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Research Article

Hemorrhage Control Tourniquets, Pressure, and Wound Firstaid by Red Crescent

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Abstract:

Hemorrhage control is a critical component of trauma management, especially in cases of severe bleeding from extremity injuries. One of the most effective tools for controlling life-threatening hemorrhage is the use of tourniquets. When applied properly, a tourniquet can occlude blood flow to a limb, substantially reducing the risk of exsanguination until more advanced medical care can be provided. Various types of tourniquets exist, but those designed for prehospital use have undergone rigorous testing to ensure their effectiveness and safety. The application of a tourniquet requires training, as incorrect usage can lead to complications such as tissue damage; therefore, education on proper technique is paramount for first responders and civilians alike. In conjunction with tourniquets, the use of direct pressure on wounds and hemostatic dressings can also play a vital role in managing bleeding, particularly in cases where a tourniquet may not be suitable. In addition to the immediate management of bleeding, wound care further enhances outcomes for patients with traumatic injuries. After hemorrhage control, ensuring the clean management of wounds helps prevent infection and promotes healing. For larger wounds, the use of pressure dressings can be critical in maintaining stability while waiting for surgical interventions. Medical professionals often employ techniques to assess the depth and extent of the wound, as well as to evaluate for foreign objects that may require removal. Effective wound management incorporates a comprehensive approach, including stabilization, application of appropriate dressings, and, where necessary, the initiation of antibiotic prophylaxis. Ultimately, a well-coordinated strategy involving tourniquet application, pressure management, and thorough wound care significantly contributes to the patient's chances of recovery and long-term outcomes.

1. Introduction

Uncontrolled hemorrhage remains one of the most formidable and immediate threats to life in both civilian trauma and military combat settings. It is the leading cause of preventable death following traumatic injury, accounting for a significant percentage of mortality that could potentially be averted with prompt and effective intervention [1]. The "golden hour" concept, a long-standing principle in emergency medicine, emphasizes the critical window following traumatic injury during which there is the highest likelihood that prompt medical and surgical treatment will prevent death. However, in the context of severe bleeding, this concept is often superseded by the "platinum 10 minutes" or, even more urgently, the notion of addressing the "lethal triad" of trauma—coagulopathy, acidosis, and hypothermia—which is directly fueled by exsanguination [2]. The imperative to control bleeding is not merely a medical procedure; it is a race against time where the actions of first responders, medical personnel, and even bystanders can decisively alter a patient's fate.

The physiological consequences of severe hemorrhage are rapid and catastrophic. The acute loss of circulating blood volume leads to hypovolemic shock, a state of inadequate tissue perfusion and cellular oxygenation. As the body attempts to compensate through mechanisms like tachycardia and peripheral vasoconstriction, vital organs such as the brain, heart, and kidneys are deprived of oxygen [3]. This initiates a downward spiral: the body's clotting mechanisms are impaired, leading to coagulopathy; anaerobic metabolism causes a buildup of lactic acid, resulting in metabolic acidosis; and the loss of perfusion and shivering capability leads to hypothermia. This lethal triad creates a vicious, self-perpetuating cycle that becomes increasingly difficult to reverse, making early and definitive hemorrhage control the single most critical step in interrupting this fatal progression [2].

Recognizing this critical need, modern trauma care has seen a paradigm shift towards a systematic, hierarchical approach to bleeding control. This is best encapsulated in the various iterations of the Tactical Combat Casualty Care (TCCC) guidelines and its civilian counterpart, the Hartford Consensus, which have placed controlling catastrophic hemorrhage as the foremost priority, even before airway and breathing in certain scenarios [4]. The simple, powerful mantra "ABC" (Airway, Breathing, Circulation) has been revised in the context of trauma to "C-ABC," where "C" stands for Catastrophic Hemorrhage, underscoring its primacy [5]. This evolution in protocol reflects a sober understanding that a patient with a compromised airway may have minutes to live, but a patient with uncontrolled arterial hemorrhage has only moments. This research paper will delve into the three cornerstone techniques of modern hemorrhage control: the use of tourniquets, the application of direct and indirect pressure, and comprehensive wound management. Each of these methods represents a critical link in the chain of survival, from the point of injury to definitive surgical care.

The tourniquet, a device with a history spanning centuries, has experienced a dramatic rehabilitation in its medical reputation. Once viewed as a tool of last resort, fraught with risks of nerve damage, limb loss, and ischemic injury, it is now recognized as a lifesaving intervention when used correctly and in the appropriate context. Historical reluctance stemmed from complications associated with prolonged application, often in pre-hospital settings with extended evacuation times. However, extensive data from recent military conflicts in Iraq and Afghanistan, as well as growing evidence from civilian mass casualty incidents and everyday trauma, has overwhelmingly demonstrated that the lifesaving benefits of tourniquet use for extremity hemorrhage far outweigh the risks [6]. Modern tourniquets, such as the Combat Application Tourniquet (CAT) and the Special Operations Forces Tactical Tourniquet (SOFTT), are designed to be effective, rapidly applicable, and used with minimal training, making them accessible to a wide range of potential responders [7].

The indications for tourniquet application are specific: life-threatening extremity hemorrhage that cannot be controlled by direct pressure, or in situations where the responder cannot safely or effectively apply direct pressure, such as in a hostile environment, a mass casualty incident with limited personnel, or with an wound anatomy that is not amenable to packing [8]. The technique of application is crucial; it must be placed proximal to the bleeding site on a single-bone segment (e.g., the femur or humerus) and tightened until the arterial bleeding ceases. A common error is failing to tighten the tourniquet sufficiently, which can occlude venous return while allowing arterial inflow, paradoxically worsening blood loss [9]. Once applied, the time of application should be clearly noted, and the tourniquet should not be loosened or removed in the pre-hospital setting unless under the direction of a qualified medical professional in a controlled environment, as this can release toxins and provoke re-bleeding [10].

