Emergent Vascular Access

A Guide for Healthcare Professionals

James H. Paxton
Editor

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Preface

Emergency care providers are accustomed to figuring things out for themselves. Whether at "home" in the prehospital arena, emergency department, inpatient wards, or the intensive care unit, healthcare providers who work with critically-ill patients face austere circumstances and unexpected challenges every day. When time is limited, care must be provided even in the absence of information. This lack of real-time information underscores the importance of being prepared for a wide variety of circumstances. Providers learn from their own successes and failures in obtaining vascular access, as well as those of their colleagues and mentors. But an overreliance on anecdotal evidence and apprentice-style learning can leave gaps in one's training. Although most providers will pick up what they need to know as they advance in their careers, better formalized training in emergent vascular access techniques is needed. Emergency care providers should not have to figure it out for themselves.

Vascular access is an essential component in the treatment of unstable patients across a wide spectrum of disease, and techniques for establishing vascular access are included in most clinical medical textbooks. But medical textbooks are typically written for a broad audience, with a general scope of content intended to capture an entire medical specialty or discipline between its covers. Those of us who treat critically-ill patients under emergent conditions inherently understand that what we do every day is different than what is done for stable patients in a controlled environment. Yet, even within our own disciplines, the techniques and thought processes espoused in medical textbooks often fail to relate to the urgency and chaos that characterizes patient management in the acute care setting.

We need our own resources, our own educational materials, and our own research to inform the practice of establishing emergent vascular access. Traditionally, those who provide emergent vascular access have been obliged to scavenge practice tips from a confusing array of often-contradictory resources, including medical textbooks, blogs, and podcasts. It is time for us to centralize these resources into a coherent, targeted educational curriculum. This book is intended to begin this process of consolidating resources across the spectrum of nursing, critical care, and prehospital and emergency medicine texts into a single reference that may help to inform the practice of providing emergent vascular access. This book is not a primer, as it also includes many advanced concepts. But it is not a truly comprehensive reference, as no single resource can hope to inform the great diversity of practice seen in the modern healthcare environment. New evidence emerges almost daily in our field. Clinical practice defies our efforts to inform providers on every eventuality. However, we hope that this guide will serve as a starting-off point for those whose daily clinical duties involve establishing emergent vascular access for critically-ill patients. It is the first of what we hope will be many future references to educate and advance the field of emergent vascular access.

This textbook is intended to be of value to both the novice and advanced provider. It includes expert opinion as well as evidence-based guidance on vascular access device selection, including the potential advantages and disadvantages of various techniques. However, no book can replace our greatest educational tool: clinical experience. Guidelines and policies on vascular access are constantly being released and updated, and providers must know which practices represent standard of care in their own local healthcare environment. Providers should use their own clinical judgment in interpreting the guidance provided in this book. New evidence must be carefully weighed in the context of contemporary practice, and clinical decisions should continue to be made utilizing the best available evidence. However, great effort has been made to justify the suggestions made in this book using modern references from the medical literature. As conflicting evidence may exist, these recommendations should be considered in the clinical and historical context within which they are delivered. Despite these limitations, this reference will provide at least a rudimentary understanding of the basic principles underlying our chosen practice.

Chapter 1 offers a definition for "emergent vascular access," recognizing the importance of timing and acuity when considering vascular access selection. This discussion sets the stage for the rest of the book.

Chapter 2 introduces the reader to the physics and physiology of vascular access. Many of the factors that influence our decision-making regarding device and site selection relate to basic human physiology and anatomy. Thus, an understanding of the scientific principles underlying vascular access technologies is key.

Chapter 3 relates to landmark-based peripheral intravenous (i.e., "peripheral IV") line placement. This remains the "gold-standard" technique against which all other techniques are measured. Practical advice and tips to improve the likelihood of successful peripheral IV insertion are provided.

Chapter 4 builds upon the previous chapter with special attention to the use of ultrasound guidance in identifying target vessels and facilitating peripheral IV insertion. The use of ultrasound guidance for peripheral line placement has dramatically changed practice, but this approach requires specific training and an understanding of its limitations.

Chapter 5 describes the historical landmark-based approach to central venous catheter (i.e., "central line") insertion at various sites. Although most major guidelines now recommend the use of ultrasound guidance for central line placement, emergent conditions may still necessitate landmark-based methods in specific circumstances. Providers should be aware of these techniques and be confident in their performance for those rare circumstances in which an ultrasound-guided approach is not feasible.

Chapter 6 builds upon the previous chapter by describing how ultrasound-guidance can be used to facilitate and confirm central venous catheter placement. The use of ultrasound guidance for central line placement has led to substantial improvements in the safety and first-attempt success rates for certain central venous access techniques. However, these benefits are best realized when providers are familiar with the pitfalls and potential limitations of this approach.

Chapter 7 discusses intraosseous catheter placement, including the most commonly-seen devices encountered by emergency care providers. Intraosseous cannulation represents an under-utilized approach to indirect venous access, and is associated with certain advantages and disadvantages when compared to direct peripheral venous access techniques. Considerations relating to device and site selection are described, including limitations of this often life-saving technique.

Chapter 8 incorporates information from the previous chapters into a targeted discussion relating to pediatric vascular access. Children present providers with very different vascular access challenges than adults, including differences in anatomy, compliance, and complication risks. Providers should be aware of these differences and incorporate them into their decision-making process when managing critically-ill children, infants, and neonates.

Chapter 9 addresses emergent vascular access in cardiac arrest, including evidence from the medical literature and recent guidelines. In many ways, managing cardiac arrest is the ultimate challenge for vascular access providers. Delays in establishing vascular access for cardiac arrest victims are simply unacceptable, as the inability to rapidly infuse resuscitative medications may reduce a patient's likelihood of survival with good neurologic outcomes.

