require large sample sizes if outcomes are rare and therefore only associations, and not causation could be determined.

Furthermore, **Papers IV** and **V** described studies that were conducted at Haukeland Hospital; however, patients who died on the scene or during transport were excluded. Additional limitations pertained to the analysis of predictive factors of mortality following serious thoracic trauma in **Paper IV**, in which we excluded patients transferred from other smaller trauma centres and not primarily evaluated by the Haukeland Hospital trauma team. Again, we may have underestimated the effects potentially due to missing data on comorbidities, medication use, and complications in patients who died within the first 24 h after the accident.

Finally, in **Paper IV,** complications were defined as all adverse events graded using the Clavien–Dindo scale, and occurring after admission in patients after the initial treatment. This could be a limitation in the analysis of risk factors for mortality among patients who died in the first 48 h.

6 Conclusions

This study is the first to characterise the nationwide epidemiology of severe vascular trauma in Iceland and an organised Norwegian trauma system. The published results from Iceland are representative of the entire country, and to the best of our knowledge, such population-based figures for vascular trauma in road traffic accidents, emergency thoracotomy procedures, or penetrating injury have not been previously reported.

Major vascular trauma following a traffic accident is an uncommon injury in Iceland with an incidence of 1.7 per 100 000 inhabitants as reported in **Paper I**. Two of every three (66%) individuals who sustained major vascular trauma died before reaching the hospital and most were injured in the rural parts of Iceland. Four times more men than women were injured. The most serious vascular injuries impacted the thoracic aorta, most often due to a frontal car collision. **Paper I** highlights the high mortality rate following aortic injury and demonstrates how survival chances diminish with increasing transport time. Patients who were admitted alive were often severely injured and needed emergency surgery, with high demands on hospital resources. Most admitted patients survived to discharge (71%) with excellent long-term survival.

Paper II shows that emergency thoracotomy is rarely performed in Iceland where blunt trauma, like in Bergen, dominates. The results are nonetheless encouraging as five out of nine severely injured patients survived the procedure. With a good selection of patients according to ATLS guidelines and training of trauma staff, emergency thoracotomy might be considered in more cases.

Paper III showed that penetrating stab injuries were rare in Iceland over the 16-year study period. More importantly, the incidence does not seem to be increasing, which is in line with reports from high-volume centres. The mortality rate was very low in comparison to many previous studies even though a large proportion of patients needed surgical interventions.

In **Paper IV**, an analysis of serious thoracic injury showed that in evaluating a trauma patient, prior medical history, as well as the mechanism of injury, is highly important. Risk factors for mortality following severe thoracic trauma include female sex, more than nine comorbidities and concurrent medications, TRISS, as well as severe complications. Comorbid conditions predict mortality independently of age. The subgroup analysis, which included isolated thoracic trauma and polytrauma with and without traumatic brain injury, did not demonstrate other predictive factors for mortality. The overall complication rate of thoracic trauma was comparable to complication rates mentioned in recent studies. This study provides, for the first time, to the best of our knowledge, an overview of all complications that occur after severe thoracic trauma.

Paper V demonstrates that traumatic major vascular injuries are uncommon in civilian settings in Western Norway. However, the incidence is in line with other studies conducted in settings with similar socioeconomic backgrounds and specialised trauma centres such as Australia and the US. Most cases of vascular injury in Western Norway occurred secondary to blunt trauma caused by motor vehicle accidents, unlike in the US and UK, where gunshot/penetrating injuries dominate.

Even though endovascular technology is well established in both Iceland and Bergen, a majority of vascular trauma patients in our study were still treated via open surgery as reported in **Papers I** and **V**. At Haukeland University Hospital, a majority of patients were operated on by vascular or thoracic surgeons most often with simple suturing. None of the patients sustained loss of an extremity.

Although Iceland and Norway have level 1 trauma centres with low patient volumes and often difficult transport routes, the rate of treatment success is similar to those reported in international studies conducted at high-volume centres. We hope that our findings might help to identify vascular and thoracic patients at risk of an adverse outcome to improve their management and reduce the risk of complications.

6.1 Clinical implications and future work

Major vascular and thoracic injuries are rare but often lethal and remain a challenge to the trauma surgeon. Among Nordic countries, there is a high level of activity in trauma research, particularly pertaining to the development of an efficient team and simulation-based trauma training (291, 292). However, in both Iceland and Norway, trauma patient management remains challenging, primarily because a significant proportion of the population lives in rural areas where long distances and a harsh winter climate call for well-organised utilisation of resources. It is therefore important to regularly evaluate outcomes of treatment at regional trauma centres, particularly, centres with low patient volumes.