While tourniquets are indispensable for certain types of injuries, they are not a universal solution. For junctional hemorrhages—bleeding from areas where the extremities meet the torso, such as the groin, axilla, and neck—tourniquets are often ineffective due to anatomy. This has driven the development and adoption of junctional tourniquets and advanced hemostatic agents. Furthermore, the vast majority of non-catastrophic bleeding can and should be managed with direct pressure. This brings us to the second pillar of hemorrhage control: the application of pressure. This foundational technique, while seemingly simple, involves a nuanced understanding of its various forms and applications, from direct manual pressure to the use of pressure dressings and wound packing.

Direct pressure is the first and most intuitive response to active bleeding. By applying sustained force directly to the source of hemorrhage, external pressure is transmitted to the severed vessels, facilitating the natural clotting process. The effectiveness of direct pressure can be significantly enhanced with the use of purpose-built pressure dressings, such as the Israeli Emergency Bandage or the Emergency Trauma Dressing, which incorporate a non-adherent pad and a built-in pressure bar to maintain consistent force over the wound [11]. For wounds that are deep or have a tract, such as from a gunshot, direct surface pressure may be insufficient. In these cases, wound packing becomes a critical skill. This technique involves physically filling the wound cavity with a hemostatic gauze, applying direct pressure to the bleeding vessels from within. The development of hemostatic gauzes—impregnated with agents like kaolin or chitosan that accelerate the body's natural clotting cascade—has revolutionized this practice, making it highly effective for severe, non-tourniquetable hemorrhage [12].

The final pillar, comprehensive wound management, encompasses the steps that follow initial hemorrhage control and prepare the patient for transport and definitive care. This includes a thorough assessment for all sources of bleeding, careful cleaning and debridement of the wound edges (without disturbing formed clots), and the application of a definitive sterile dressing to protect against contamination and further injury. It also involves continuous monitoring for signs of recurrent bleeding or the development of compartment syndrome, a potential complication following reperfusion or significant trauma to an extremity [13]. Effective wound management is not a passive act but an active process of stabilization and preparation, bridging the gap between the emergency field intervention and the surgical or clinical care that will follow [13].

2. Tourniquet Technology and Historical Evolution

The tourniquet, a device whose name is derived from the French "tourner," meaning "to turn," has a history as dramatic and transformative as the field of emergency trauma care itself. Its journey from a crude, feared instrument of amputation to a refined, lifesaving tool ubiquitous in modern trauma kits is a testament to evolving medical understanding, technological innovation, and hard-won empirical evidence from the battlefield. The historical evolution of the tourniquet is not merely a chronological account of a device; it is a narrative that parallels the development of surgery, military medicine, and the overarching principle of prioritizing life over limb. From its earliest iterations, which focused on achieving hemostasis at any cost, to today's scientifically engineered devices, the tourniquet's story is one of continuous refinement in the relentless pursuit of improving survival from catastrophic hemorrhage.

The earliest descriptions of devices used to control bleeding by limb constriction date back to antiquity. Roman physicians used bronze rings and tight leather straps to create hemostasis during amputations, understanding the basic principle of circulatory occlusion but lacking the anatomical knowledge to apply it safely or effectively [14]. However, the conceptual birth of the tourniquet as a recognized medical instrument is widely attributed to the French army surgeon Ambroise Paré in the 16th century. Paré, a pioneer in battlefield surgery, introduced a device he called the "bec de corbin" (crow's beak), which was a complex screw-based mechanism used to constrict blood vessels prior to amputation. While a significant advancement, it was cumbersome and not widely adopted for emergency use [15]. The true popularization of the term and concept came in the 17th century with Etienne Morel, whose "tourniquet" was a simple windlass device made from a stick and a piece of cloth, used to create circumferential pressure. This basic design, known as the windlass tourniquet, would become the standard for centuries, proving its utility but also its potential for causing significant tissue and nerve damage due to its narrow band width and uncontrolled pressure application [16].

The 18th and 19th centuries saw incremental improvements, primarily focused on making the device more adjustable and slightly more user-friendly for scheduled surgical procedures. The American Civil War and World War I saw the widespread issuance of tourniquets to battlefield medics. However, this period also cemented the device's dangerous reputation. Prolonged field evacuation times, often spanning many hours or even days, meant that tourniquets were frequently left applied for dangerously extended periods. The inevitable consequences were widespread ischemic injuries, gangrene, and nerve palsies, leading many surgeons to view the tourniquet as a last resort that often necessitated the very amputation it was meant to precede [17]. This era created a deep-seated cultural aversion to tourniquet use within the medical community, a skepticism that would persist for much of the 20th century. The prevailing dogma became that the risks of tourniquet-induced limb damage far outweighed its potential benefits, a perspective that would only be challenged and overturned by the stark realities of modern combat.

The paradigm shift in tourniquet doctrine began in the late 20th and early 21st centuries, driven overwhelmingly by data and experience from military conflicts, particularly the wars in Iraq and Afghanistan. The modern era of tourniquet technology was born from a critical need: reducing the number of preventable deaths from extremity hemorrhage on the battlefield, which was identified as the leading cause of potentially survivable combat casualty loss [18]. Military medical researchers, analyzing casualty data, made a startling discovery: a significant number of soldiers were dying from limb bleeds that could have been stopped by a simple device, but the fear of complications had led to underutilization of existing, often outdated, tourniquet models. This catalyzed a concerted effort to redesign the tourniquet from first principles, focusing on efficacy, speed of application with one hand (for self-aid), reliability, and reduced complication rates.