Chapter 10 provides a multi-faceted clinical context for "difficult vascular access" (DVA), a concept which has been inconsistently dealt with in the existing literature. This is an area of increasing research activity, as modern humans are living longer with a greater burden of chronic disease. Patients with DVA may test our competence and our patience, but learning how to care for them properly can make us better providers for all our patients.

Chapter 11 tackles decision-making in providing emergent vascular access, which is (and should be) a deeply-personalized subject. No single resource can fully elucidate this process, but a systematic approach may be helpful. Factors affecting decision-making are discussed, and examples of algorithms including appropriate references are provided.

Chapter 12 provides insight into the future of emergent vascular access, including techniques and technologies that are just beginning to influence our practice. Although traditional methods and devices will likely be around for a long while, new adjuncts and techniques are available and needed.

Chapter 13 addresses our patients' arterial access needs. Most of this book is committed to (direct or indirect) venous access, as it is far more common than arterial access in clinical practice. Although some of the underlying principles of cannulation are common to both arterial and venous access, many differences exist and deserve special attention.

Throughout this book, you will find illustrative examples and helpful references for those who wish to read more about a specific topic. Each of the authors has been carefully selected for his or her expertise in the area, including healthcare professionals from a wide variety of backgrounds. Each chapter provides a mix of basic and advanced concepts, with the aim of providing valuable content for providers of all experiential levels. We hope and expect that every reader will find something of value in each chapter, regardless of their previous training and experience.

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Contents

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Abbreviations

ABG	Arterial blood gas
AC	Antecubital
ACEP	American College of Emergency Physicians
ACLS	Advanced cardiac life support
ACS	American College of Surgeons
AHA	American Heart Association
AHRQ	Agency for Healthcare Research and Quality
AP	Anterior-posterior
AS	Accelerated Seldinger
ASIS	Anterior superior iliac spine
ATLS	Advanced trauma life support
AV	Arteriovenous
AVA	Association for Vascular Access
AVF	Arteriovenous fistula
AVG	Arteriovenous graft
AX	Axillary
BC	Brachiocephalic
BIG	Bone injection gun
BMI	Body mass index
CA	Cardiac arrest
CA	Carotid artery
CCA	Common carotid artery
CDC	Centers for Disease Control and Prevention
CFA	Common femoral artery
CHG	Chlorhexidine gluconate
CKD	Chronic kidney disease
CLABSI	Central line-associated bloodstream infection
cm	Centimeters
CoN	Catheter over needle
CPR	Cardiopulmonary resuscitation
CRBSI	Catheter-related bloodstream infection
CRT	Catheter-related thrombosis
CT	Computed tomography
CV	Central venous

CVAD	Central venous access device
CVC	Central venous catheter
CVR	Catheter-to-vein ratio
DBP	Diastolic blood pressure
DFA	Deep femoral artery
DH	Dorsal hand
DS	Direct Seldinger
DVA	Difficult vascular access
DVT	Deep vein thrombosis
ECG	Electrocardiogram
ED	Emergency department
EDTA	Ethylenediaminetetraacetic acid
EJ	External jugular
EMLA	Eutectic mixture of lidocaine and prilocaine
EMS	Emergency medical services
ENA	Emergency Nurses Association
ESD	Engineered stabilization device
ESRD	End-stage renal disease
FDA	Food and Drug Administration
FEM	Femoral
FIND	Fast intelligent needle delivery
Fr	French
gtt	Drops
HHS	Department of Health and Human Services
ICA	Internal carotid artery
ICU	Intensive care unit
IJ	Internal jugular
IM	Intramuscular
IN	Intranasal
INR	International normalized ratio
INS	Infusion Nurses Society
IO	Intraosseous
IV	Intravenous
IVC	Inferior vena cava
LED	Light-emitting diode
LPC	Long peripheral catheter
MAC	Multi-access catheter
MAGIC	Michigan Appropriateness Guide for Intravenous Catheters
MAP	Mean arterial pressure
mL	Milliliters
MLC	Midline catheter
mm	Millimeters
mOsm	Milliosmoles
mRSS	Modified Rodnan Skin Score
MS	Modified Seldinger

NIR	Near-infrared
OHCA	Out-of-hospital cardiac arrest
OR	Operating room
PA	Pulmonary artery
PaCO2	Partial pressure of carbon dioxide
PALS	Pediatric Advanced Life Support
PaO2	Partial pressure of oxygen
PEA	Pulseless electrical activity
PEBA	Polyether-block-amide
PFA	Profunda femoris artery
PHIO	Proximal humerus intraosseous
PICC	Peripherally inserted central catheter
PIV	Peripheral intravenous
PIVC	Peripheral intravenous catheter
PO	Per os (by mouth)
PR	Per rectum
PT	Prothrombin time
PTFE	Polytetrafluoroethylene
PTIO	Proximal tibial intraosseous
PTT	Partial thromboplastin time
PTX	Pneumothorax
PUD	Portable ultrasound device
PUR	Polyurethane
PVC	Polyvinyl chloride
pVT	Pulseless ventricular tachycardia
RA	Right atrium
RBC	Red blood cell
ROSC	Return of spontaneous circulation
RSI	Rapid sequence induction
SBP	Systolic blood pressure
SC	Subclavian
SCM	Sternocleidomastoid
ScvO2	Central venous oxygen saturation
SD	Standard deviation
SFA	Superficial femoral artery
SHEA	Society for Healthcare Epidemiology of America
SL	Sublingual
SQ	Subcutaneous
ST	Sternal
SVC	Superior vena cava
TALON	Tactically Advanced Lifesaving Intraosseous Needle
TdP	*Torsades de pointes*
TLC	Triple-lumen catheter
UAC	Umbilical artery catheterization
US	Ultrasound

USG	Ultrasound-guided
US-PIV	Ultrasound-guided peripheral intravenous
UVC	Umbilical vein catheterization
VAD	Vascular access device
VASD	Vascular access support device
VBG	Venous blood gas
VF	Ventricular fibrillation
VHP	Vessel health and preservation
VP	Ventriculoperitoneal
VT	Ventricular tachycardia

What Is Emergent Vascular Access?