The present studies indicate that it is possible to build an efficient low-volume level 1 trauma centre with similar outcomes as larger trauma centres in the US and UK. Training of trauma staff is also essential in low-volume trauma centres. Timely diagnosis and treatment are vital for a good outcome, in addition to high technology equipment with 24/7 availability of imaging and treatment technology and the involvement of preferably vascular surgeons.

In both Iceland and Bergen, major vascular and thoracic trauma is related to road traffic accidents in civilian settings. The studies, therefore, underscore the need for preventive measures when it comes to improved roads and the design of secure vehicles. Furthermore, it emphasises the importance of well-established and efficient transport methods for rural trauma patients to minimise the time between an accident and hospital admission, as well as the importance of prehospital care.

When treating trauma patients, particularly those who have sustained vascular and/or thoracic trauma, it is important to have knowledge of risk factors that can affect morbidity and mortality. This would make it easier to implement preventative measures and develop safety measures in automobiles, in addition to knowing when admission to the ICU is indicated.

The high 24 h mortality rate in the subgroup of patients highlights the importance of initiating treatment among polytrauma patients at the accident site. When possible, patients with major vascular and/or thoracic trauma, particularly, polytrauma patients, should be transported to specialised trauma centres as soon as possible sooner than later, ideally to one with most surgical specialities available, including a vascular surgeon with access to preferably hybrid suites and an effective blood bank service. Fortunately, this is where most trauma centres within Europe are heading and this is expected to benefit future trauma patients.

Papers I–V in this thesis highlight the need for consensus regarding the use of trauma scores in evaluating trauma patients. They also demonstrate how trauma registries can facilitate the evolution of treatment options and improve outcomes, making it possible to self-evaluate treatment outcomes as well as compare results with other trauma centres. Special vascular and thoracic registries focusing on vascular trauma have been established in some European and North American countries. Implementing such registries in addition to trauma registries at Haukeland University Hospital in Bergen and Landspitali University Hospital in Reykjavik should be an important future goal at both institutes. This is especially true, to further maintain and improve the treatment of this important patient group.

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Paper I

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Paper III

Paper IV

Paper V

Appendix A. Trauma Centre Designations and Levels

A trauma Centre is a healthcare facility that has the resources to provide care for major trauma patients. The American College of Surgeons (ACS) has outlined criteria for categorising trauma centres (48). Below are descriptions of the categories according to the American Trauma Society based on the ACS criteria:

A **Level I Trauma Centre** is a tertiary care facility central to the trauma system that can provide total care for polytrauma patients. Tertiary care is defined as highly specialised medical treatment. A Level I Trauma Centre is characterised by a 24 h availability of general surgeons as well as other medical specialists in fields such as orthopaedic surgery, neurosurgery, anaesthesiology, emergency medicine, radiology, internal medicine, plastic surgery, oral and maxillofacial surgery, paediatrics, and critical care.

A **Level II Trauma Centre** must be able to initiate definitive care for all trauma patients. A general surgeon must be on call 24 h a day, in addition to other specialists in other fields such as orthopaedic surgery, neurosurgery, anaesthesiology, emergency medicine, radiology, and critical care. Patients requiring more advanced care, such as cardiac surgery, haemodialysis, and microvascular surgery may be referred to a Level I Trauma Centre.

A **Level III Trauma Centre** must have 24 h coverage by emergency medicine physicians and availability of general surgeons and anaesthesiologists. The facility must be capable of providing early assessment, resuscitation, surgery, intensive care, and stabilisation of trauma patients, as well as emergency operations.

A **Level IV Trauma Centre** must be capable of providing advanced trauma life support before trauma patients are transferred to a higher-level trauma centre. In addition to 24 h laboratory coverage, trauma nurses and physicians need to be available upon patient arrival. A Level IV Trauma Centre may sometimes provide surgical and critical-care services if available.

A **Level V Trauma Centre** provides advanced trauma life support before trauma patients are referred to a higher-level trauma centre. Trauma nurses and physicians need to be available upon patient arrival. An after-hours activation protocol must be in place if the facility is not open 24 h a day. Sometimes, such a facility may provide surgical and critical-care services if available.