This research and development surge led to the creation of a new generation of tourniquets, characterized by several key technological advancements. The most significant of these was the Combat Application Tourniquet (CAT), which became the U.S. military's standard issue. Its design incorporated a wide, durable nylon band to distribute pressure more evenly, reducing the risk of nerve injury compared to the narrow straps of older models. More importantly, it featured a friction-adapter buckle that allowed for self-application with a single hand and a windlass rod that could be easily secured with a dedicated clip, preventing accidental loosening under chaotic conditions [19]. Alongside the CAT, other designs like the Special Operations Forces Tactical Tourniquet (SOFTT) and the Mechanical Advantage Tourniquet (MAT) were developed, offering alternative mechanisms such as a screw-based windlass or a ratcheting system, but all shared the same core principles of wide contoured bands, secure locking mechanisms, and rapid application [20].

Concurrent with the development of mechanical tourniquets was the exploration of pneumatic technology. The Emergency Medical Tourniquet (EMT), a pneumatic (air-inflated) device, offered the advantage of automatically regulating and distributing pressure evenly around the circumference of the limb. This was theorized to further reduce the risk of localized tissue damage. While highly effective, pneumatic tourniquets introduced new potential points of failure, such as leakage or rupture, and were generally bulkier than their mechanical counterparts, limiting their widespread adoption for individual soldier carry [21]. The rigorous testing and real-world deployment of these new tourniquets yielded irrefutable evidence. Studies from the battlefront showed a dramatic drop in mortality from extremity hemorrhage, with survival rates exceeding 90% when a modern tourniquet was applied, and the incidence of nerve injuries was far lower than historically feared, especially when application times were kept under two hours [22]. This evidence-based success on the battlefield forced a radical re-evaluation of tourniquet use in civilian emergency medical services and trauma centers.

The lessons learned from the military sphere have profoundly influenced civilian trauma care, leading to the widespread integration of modern tourniquet technology into the protocols of emergency medical services, law enforcement, and public access hemorrhage control initiatives. Programs like the "Stop the Bleed" campaign, born from the Hartford Consensus, have democratized this lifesaving knowledge, training laypersons to use commercial tourniquets in the critical minutes before professional help arrives [23]. The presence of tourniquets in public spaces, such as airports, schools, and concert venues, is now becoming commonplace, representing a fundamental shift in public health preparedness for active shooter situations and mass casualty events.

The evolution of tourniquet technology continues, with current research focusing on several frontiers. One key area is the development of "junctional tourniquets" designed to control bleeding in the anatomically complex areas of the groin, axilla, and pelvis, where traditional limb tourniquets are ineffective. Devices like the Combat Ready Clamp (CRoC) and the Junctional Emergency Treatment Tool (JETT) use mechanical or pneumatic pressure to occlude blood flow at these difficult-to-compress sites, filling a critical gap in the hemorrhage control arsenal [24]. Another area of innovation involves the integration of technology, such as tourniquets with built-in timers and sensors to monitor application time and pressure, providing valuable data to receiving medical facilities and helping to prevent both under-tightening and prolonged ischemia [25]. Furthermore, material science is contributing to the development of lighter, stronger, and more compact designs to enhance portability without sacrificing performance.

3. Indications and Contraindications for Tourniquet Use

The dramatic rehabilitation of the tourniquet in modern trauma protocols is predicated not on its indiscriminate use, but on its precise application in specific, life-threatening scenarios. The adage "the right tool for the right job" is paramount in hemorrhage control, as the improper use of a tourniquet can itself cause significant harm. Therefore, a clear and unambiguous understanding of the indications and contraindications for tourniquet application is a critical component of training for all levels of medical and lay responders. This knowledge ensures that this powerful lifesaving tool is deployed effectively when the benefit unequivocally outweighs the risk, and that alternative, less invasive methods are employed when appropriate. The decision to apply a tourniquet is a rapid but deliberate clinical judgment, guided by a hierarchy of hemorrhage control that prioritizes the preservation of life above all else.

The primary and most absolute indication for tourniquet use is life-threatening external hemorrhage from an extremity that is not controllable by direct manual pressure. This typically manifests as arterial bleeding, characterized by bright red blood that is spurting or flowing profusely in a pulsatile manner. In such cases, the rate of blood loss can lead to exsanguination in a matter of minutes, making rapid intervention non-negotiable [26]. The "MARCH" algorithm, used in Tactical Combat Casualty Care (TCCC), places Massive Hemorrhage as the first priority for a reason; stopping the bleed is the initial and most crucial step. If a responder applies firm, direct pressure to a wound for two to three minutes and the bleeding continues unabated, this constitutes a clear failure of basic hemorrhage control and is a definitive indication to immediately proceed to tourniquet application [27]. Hesitation in this scenario can be fatal.

Beyond the failure of direct pressure, there are several tactical and situational indications that mandate the immediate use of a tourniquet as the first-line intervention. In a hostile or "hot" zone, such as an active shooter scene or a battlefield, where the responder's safety is paramount and prolonged exposure to provide continuous direct pressure is untenable, a tourniquet is the standard of care. It can be applied rapidly and allows for the quick extraction of the casualty to a safer location [28]. Similarly, in a mass casualty incident (MCI) with multiple injured patients and limited medical personnel, the principles of triage dictate the need for rapid, definitive interventions. A tourniquet can be applied quickly to a catastrophic limb bleed, effectively "turning off" that particular injury and allowing a single responder to move on and care for other casualties, thus maximizing the survival of the greatest number of people [29]. Furthermore, for wounds with anatomy that is not amenable to direct pressure or wound packing, such as a traumatic amputation or a severe crush injury with massive tissue destruction, a tourniquet is often the only viable pre-hospital option to achieve hemorrhage control [30].