1

James H. Paxton

Introduction

According to the US Centers for Disease Control (CDC), Americans logged approximately 136.9 million visits to the emergency department (ED) in 2015, with about 12.3 million (7.4%) visits resulting in a hospital admission [1]. According to these same figures, 31.3 million patients (23%) receive intravenous (IV) fluids, and 752,000 patients (0.6%) require central venous catheter (CVC) placement annually in the United States [1]. Although these figures do not address the acuity of line placement, they do reflect the reality that many patients require immediate vascular access in the ED to treat their presenting medical condition. But the ED is not the only place that "crash" lines are placed. Paramedics and Emergency Medical Technicians (EMTs) commonly establish venous access in the prehospital environment, often in more austere environments and under greater time constraints than other providers. Rapid response teams are often called to beds on the inpatient floors to help stabilize crashing patients, many of whom have inadequate vascular access and require immediate intervention. In fact, most physicians, nurses, and technicians who provide direct clinical care to patients will be called upon at some point to establish venous access under emergent conditions. Unfortunately, it is not always clear how decision-making can and should be different during emergent line placement, as compared to the low-acuity line placement techniques that are universally taught to health professionals. Scores of authoritative organizations have published extensive guidelines on how vascular access devices (VADs) should be placed, managed, and removed. But few of these guidelines address the thought processes that clinical care providers utilize when making decisions about VAD placement, or

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offer any useful insight into how providers should approach the emergent patient's vascular access needs differently than those of other patients.

In the real world, providers are expected to determine the acuity of a patient's condition, including the degree of a patient's need for vascular access, on their own. No single resource can hope to teach providers everything that they need to know about VAD placement, or account for every potential set of clinical conditions. A wide range of VADs, including *peripheral intravenous* (PIV) catheters, *intraosseous* (IO) catheters, and *central venous catheters* (CVCs), are readily available to providers in the ED and other acute care settings, but very little guidance is typically offered to clinicians in their selection of the appropriate VAD for a patient's presenting medical condition. Consequently, clinicians must often rely upon their own understanding of VADs when selecting the most appropriate approach for their patients. This can lead to great variability in clinical practice, thereby promoting great variability in VAD appropriateness.

Schools of medicine and nursing do spend time instructing physicians and nurses on the proper placement of VADs, including indications and techniques recommended for VAD placement in a generic acute care setting. However, very little time is spent in these curricula explaining the rationale and decision-making behind the decision to select a specific VAD for specific patient presentations. In many ways, *the provider's choice of VAD dictates the care that is subsequently available to a patient*. Infusions of various medications and fluids are often required in the care of emergent patients, but the provider's ability to effectively provide these interventions can be easily undermined by inadequate or otherwise inappropriate vascular access. This underscores the importance of making the right decisions about VAD selection and placement technique as early as possible in the care episode. Bad vascular access decisions can delay or even prevent the provision of necessary intravenous therapies. In order to make the *right* decisions, providers must understand how clinical conditions can and should influence their VAD choices.

Recognition of the need for "emergent" vascular access carries with it many implications for the provider, as well as the patient. The goals of care served by establishing vascular access will vary according to the patient's presenting condition and other factors. However, this book is designed to be of greatest use to the provider who requires immediate vascular access for their patient, to facilitate a wide range of anticipated interventions. The concepts in this book will be most relevant when vascular access is needed "emergently," in other words, to *provide some intervention for a patient that must be administered as soon as possible*. Whether this intervention is the administration of intravenous fluid, pain medication, vasopressors, antibiotics, or other medications, it is understood in this context that the intervention is expected to convey some time-dependent benefit to the patient that is less valuable (or perhaps futile) if it is delayed.

In general terms, an "emergency" may be defined as an unexpected but potentially dangerous situation requiring immediate action. Thus, an emergent condition should be both serious and requiring immediate intervention. In other words, emergent vascular access must be both: 1) *required to correct a serious problem; and 2) immediately necessary*. What constitutes a "serious" medical problem is subject to provider interpretation, as is the acuity of the need for intervention. Consequently, declaration of the need for "emergent vascular access" is predicated upon several inter-related factors:

- The provider's perception of the seriousness of the patient's presenting medical condition.
- The patient's actual medical condition, including the presence of hemodynamic instability or other evidence of risk to "life or limb".
- The availability and anticipated efficacy of immediate interventions to correct or treat the presenting condition.
- The risks of delayed intervention, including the risks of reduced efficacy and futility.

In other words, whether vascular access is considered "emergent" or not *depends upon a combination of patient-, provider-, and intervention-specific factors*. In this book, we assume that the patient's underlying medical condition is agreed to be serious (i.e., life- or limb-threatening), and that the intervention to be provided is considered to be time-critical.