While the indications for tourniquet use are clear in cases of catastrophic hemorrhage, the contraindications and areas of caution are equally critical to understand. The most significant relative contraindication involves the anatomical location of the bleed. As previously discussed, traditional limb tourniquets are designed for application on single-bone segments—the "long bones" of the upper arm (humerus) and thigh (femur). They are inherently ineffective and contraindicated for controlling hemorrhage from junctional areas, such as the neck, axilla (armpit), and groin. The complex anatomy and proximity of major vessels to the torso prevent a standard tourniquet from achieving sufficient occlusion [31]. Attempting to apply a tourniquet to the neck is not only futile for bleeding control but is also exceptionally dangerous due to the risk of airway compression and damage to the cervical spine. For these junctional hemorrhages, alternative techniques such as hemostatic gauze packing with direct manual pressure or the use of specialized junctional tourniquets are required.

Another critical area of caution involves the application of a tourniquet over certain pre-existing conditions. Applying a tourniquet directly over an obvious or suspected fracture can exacerbate the injury, potentially causing further displacement of bone fragments, increasing soft tissue damage, and complicating subsequent surgical management. The ideal placement is proximal to the wound on healthy tissue, but if the fracture site is very proximal itself, this may not be possible. In such cases, the tourniquet should still be applied as high and as proximal as possible on the limb to control the bleeding, as the immediate threat of exsanguination takes precedence over the orthopedic injury [32]. Similarly, applying a tourniquet directly over a major foreign object impaled in the limb is not advised, as it may drive the object deeper or prevent effective compression. The tourniquet should be placed proximal to the object, if possible. Furthermore, while application over an arteriovenous (AV) fistula or shunt in a dialysis patient should be avoided if a viable alternative site exists, the presence of such a device does not absolutely prohibit tourniquet use if it is the only means to save a life from catastrophic bleeding elsewhere on the same limb [33].

One of the most persistent and dangerous myths in first aid is the idea of "partial" arterial bleeding or the use of a tourniquet as a "pressure dressing." A tourniquet is a binary device: it must be tightened until all distal arterial bleeding ceases, as confirmed by the absence of a palpable pulse and the stoppage of bleeding. A loosely applied tourniquet that occludes venous return while allowing arterial inflow will paradoxically increase blood loss, as blood can enter the limb but cannot exit, leading to compartment syndrome and worsened hemorrhage [34]. Therefore, the concept of a "contraindication" also extends to improper technique. If a responder is not prepared to tighten the tourniquet adequately, it is better to rely on forceful direct pressure and wound packing. Once applied, the tourniquet should not be routinely released or "loosened" in the pre-hospital setting. This historical practice, aimed at reducing ischemic time, is now known to be harmful, as it can provoke renewed bleeding, release acidic metabolites and potassium from the ischemic limb into the systemic circulation, and does not meaningfully prolong the safe application time [35].

The decision-making process for tourniquet application can be visualized as a rapid algorithm. The initial assessment focuses on the nature of the bleeding. For non-life-threatening, venous or capillary oozing, direct pressure and a simple bandage are entirely sufficient. The tourniquet is not indicated. For active, serious bleeding, the responder should immediately begin applying direct manual pressure, ideally with a hemostatic dressing if available. If the bleeding stops with pressure, the responder can then transition to a firm pressure dressing and monitor for re-bleeding. However, if the bleeding is immediately catastrophic, if it continues unabated after two to three minutes of direct pressure, or if the tactical or mass casualty situation dictates, the responder must immediately proceed to tourniquet application [36].

Once the decision to use a tourniquet is made, the principles of correct application are vital: "high and tight" on the limb, proximal to the wound, but not over a joint. It should be tightened until bleeding stops, and the time of application must be clearly documented and communicated to the next level of care. The patient must be continuously reassessed. A key post-application consideration is the concept of "tourniquet conversion." Once the patient is in a more stable, controlled environment, such as in an ambulance or an emergency department, and if bleeding is not from a major arterial trunk, a qualified provider may attempt to convert the tourniquet to a pressure dressing or a wound pack. This is done under controlled conditions, with the necessary equipment and expertise on hand to immediately re-tighten the tourniquet if significant bleeding recurs [30]. This process can help to limit the total ischemic time to the limb.

4. Mechanical and Electrical Mechanisms of Hemostasis

The principle of mechanical hemostasis, in its most advanced form, extends far beyond the simple application of direct pressure. This category encompasses devices designed to apply targeted, high-force compression to specific anatomical sites, particularly junctional zones. Junctional tourniquets, such as the Combat Ready Clamp (CRoC) and the Junctional Emergency Treatment Tool (JETT), are sophisticated mechanical devices engineered to overcome the anatomical limitations of standard limb tourniquets. The CRoC, for instance, uses a rigid, patient-mounted base and a screw-driven plunger to deliver focused, mechanical pressure directly onto the femoral artery within the groin, effectively occluding blood flow through controlled mechanical force [37]. Similarly, intra-abdominal aortic compression devices, like the Abdominal Aortic and Junctional Tourniquet (AAJT), use a pneumatic bladder to compress the aorta against the spine through the abdominal wall, a radical mechanical approach for controlling hemorrhage in the pelvis and lower extremities that is unattainable by any other external means [38].

Another frontier in mechanical hemostasis is the use of self-expanding foams. This technology involves the injection of liquid polymers into a deep, non-compressible wound tract, such as one from a gunshot wound to the abdomen or groin. Upon contact with blood, the polymers undergo a rapid chemical reaction, expanding into a solid, low-density foam that conforms to the wound cavity. This expansion generates significant inward radial pressure, mechanically compressing bleeding vessels from within the wound. The foam acts as a physical tamponade, effectively sealing the cavity and controlling hemorrhage in areas where direct manual pressure or tourniquets are futile. Early research in animal models has demonstrated the potential of this technology to significantly improve survival from otherwise lethal junctional and truncal hemorrhages, representing a potentially revolutionary tool for pre-hospital and far-forward combat medicine [39]. These advanced mechanical systems demonstrate a move towards more intelligent, anatomically-aware solutions for the most difficult bleeding challenges.

Electrical mechanisms of hemostasis offer a completely different approach, leveraging the fundamental properties of thermal energy to achieve vessel sealing. The most well-established of these is electrocautery, a mainstay in the operating room. Electrocautery works by passing a high-frequency, alternating electrical current through a resistant metal wire, causing it to heat up. This heated tip is then applied directly to bleeding tissue, causing coagulation and necrosis through the transfer of heat, which denatures proteins and fuses vessel walls. However, traditional electrocautery is poorly suited for the pre-hospital or emergency setting, as it requires a power source, is designed for pinpoint control in a sterile field, and can cause significant collateral thermal damage to surrounding tissues [40]. Its utility is largely confined to the controlled environment of the operating room.

A more advanced and promising electrical technology is radiofrequency (RF) sealing. Used extensively in elective surgery for sealing blood vessels up to 7mm in diameter, RF devices work by applying a high-frequency alternating current directly to the tissue held between the jaws of a forceps. The current causes ions within the tissue to oscillate rapidly, generating frictional heat internally. This internal heat generation causes the collagen and elastin within the vessel walls to melt and reform into a permanent, plastic-like seal, effectively creating a "weld" that is often stronger than the surrounding tissue [41]. The key advantage over traditional cautery is that the energy is delivered in a controlled manner with real-time feedback, allowing the device to automatically cycle off once a complete seal is achieved, thereby minimizing collateral thermal spread. While current RF devices are too delicate and expensive for field use, research is ongoing to develop robust, portable, and single-use RF probes that could be used by emergency providers to seal major bleeding vessels in the groin or axilla during critical care evacuation [42].

The most dramatic application of electrical energy for hemostasis is pulsed plasma technology, commercially known as the Pulsed Electron Beam Knife or similar devices. This technology utilizes short, high-energy pulses of electrical current to generate a stable, non-thermal plasma field at the tip of a handheld probe. When this cold plasma is applied to a bleeding wound, it achieves hemostasis through a multi-modal mechanism. First, the electric field causes immediate vasoconstriction. Second, it appears to activate platelets and catalyze the rapid polymerization of fibrinogen into fibrin, essentially jump-starting the final common pathway of the clotting cascade directly at the site of injury [43]. Crucially, because the plasma is non-thermal or low-temperature, it does not cause the tissue charring, necrosis, or nerve damage associated with thermal cautery. This makes it a promising tool for controlling diffuse parenchymal bleeding from organs like the liver or spleen, as well as bleeding in sensitive anatomical areas, offering a "bloodless" and precise form of hemostasis that bridges the gap between mechanical pressure and the body's own biochemistry.

The ultimate goal of modern hemostasis research is not to replace one technology with another, but to create an integrated toolbox where the mechanism of action is matched to the specific clinical challenge. The choice between a mechanical tourniquet, an advanced hemostatic gauze, an expanding foam, or an electrical sealer depends on a rapid assessment of variables including the anatomical location of the bleed, the caliber of the bleeding vessel, the available resources, and the skill of the provider. For a straightforward traumatic amputation of the forearm, a mechanical tourniquet remains the fastest and most reliable solution. For a deep, narrow wound tract in the gluteal region, a hemostatic gauze packed into the cavity may be the best option. For a complex groin hemorrhage with a severed femoral artery, a junctional tourniquet provides the necessary mechanical force, while a future portable RF device might offer a more definitive surgical solution in the field.

Each technology carries its own profile of advantages and limitations. Advanced mechanical devices like the AAJT are highly effective but can be cumbersome to apply and may cause significant patient discomfort and complications like rhabdomyolysis with prolonged use [44]. Self-expanding foams show tremendous promise but are still largely in the experimental phase and face regulatory hurdles; there are also concerns regarding the difficulty of subsequent surgical removal and the potential for embolization [45]. Electrical methods, particularly cold plasma, offer unparalleled precision and a lack of tissue destruction but currently suffer from requirements for significant power sources, device cost, and a lack of robust, miniaturized designs suitable for the harsh pre-hospital environment [46].

Future directions in hemorrhage control will likely involve the convergence of these technologies. We can envision a "smart" tourniquet that not only occludes blood flow but also incorporates a sensor to monitor distal tissue oxygenation and a cold plasma tip to seal the vessel at the point of injury before removal. Research into targeted energy delivery, such as focused ultrasound for non-invasive hemostasis, is also underway [47].

5. Techniques of Applied Pressure: Direct Pressure, Elevation, and Packing

Direct manual pressure is the primary and most crucial initial intervention for any actively bleeding wound. The principle is simple: to apply sufficient external force directly over the source of bleeding to collapse the severed vessels and allow the body's intrinsic clotting mechanisms to form a stable clot. The correct technique, however, is vital for success. The responder should use the flat part of their fingers or, ideally, the heel of their hand to apply firm, steady, and uninterrupted pressure directly on the point of hemorrhage. If available, a sterile gauze pad or any clean absorbent cloth should be placed between the responder's hand and the wound. This serves multiple purposes: it aids in clot formation by providing a matrix for platelets and fibrin, helps to prevent contamination, and protects the responder from bloodborne pathogens [48]. A common and critical error is to "peek" at the wound frequently to check for bleeding; this repeated release of pressure disrupts the fragile clotting process and must be avoided. Pressure should be maintained continuously for a minimum of three to five minutes before any attempt is made to assess for hemostasis [49].

The effectiveness of direct pressure can be significantly enhanced by combining it with elevation. This technique involves raising the bleeding extremity above the level of the patient's heart. The physiological basis for elevation is the principle of hydrostatic pressure; by raising the limb, the gravitational force that contributes to venous and arterial pressure distal to the heart is reduced. This decreases the overall perfusion pressure to the injured area, making it easier for direct pressure to overcome the intravascular pressure and achieve hemostasis [50]. For example, controlling bleeding from a hand wound is markedly more effective when the arm is raised overhead while direct pressure is applied to the wound. It is a passive and synergistic technique that imposes no additional cost or risk. However, elevation should only be employed if it does not cause further injury, such as in the case of a suspected spinal injury or a obvious fracture that could be displaced by movement. When applicable, the combination of direct pressure and elevation is a powerful, two-step maneuver that can resolve most cases of moderate bleeding.