Throughout this book, we will discuss factors contributing to a provider's decision on which VAD and insertion site is appropriate under various clinical conditions. We will also provide "tips and tricks" to improve the likelihood that the provider will successfully achieve the vascular access solution that they are attempting. The experienced clinician (whether MD, RN, paramedic, EMT, or other) will undoubtedly recognize many of the clinical vascular access scenarios presented in this book. It is our hope that both the casual and careful reader of this text will gain additional skills augmenting their ability to provide immediate and appropriate vascular access to patients experiencing an emergent medical condition.

The provision of emergent vascular access is a poorly-defined aspect of medical care, and those individuals charged with the task of providing it often go unrecognized in their efforts. Medical textbooks spend a great deal of time describing the interventions required to treat emergent medical conditions, without adequate attention paid to the vascular access methods by which these therapies are achieved. In this book, we hope to correct some of these oversights.

That said, reading this book will not transform the novice into an expert vascular access provider overnight. Skill acquisition in this area requires confidence, insight, and experience (including past successes and failures), which must be gained through clinical practice. The medical information provided in this book will supplement, but not replace, expert knowledge and training. As with all medical training, the information in this book should be viewed with a critical eye towards continuous improvement. Emergent vascular access is a constantly changing field, with new strategies and approaches constantly being developed. That said, much can learned from the insight that this book's authors have gleaned from years (sometimes decades) of experience providing emergent vascular access. We hope you enjoy it, and maybe learn a thing or two.

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2 The Physiology and Physics of Vascular Access

James H. Paxton and Megan A. MacKenzie

Introduction

Vascular access, for purposes of clinical care, refers to access to the anatomic system of veins and arteries that serve as conduits for the flow of blood through the human body. Of course, most healthcare providers are focused upon accessing the *venous* system for the infusion of fluids and medications for the emergent management of their patients. Consequently, most of the attention paid to this topic is related to venous access.

Vascular access is an essential first step in the care of many patients in the emergency department and inpatient wards. Although many other routes exist for the introduction of fluids and medications into the vascular system, including the oral, subdermal, subcutaneous, intramuscular, rectal, and endotracheal routes, the intravascular approach is often the fastest and most efficacious route available for the infusion of fluids and medications required for the emergent management of critically ill patients. Consequently, an understanding of the cardiovascular system and its routes of ingress is indispensable to the emergent vascular access provider.

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Anatomy of the Cardiovascular System

It is generally understood that the cardiovascular system consists of both arterial and venous channels, which can be accessed by clinicians for myriad purposes. Clinically, access to the arterial system allows providers the ability to monitor the arterial blood supply for measurements and blood samples that provide insight into the patient's arterial blood pressure, carbon dioxide tension, and oxygenation. While these measurements and samples may provide information pertaining to the patient's relative concentrations of oxygen and carbon dioxide and may also provide insight into the patient's arterial blood pressure, arterial cannulation is not generally of great use for the infusion of therapeutic interventions. Venous cannulation, on the other hand, is of great use to the clinician as a route by which fluids and medications can be introduced to the systemic circulation. With the routine use of central venous punctures, a thorough knowledge of anatomy is required by the physician to reduce complications.

Human medicine has developed over thousands of years, with common vascular access points predicated upon many generations of medical providers and their collective decisions relating to the best site for venous and arterial cannulation. In general, medical providers have come to select cannula insertion points that are superficial and easily accessible. In the last few decades, the use of prosthetic arteriovenous graft (AVG) and central venous catheters (CVCs) has allowed physicians to choose the most beneficial method of vascular access for their patients. Patients with a variety of conditions, such as those on hemodialysis, are now experiencing higher life expectancy and quality of life with these methods [1]. At the same time, all medical specialties including vascular surgeons, emergency medicine physicians, and members of the dialysis staff benefit from these options in providing care. A well-planned procedure, along with an acute awareness of both the surface anatomy and underlying vascular structures, can allow for precise procedures and minimal trauma.

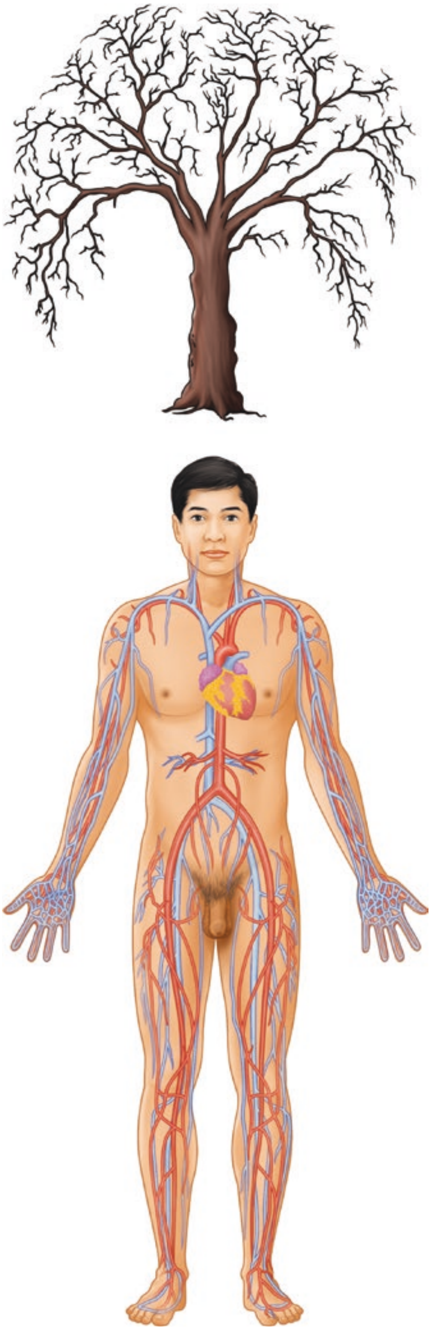
The Arterial System

By definition, the *arterial system* carries blood away from the heart. While this blood is usually oxygenated, the pulmonary arteries provide an exception to this rule by carrying deoxygenated blood from the heart to the lungs. However, for purposes of peripheral artery cannulation and blood sampling, it can be assumed that arterial blood should be more highly oxygenated than blood sampled from the venous system.