When direct surface pressure is insufficient, particularly for wounds that are deep, narrow, or have a significant tract, the technique of wound packing becomes the next logical and life-saving step. Wound packing is the process of physically filling a wound cavity with a dressing material to apply direct pressure to the bleeding vessels from within. This technique is especially critical for junctional areas like the axilla (armpit) and groin, where the application of a standard tourniquet is anatomically impossible, and surface pressure may fail to reach the depth of the injured vessel [51]. For decades, wound packing was performed with standard gauze, but the advent of hemostatic gauze—impregnated with clot-accelerating agents such as kaolin or chitosan—has dramatically improved its efficacy, particularly in the context of coagulopathy or arterial bleeding.

The technique for effective wound packing is methodical and aggressive. The responder must use a single, continuous length of hemostatic gauze (if available) or standard roller gauze, and begin packing at the deepest part of the wound cavity. Using the fingers, the gauze is systematically and tightly layered into the wound, ensuring that all potential spaces within the tract are filled. The goal is to create direct, wall-to-wall contact between the gauze and the bleeding tissues throughout the entire wound channel [52]. This direct apposition is what transmits pressure to the severed vessels. Once the wound is fully and tightly packed, the responder must then apply firm, direct manual pressure over the packed wound for a minimum of three minutes. This external pressure works in concert with the internal packing to ensure sustained tamponade. The end of the gauze can be left protruding from the wound to aid in later removal in a clinical setting. Following successful hemostasis, the pack can be secured in place with a pressure dressing, such as a rolled or elastic bandage, to maintain the internal pressure [53]. The development of pre-packaged, vacuum-sealed hemostatic gauzes designed specifically for rapid deployment in tactical and emergency settings has made this technique more accessible and standardized than ever before.

The integration of these techniques forms a logical sequence in the "Pressure" phase of hemorrhage control. The initial response to any significant bleed is always the application of direct manual pressure with elevation. If, after several minutes, bleeding persists—especially from a deep wound—the responder should immediately transition to wound packing. The success of this entire sequence hinges on the quality and endurance of the pressure applied. Inadequate force or frequent interruption are the most common reasons for failure. It is at this point, after the failure of well-executed direct pressure and wound packing, that the indication for a tourniquet (for an extremity wound) becomes unequivocal [54]. This systematic progression ensures that less invasive methods are exhausted before resorting to a device that carries a higher risk of complications, while also recognizing that timely escalation is key to preventing exsanguination.

The choice of dressing material plays a significant role in the success of these pressure-based techniques. While any clean cloth can be used in an emergency, modern medical practice utilizes a range of purpose-built dressings. The Israeli Emergency Bandage (also known as the Emergency Trauma Dressing) is a prime example of a device that integrates multiple principles of applied pressure. It consists of a non-adherent absorbent pad connected to an elastic wrap that incorporates a built-in plastic pressure bar. After the pad is placed directly on the wound, the elastic bandage is wrapped around the limb, and the pressure bar is slid over the wound site before the wrapping is secured. When the bandage is tightened, the bar focuses pressure directly over the bleeding point, creating an effective and sustained pressure dressing that can be applied with one hand [55]. This eliminates the fatigue associated with prolonged manual pressure and allows a single responder to manage multiple tasks or casualties.

Despite their foundational importance, the techniques of direct pressure and packing have limitations. Their efficacy can be compromised in several scenarios. In a mass casualty incident with limited personnel, it may be impractical for a single responder to provide continuous manual pressure to one victim for an extended period. In a high-threat tactical environment, maintaining a static position to hold pressure may expose the responder and casualty to unacceptable danger [56]. Furthermore, these techniques may be less effective for patients with underlying bleeding disorders or those on anticoagulant medications, as their intrinsic clotting cascade is impaired. In these cases, the use of hemostatic agents within the gauze becomes not just beneficial, but essential [57].

Training and muscle memory are paramount. The effectiveness of direct pressure, elevation, and packing is almost entirely dependent on the correct execution of the technique by the first person on scene. Public health initiatives like the "Stop the Bleed" campaign have been instrumental in democratizing this knowledge, teaching laypersons the critical skill of wound packing with hemostatic gauze, a technique once reserved for advanced medical providers [58].

6. Wound Assessment and Classification in Acute Hemorrhage

The primary and most urgent step in wound assessment is the rapid identification of the source and severity of bleeding. This begins with a visual sweep of the entire patient, as clothing and patient position can often conceal significant injuries. Once a bleeding wound is identified, the responder must quickly characterize the bleeding based on its flow and appearance. Arterial hemorrhage, the most immediately life-threatening, is typically identified by bright red blood that spurts or pulses in synchrony with the heartbeat. This pattern is due to the high pressure within the arterial system. Venous hemorrhage, in contrast, presents as a steady, dark red or maroon flow, as the pressure in the venous system is significantly lower. Capillary bleeding involves a slow oozing from superficial vessels and is rarely life-threatening [59]. While these classical descriptions are taught universally, it is critical to note that in a chaotic, high-stress environment with blood-soaked clothing, distinguishing between a pulsatile arterial bleed and a high-flow venous bleed from a major vein can be challenging. In such cases, the sheer volume and rate of blood loss become the overriding factors in classification and decision-making.