Vascular systems (including the arterial and venous systems) may be considered analogous to a "tree," with the largest vessels (e.g., aorta) forming the trunk of the tree and the branches becoming progressively smaller as one approaches the periphery of the tree. Figure 2.1 demonstrates this analogy.

The network of arteries forming the arterial "tree" originates from the large elastic arteries (e.g., the aorta and its major branches), which divide into medium muscular arteries, thence to small arteries, arterioles, and the capillary beds. In the

Fig. 2.1 The human vascular system



capillary beds, the blood passes through the peripheral tissues, off-loads a portion of its oxygen content, and is then picked up by the post-capillary venules. Once the blood has entered the venules, it may be taken up into the venous system, ultimately returning to the heart to begin the cycle again.

Elastin is a protein found in the extracellular matrix, which allows tissues to return to their original form after being stretched – so-called reversible elasticity [2]. Elastic fibers are formed only during early human development and childhood, and are gradually degraded in the aging process. The aorta and major central vessels have a substantial amount of elastin in their composition, which allows "smoothening of the discontinuous blood flow and pressure" generated by the heart's pumping function [3]. Smaller arteries, near the periphery of the arterial tree, have much less elastin than the central vessels. This allows them to vasodilate or vasoconstrict more easily and rapidly than the larger vessels, in response to changes in the systemic blood pressure. The variation in size of these arteries is important in pathology, as each class of vessel is predisposed to particular types of disease. Importantly, elastin is lost with the aging process, resulting in a host of cardiovascular maladies with advanced age, including hypertension, atherosclerosis, arterial calcification, and aortic dissection / aneurysm formation.

Because of the high pressures applied to the arterial system by the heart's pumping, arteries have thicker, more muscular walls than their venous counterparts. This makes the arterial system less prone to collapse than the venous system in the setting of hypovolemia [4]. Arteries and arterioles are also highly responsive to circulating catecholamines and other vasoactive substances, especially as mediated by the alpha-1 and beta-2 adrenergic receptors. The smallest members of the arterial tree are the capillaries, with walls composed of only a single layer of endothelial cells surrounded by the basal lamina. Nutrients, gases, water, and solutes are exchanged in the capillary beds. Selective perfusion of the capillary beds is determined by the degree of dilation or constriction of the arterioles, enabling the body to react quickly to a variety of clinical conditions [4].

Arterial cannulation is often performed emergently when arterial blood sampling is required, or to facilitate continuous blood pressure monitoring. Pressure waveforms from arterial lines can allow the clinician to detect sudden changes in blood pressure that may require a timely intervention. The radial and femoral arteries are the two arteries that are most frequently cannulated for such purposes. Other arteries, such as the brachial artery, tend to have a higher risk of complications due to the lack of collateral blood flow and the risk of distal extremity ischemia [4]. The carotid artery is another large and superficial artery, but it is not often used for arterial monitoring due to concerns about embolization events to the brain and the risk of hematoma formation with subsequent airway impingement [4].

The *radial artery* access site is located on the radial side of the distal forearm, with minimal overlying soft tissue. It can be traced along the lateral aspect of the forearm through the anatomic snuff box and is palpable at the distal radius. Luckily, less anatomic variation is found in the distal forearm, where cannulation is typically performed. This site is the most used for access both in adults and pediatrics and is quite useful for blood sampling and preoperative period information [5]. This artery is often easily accessible in the operating room and is not adjacent to clinically important nerves.

The *femoral artery* is found in the so-called femoral triangle and is easily palpable in even the most obese patients. It is sufficiently proximal to approximate central blood pressure, but remains quite distal to the heart. The femoral artery is generally larger than most other available arteries, and therefore it is often a viable target for arterial line placement even when other vessels (e.g., the radial or ulnar arteries) cannot be cannulated. When accessing the femoral artery, bleeding risk is increased in relation to the radial artery due to the greater diameter of the femoral vessel [5]. A femoral approach may also increase the risk of catheter-related infection in the perineum [6].

In emergent situations, critically ill patients require arterial lines to monitor blood pressure and obtain blood samples for blood gases. Once the catheter is inserted into the radial artery, a transducer system will continuously infuse a 0.9% sodium chloride solution under pressure. The arterial pressure is sensed by the transducer and then converts that signal into a waveform, reflecting the pressure generated by the left ventricle during systole. This bedside monitoring system allows for easier interpretation of a patient's vitals [6]. Even in the event of decreased or near-absent pulse, a reliable measurement of arterial blood pressure can still be measured.

The human arterial system is depicted in Fig. 2.2.