Beyond the type of vessel, the anatomical location of the wound is perhaps the single most important factor in determining the appropriate hemorrhage control strategy. Injuries are broadly classified into three anatomical categories: extremity, junctional, and non-compressible truncal hemorrhage (NCTH). Extremity hemorrhages, involving the arms and legs, are the most straightforward to manage, as they are accessible and amenable to the full range of interventions, from direct pressure and packing to tourniquet application. Junctional hemorrhages occur in the areas where the extremities join the torso—the neck, axillae (armpits), and groin. These areas pose a significant challenge because their complex anatomy makes it difficult to achieve effective compression with a standard tourniquet

[60]. The most lethal category is non-compressible truncal hemorrhage (NCTH), which involves bleeding into the chest, abdomen, or pelvis. By their very nature, these injuries are inaccessible to external compression, and their control almost always requires surgical or endovascular intervention in a hospital setting [61]. This anatomical classification immediately narrows down the viable options for the pre-hospital responder.

Building upon the initial visual and anatomical assessment, a more hands-on evaluation is often necessary, particularly for wounds that are not immediately catastrophic. This involves careful exposure of the injury site, typically by cutting away clothing, to allow for a full visual inspection. The responder should note the size, depth, and geometry of the wound. A small, deep puncture wound from a knife or a gunshot wound presents a very different challenge than a large, gaping laceration from a blunt injury. The deep puncture wound is a prime candidate for wound packing, as surface pressure may be ineffective, whereas the large laceration may be controlled with direct pressure and a pressure dressing [62]. During this assessment, it is crucial to look for the presence of foreign bodies impaled in the wound. If a significant object is present, it should not be removed, as it may be providing tamponade to injured vessels. The responder should instead attempt to stabilize the object and pack gauze around it before applying a stabilizing dressing [63].

The clinical integration of this assessment data leads to a functional classification of the hemorrhage that directly guides treatment. This is often conceptualized in a triage-oriented manner:

1. **Life-Threatening (Immediate) Hemorrhage:** This includes any arterial bleeding or high-volume venous bleeding from an extremity or junctional site that cannot be controlled by direct pressure after a brief attempt. This category demands immediate and definitive action, which for an extremity is the rapid application of a tourniquet, and for a junctional area is aggressive wound packing with hemostatic gauze [64].
2. **Significant (Delayed) Hemorrhage:** This involves bleeding that is controlled with direct pressure but is likely to recur if pressure is released. These wounds require the application of a secure pressure dressing and ongoing monitoring. They are not immediately life-threatening but have the potential to become so.
3. **Minor (Minimal) Hemorrhage:** This includes minor oozing or capillary bleeding that is easily controlled with simple dressings. These injuries require basic first aid but do not consume significant resources in a mass casualty scenario.

This functional classification must be continuously re-evaluated. A wound that was initially classified as "significant" and controlled with a pressure dressing may later become "life-threatening" if the dressing becomes saturated or the clot dislodges, a phenomenon known as re-bleeding. This underscores the importance of the ongoing "M" in the MARCH algorithm, which stands for Re-assessment for Major Hemorrhage [65]. The patient's physiological response is a key part of this re-assessment. The development of signs of shock—such as tachycardia, tachypnea, pale and cool skin, and altered mental status—in a patient with a previously "controlled" wound is a red flag indicating ongoing occult blood loss or re-bleeding, demanding immediate re-evaluation of all wounds and interventions.

The final component of a comprehensive wound assessment in the context of acute hemorrhage involves recognizing complicating factors that can alter management or predict a poor outcome. One of the most significant of these is the presence of a traumatic amputation or a near-amputation with only a small bridge of tissue remaining. These injuries are almost always associated with severe, life-threatening hemorrhage and are a clear and immediate indication for tourniquet application [66]. Another critical factor to assess is the mechanism of injury. A high-energy mechanism, such as a blast injury, a fall from height, or a high-speed motor vehicle collision, should raise a high index of suspicion for multisystem trauma, including non-compressible truncal hemorrhage and underlying tissue damage that may not be immediately apparent. In such cases, the visible external bleeding may only be the "tip of the iceberg."

The environment of the care also dictates the depth and nature of the assessment. In a secure medical facility, a more detailed secondary survey can be conducted. However, in a tactical or hazardous environment, the assessment is deliberately abbreviated to the most critical elements: find the source of major bleeding and control it in the fastest way possible. The TCCC guidelines emphasize this by making the initial assessment and control of massive hemorrhage the absolute first step, often performed with minimal exposure of the patient to avoid exposing the caregiver to threat [67]. This principle, known as "care under fire," prioritizes a rapid anatomical and visual classification to apply a tourniquet if indicated, with a more detailed assessment reserved for when the casualty is moved to a safer location.

7. Training, Protocols, and Clinical Governance for Bleeding Control

The development of effective hemorrhage control techniques, from tourniquets to hemostatic dressings, represents a monumental advancement in trauma care. However, these technological tools are inert without the knowledge and skill to deploy them correctly. The bridge between innovation and improved patient outcomes is built upon a robust foundation of standardized training, evidence-based protocols, and a rigorous system of clinical governance. It is not enough to simply place tourniquets in public spaces or ambulances; a coordinated, system-wide approach is required to ensure that both laypersons and healthcare providers are prepared to act decisively and effectively in the face of catastrophic bleeding. This involves creating and disseminating clear guidelines, implementing repetitive and realistic training, and establishing feedback loops to monitor performance and update practices based on real-world data. The ultimate goal is to create a "culture of readiness" where the response to life-threatening hemorrhage is swift, standardized, and successful, regardless of who the first responder is.

The cornerstone of modern bleeding control education for the public is the "Stop the Bleed" campaign. Born from the Hartford Consensus, a collaborative effort led by the American College of Surgeons and other medical and law enforcement organizations, this initiative recognized that bystanders are often the true first responders in mass casualty events and everyday accidents [68]. "Stop the Bleed" democratizes life-saving knowledge by teaching a simplified, yet highly effective, algorithm: 1) Ensure your own safety, 2) Call for emergency help, 3) Identify the source of bleeding, 4) Apply firm, direct pressure, and if that fails, 5) Pack the wound and/or 6) Apply a tourniquet. By providing hands-on training with tourniquets and hemostatic gauze, the program empowers civilians to take action in the critical minutes before professional help arrives, effectively turning them from potential victims into immediate responders. The widespread dissemination of this program in schools, workplaces, and community centers is a public health strategy that has proven to save lives [69].