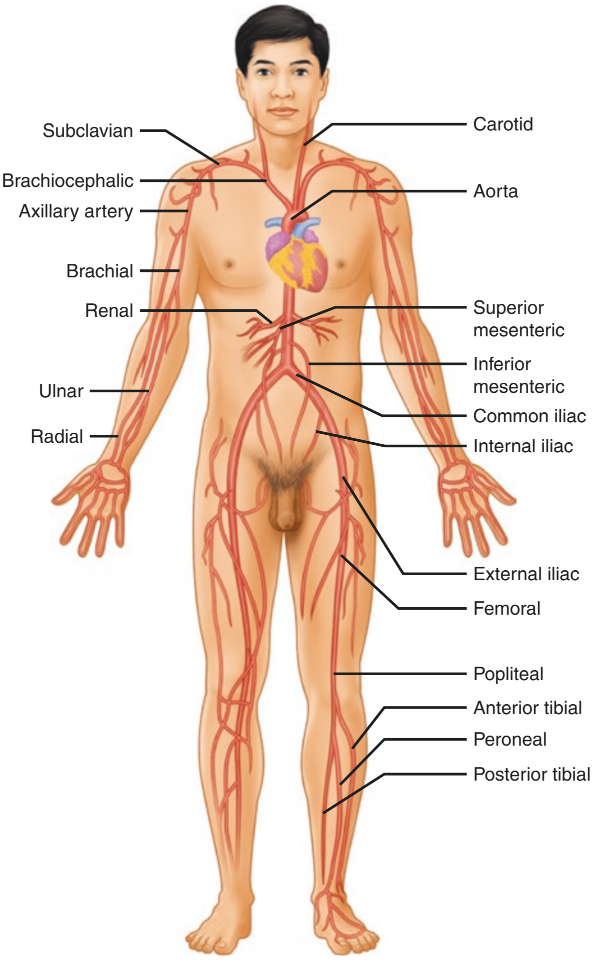
The Venous System

Central venous sites that are frequently selected for cannulation include the internal jugular vein, the subclavian vein, and the femoral vein. More peripheral sites include the external jugular vein; the brachial and cephalic veins of the forearm; and the distal veins of the wrist, hand, and fingers. In general, the peripheral veins of the lower extremities are not selected for venous cannulation, due to their greater distance from the central venous circulation.

The veins of the human body are generally thin-walled vessels with very little smooth muscle. This allows veins to collapse and expand easily to accomodate changes in intraluminal pressure. Rapid expansion or contraction of the vessels can occur in response to changes in fluid status; this ability to accomodate large volumes of fluid infusion rapidly can be advantageous when treating patients with profound hypovolemia. Additionally, veins contain the largest percentage of blood in the cardiovascular system, called the unstressed volume. The walls of the veins contain alpha-1 adrenergic receptors, which contract the veins and reduce their unstressed volume. However, the extreme collapsibility of the venous system also presents a challenge to clinicians. For example, patients can present with extreme intravascular depletion, causing their collapsed veins to become very poor targets for cannulation.

The peripheral venous system is generally divided by the superficial fascia into a superficial system, and a deep system. Blood from the superficial system drains to the deep system by way of the perforating veins. The venous system performs two main tasks: (1) returning blood to the heart; and, (2) storing blood that is not immediately needed. This second task is facilitated by the elasticity of the venous system. In general, veins are 30 times more compliant than arteries, although vascular

Fig. 2.2 The human arterial system



compliance can increase under certain conditions such as pregnancy and nitroglycerin administration [7]. Consequently, veins can accommodate changes in blood volume and can serve as a beneficial route of medication and fluid administration.

Despite this elastic property, venous obstruction can still occur, with partial or complete occlusion of the lumen. Such luminal occlusions are characteristic of deep vein thrombosis. Over 100 years ago, Virchow proposed that venous thrombosis could be caused by venous stasis, changes in vessel walls, or changes in blood components [8]. These venous thrombi are composed of fibrin and red blood cells. In preparation for a long-term venous access, it is important to support normal cardiac output and decrease the risk of venous thrombosis. Today, we know that high levels of some coagulation factors and defects in anticoagulants can also contribute to this risk. Due to the multitude of factors that can contribute to thrombosis, it is important to keep a patient's age, sex, and cardiovascular health in mind during cannulation.

A depiction of the human venous system is provided in Fig. 2.3.