For professional responders, including emergency medical services (EMS), law enforcement, and military medics, training must be more advanced and protocol-driven. The leading protocol in this domain is Tactical Combat Casualty Care (TCCC) and its civilian adaptation, Tactical Emergency Casualty Care (TECC). These guidelines provide a structured framework for managing trauma in high-threat and resource-limited environments. The most critical contribution of TCCC/TECC is the prioritization of massive hemorrhage control as the first step in patient care, even before airway and breathing—a paradigm shift from traditional ABCs to MARCH (Massive hemorrhage, Airway, Respiration, Circulation, Head injury/Hypothermia) [70]. These protocols provide clear, scenario-based directives on when and how to use tourniquets, wound packing, and other interventions. Training based on these protocols is not a one-time event but requires frequent, high-fidelity simulation that incorporates stress and environmental challenges to build muscle memory and clinical judgment under pressure [71].

The implementation of effective bleeding control extends beyond initial training to the development and enforcement of standardized operational protocols across entire emergency response systems. For an EMS agency or a hospital, this means having clear, written guidelines that outline the indications, techniques, and equipment for hemorrhage control. These protocols ensure consistency of care, reduce practice variation, and provide legal and clinical support for providers making high-stakes decisions in the field. A key component of such protocols is the authorization for all first responders, including law enforcement and firefighters, to carry and apply tourniquets. Studies have shown that when police officers are equipped with tourniquets and trained in their use, they can effectively control hemorrhage and improve survival rates, often arriving on scene before EMS [72]. This integrated, "all-responder" approach maximizes the chances of early intervention.

The establishment of a Clinical Governance framework is what transforms isolated protocols into a continuously improving system. Clinical governance is a systematic approach to maintaining and improving the quality of patient care within a health system. In the context of bleeding control, it involves several key processes. First, **data collection and audit**: Tracking the use of tourniquets and other hemorrhage control techniques in the pre-hospital and hospital setting is essential. This includes documenting application times, success rates, and any complications. Registries, such as the national trauma registries and specific pre-hospital quality improvement databases, are invaluable for this purpose [73]. Second, **quality improvement (QI) cycles**: The data collected must be analyzed and fed back to providers and organizations. If an audit reveals that tourniquets are frequently applied incorrectly (e.g., too loose), this triggers a targeted re-training initiative to correct the deficiency. This closed-loop process ensures that protocols are not just documents, but living guidelines that are refined by real-world experience.

Another critical pillar of clinical governance is **research and evidence-based guideline updates**. The science of hemorrhage control is not static. New devices, such as improved junctional tourniquets and hemostatic agents, are constantly being developed. Furthermore, analysis of trauma outcomes provides new insights. For example, data from the conflicts in Iraq and Afghanistan directly led to the updated TCCC guidelines that recommended the use of hemostatic gauze for junctional and non-tourniquetable wounds [74]. A robust governance system ensures that protocols are regularly reviewed and updated to incorporate this new evidence, preventing clinical practice from becoming outdated. This requires a committee structure, often at a regional or national level, with the authority to evaluate new data and officially revise treatment guidelines, ensuring that all providers within a system are practicing to the same, current standard.

Despite the clear benefits, the implementation of system-wide training and governance for bleeding control faces significant challenges. Ensuring funding and resources for large-scale public training programs like "Stop the Bleed" is an ongoing struggle. For professional organizations, the cost of high-fidelity simulation equipment and the man-hours required for frequent, mandatory training can be substantial [75]. Furthermore, maintaining skill retention is a universal challenge. The psychomotor skills of applying a tourniquet or packing a wound under stress can decay over time without practice. Therefore, moving from initial training to a model of continuous competency assessment is crucial. This may involve shorter, more frequent "just-in-time" training sessions, online modules coupled with practical skills stations, and regular drills that simulate mass casualty events to test the entire system's response.The future of bleeding control training and governance lies in technological integration and enhanced feedback mechanisms. The advent of "smart" tourniquets with sensors that record application time and pressure could provide invaluable data for audits and training debriefs, allowing for precise feedback on technique [76]. Virtual reality (VR) and augmented reality (AR) simulations offer the potential for highly realistic, repeatable, and scalable training scenarios without the cost of consumable materials. From a governance perspective, the development of national and international trauma databases will allow for larger-scale benchmarking and outcome analysis, enabling the identification of best practices and facilitating their rapid adoption across different regions and systems [77].

8. Conclusion

The battle against traumatic hemorrhage has been fundamentally transformed by a convergence of evidence-based practices, technological innovation, and a paradigm shift in pre-hospital care protocols. This research has detailed the critical journey from the rudimentary tourniquets of the past to the sophisticated, life-saving devices of today, highlighting their precise indications and the critical importance of correct application. It has reaffirmed that basic techniques of applied pressure and wound packing remain powerful, accessible tools in the initial response to bleeding. The integration of advanced mechanical and electrical technologies promises even greater capabilities for the future, particularly for anatomically complex injuries. However, the most critical finding of this synthesis is that technology and technique are inert without a robust human framework. The ultimate success of any hemorrhage control strategy hinges on widespread, repetitive training for both laypersons and professionals, guided by clear, evidence-based protocols and supported by a system of clinical governance that fosters continuous quality improvement. By uniting these elements—advanced tools, mastered skills, and a learning healthcare system—we can create a seamless chain of survival that empowers every first responder to act decisively and effectively, thereby achieving the primary goal of modern trauma care: to prevent death from preventable bleeding.

Author Statements:

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