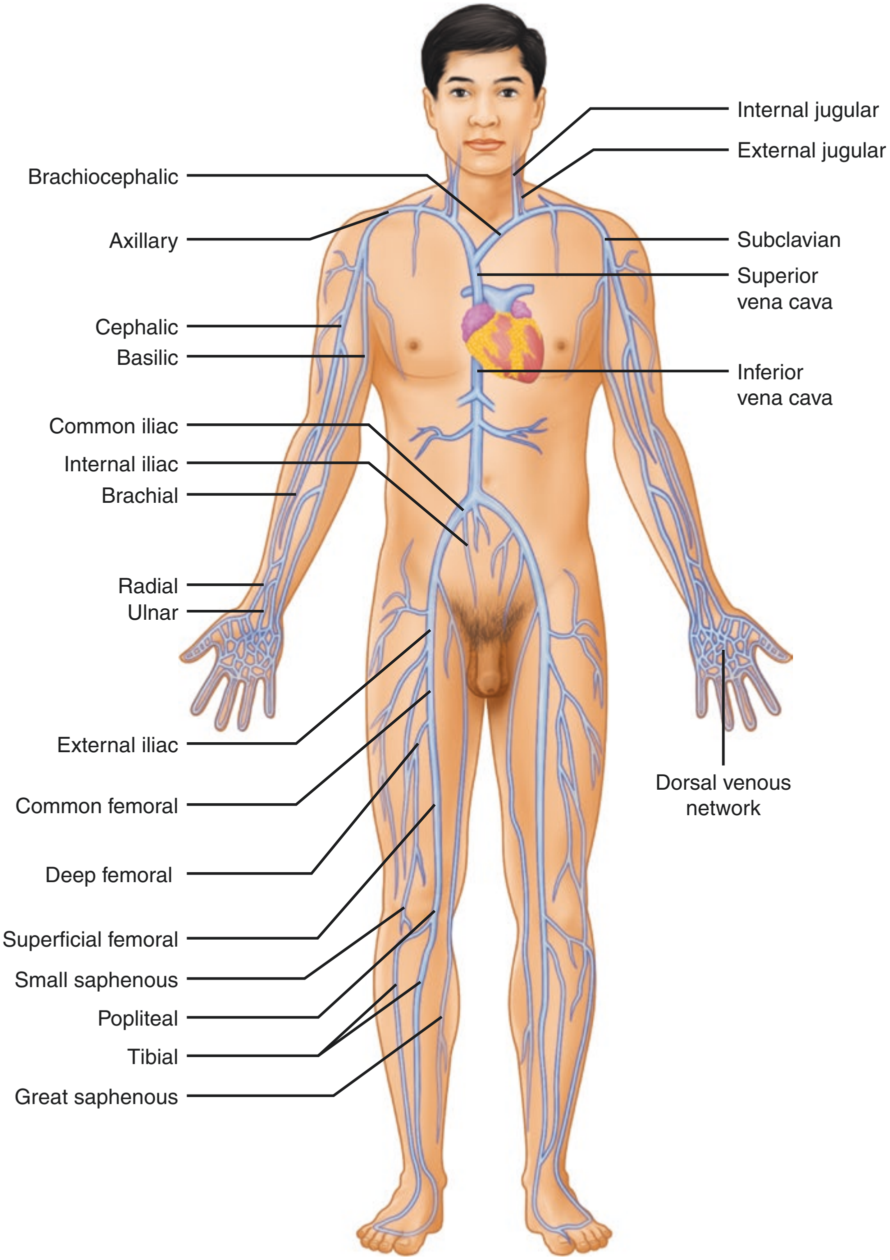


Fig. 2.3 The human venous system

Cardiovascular Physiology

The cardiovascular system is involved in numerous homeostatic functions that are governed by the laws of physics and restricted by human anatomy. This system is important in regulating arterial blood pressure, delivering hormones to target sites, and in adjusting to physiologic states such as disease, trauma, or exercise. The left and right heart have different functions: the left heart and its associated vessels are called the, **systemic circulation**, while the right side of the system is collectively called the ***pulmonary circulation***. The four chambers (two on each side) of the heart function like rooms in a house, and are separated by valves (like doors). Blood is pushed from one chamber to another before it is circulated around the body. Furthermore, the two sides of the heart are arranged in series, allowing for the cardiac output of the left ventricle to equal the cardiac output of the right ventricle. In its normal steady state, the cardiac output from the heart should equal the amount of blood returned to the heart.

One can think of the cardiovascular system as a complete circuit within the body. Oxygenated blood from the lungs flows through the *left atrium* into the *left ventricle* via the *mitral valve*. Blood is then ejected from the left ventricle into the *aorta* via the *aortic valve*. The volume of blood ejected from the left ventricle per unit time is called the *cardiac output*. The blood is distributed throughout the arterial system and to various organs. Unlike the heart in isolation, the organ systems are arranged in parallel, which allows for the distribution of cardiac output to vary among the organ systems. For example, muscles will require more energy during intense aerobic exercise in order to meet increased metabolic demand. At the end of the circuit, the blood is collected in the veins and is returned to the right side of the heart. Since the pressure in the *vena cava* is higher than in the *right atrium*, the atrium can fill with mixed venous blood. This is termed “venous return to the right atrium,” which equals cardiac output from the left ventricle. Eventually, this blood flows into the *right ventricle* through the *tricuspid valve* and is ejected into the *pulmonary artery* to become oxygenated once again. The cycle then repeats again.

The anatomy of the human cardiovascular system is depicted in Fig. 2.4. The circulatory system is depicted here with arrows representing blood circulation in the body. Blood takes many parallel paths from the left to the right heart. It can flow through arrangements in parallel and series paths, and even mix deoxygenated blood with oxygenated blood bound for the systemic arteries.

Other Physiological Considerations

Aging brings with it many physiological and morphological changes that can alter cardiovascular function. As life expectancy around the world increases, pathological conditions and age-related illnesses have become more prevalent. Vascular aging leads to an overall senescence of the vascular endothelium [9]. Functionally, the arteries become more calcified, and lose their elasticity, contributing to overall reduction in arterial compliance. Therefore, elderly patients require special considerations in the placement of VADs, especially in emergency situations.

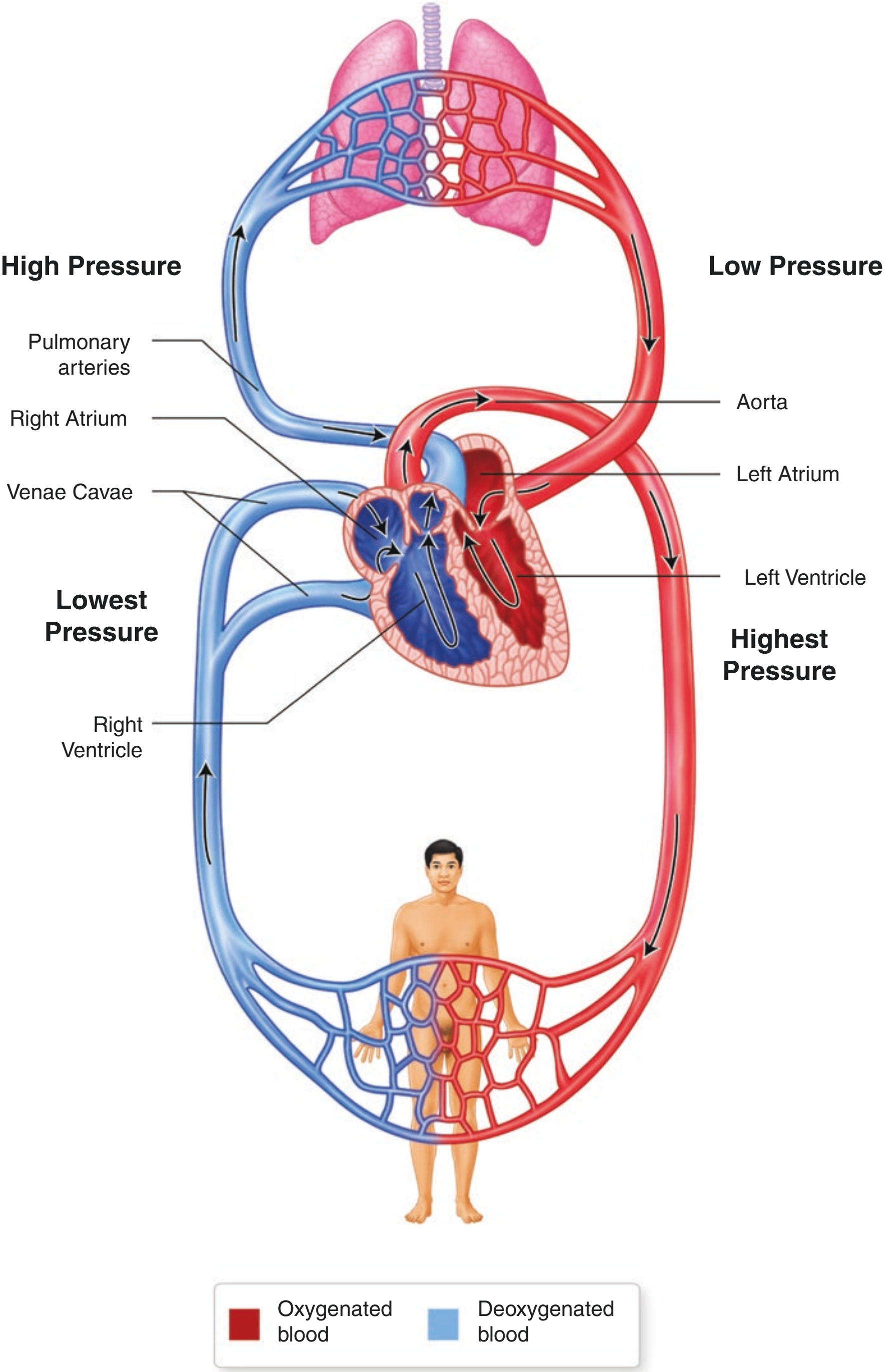


Fig. 2.4 The human cardiovascular system

Another point of consideration relates to vascular access during *pregnancy*. Pregnancy is a dynamic process full of adaptive changes to accommodate for fetal growth and development. In the systemic vasculature and kidneys, vasodilation occurs as early as 5 weeks' gestation [10]. A characteristic decrease in blood pressure typically occurs early in pregnancy, while total blood volume, plasma, and red blood cell mass increase significantly. Chronic venous insufficiency is common during the third trimester, and venous thromboembolism affects pregnant women nearly five times more than non-pregnant women [11]. Thus, for pregnant patients, clinicians should choose the smallest and least invasive device, with the fewest lumens possible, to minimize the risk of thrombotic events.

The *skeletal system* should also be considered in terms of the anatomy and physiology of vascular access. Long bones are richly vascular, with a dynamic circulation. These bones can accept large volumes of fluid and transport drugs to the central circulation. Within the bone cavity, medullary venous sinusoids drain into a central venous channel. These sinusoids accept fluids and drugs during IO infusion. The medullary cavity itself is rigid and capable of accepting these infusions even during times of profound shock or cardiopulmonary arrest [12].

The Physics of Flow

Understanding the laws of physics as they apply to the cardiovascular system allows for better vascular access placement techniques. Blood flow throughout the body is measured as the rate of blood displacement per unit time. As previously discussed, the blood vessels of the body vary in terms of diameter, cross-sectional area, and elasticity. As a simplified relationship, the velocity of flow can be considered by the equation $v = Q/A$. Here, v (velocity of blood flow in cm/s) is equal to Q (flow in mL/s) multiplied by A (cross-sectional area in cm^2). Nutrient exchange is optimized across the capillary wall in part because of the low velocity of blood flow within the capillary beds.

The success of intravenous cannulation depends heavily upon pressure gradients. The *Law of Laplace* has important consequences beyond basic physiology and is directly related to the pulmonary system and vascular access (Fig. 2.5). According to *Laplace's equation*, the tension (T) in a hollow cylinder (e.g., blood vessel) is directly proportional to the cylinder's radius (r) and the pressure (p) across the wall caused by the flow inside, according to the equation: $T = p \times r$ [13]. Though oversimplified, this equation illustrates how tiny, thin-walled capillaries can withstand surprisingly large pressures because of their tiny radii.

Vascular phenomena are further explained by *Poiseuille's Law*, which states that the flow (Q) of fluid through a cylinder is determined by the viscosity (η) of the fluid, the pressure gradient across the tubing (P), and the length (L) and radius (r) of the cylinder as: $Q = (\pi P r^4 / 8 \eta L)$ (Fig. 2.6). If one considers the vascular access device as a cylinder, it becomes quickly apparent that the rate of flow through a catheter is improved by increasing the pressure gradient (e.g., pressure bags), increasing the radius of the catheter (e.g., selecting a larger-bore catheter), decreasing viscosity of the infused fluid (e.g., saline versus blood), or decreasing catheter