Practical Transfusion Medicine

SIXTH EDITION

EDITED BY
MICHAEL F. MURPHY
DAVID J. ROBERTS
MARK H. YAZER
NANCY M. DUNBAR

WILEY Blackwell

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Preface to the Sixth Edition

The pace of change in transfusion medicine is relentless, with new scientific and technological developments and continuing efforts to improve transfusion practice. This sixth edition has been updated significantly to reflect the rapid changes in transfusion medicine since the fifth edition was published in 2017. The interval between the fifth and sixth editions has been extended by one year to allow colleagues to focus without distraction on the many challenges posed by the COVID-19 pandemic.

The primary purpose of this edition remains the same as the first, namely to provide a comprehensive guide to transfusion medicine. The book aims to include information in more depth than is contained within handbooks of transfusion medicine, and yet to present that information in a more concise and approachable manner than is seen in large, standard reference texts. The feedback we have received not only from formal and informal reviews but also from colleagues is that these objectives continue to be achieved, and that the book benefits from a consistent style and format for its chapters. We have again striven to maintain this standard in the sixth edition and to provide a text that will be useful to clinical and scientific staff, both established practitioners and trainees, who are involved in transfusion medicine and require an accessible text.

The book is divided into seven sections, which systematically take the reader through the principles of transfusion medicine, the complications of transfusion, practice in blood centres and hospitals, clinical transfusion practice, a new section on patient blood management, cellular and tissue therapy and organ transplantation and the development of the evidence base for transfusion. The main changes from the fifth edition are a new chapter on transfusion-associated circulatory overload by Alexander Vlaar to underline the condition's importance as a complication of transfusion, and a reconfiguration of the section on clinical transfusion practice to consider the transfusion management of medical, surgical and haematology patients with and without bleeding. The number of chapters has therefore been increased from 49 to 51. The first and final chapters on the recent evolution of transfusion medicine and scanning the future of transfusion medicine have always generated much interest in previous editions, and we are very grateful that Sunny Dzik, Ed Snyder, Paul Ness and Jay Menitove have provided excellent updates of their respective reviews for this edition.

We continue to develop the content and to refresh the style of the book, and are very pleased to welcome Nancy Dunbar as co-editor. The authorship has also become more international with each successive edition to provide a broad perspective. We are very grateful to the colleagues who have contributed to this book especially at this challenging time. Once again, we acknowledge the enormous support we have received from our publishers, and particularly Mandy Collison.

1 Introduction: Two Centuries of Progress in Transfusion Medicine

Walter H. (Sunny) Dzik[1] *and Michael F. Murphy*[2]

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'States of the body really requiring the infusion of blood into the veins are probably rare; yet we sometimes meet with cases in which the patient must die unless such operation can be performed.' So begins James Blundell's 'Observations on transfusion of blood', published in *The Lancet*, marking the origins of transfusion medicine as a clinical discipline [1]. Blundell (Figure 1.1) was a prominent London obstetrician who witnessed peripartum haemorrhage and whose interest in transfusion had begun as early as 1817 during his medical education in Edinburgh. He established that transfusions should not be conducted across species barriers and noted that resuscitation from haemorrhage could be achieved using a volume of transfusion that was smaller than the estimated blood loss. Despite life-saving results in some patients, clinical experience with transfusion was restricted by lack of understanding of ABO blood groups – a barrier that would not be resolved for another century.

The Nobel Prize–winning work of Karl Landsteiner (Figure 1.2) established the primacy of ABO blood group compatibility and set the stage for safer transfusion practice. Twentieth-century transfusion was advanced by the leadership of many physicians, scientists and technologists and repeatedly incorporated new diagnostics (monoclonal antibodies, genomics) and new therapeutics (plasma fractionation, apheresis and recombinant proteins) to improve patient care.

Today, the field of transfusion medicine is composed of a diverse range of disciplines including the provision of a safe blood supply; the fields of haemostasis, immunology, transplantation and cellular engineering; apheresis technology; treatment using recombinant and plasma-derived plasma proteins; and the daily use of blood components in clinical medicine (Figure 1.3). Without transfusion resources, very little of modern surgery and medicine could be accomplished.

For decades, the challenge of transmitting new information in transfusion fell to Dr Patrick Mollison (Figure 1.4), whose textbook became the standard of its era. Mollison highlighted the importance of both laboratory practice (immunohaematology, haemostasis, complement biology) and clinical medicine in our field. *Practical Transfusion Medicine*, here in its sixth edition, seeks to build on that tradition and to give readers the foundation knowledge required to contribute both academically and clinically to our discipline. For readers about to enjoy the content of this book, the following provides a sampling of the topics presented within the text by leading experts in our field.

Practical Transfusion Medicine, Sixth Edition. Edited by Michael F. Murphy, David J. Roberts, Mark H. Yazer and Nancy M. Dunbar.

Figure 1.1 James Blundell. *Source:* J. Cochran / The National Portrait Gallery, Volume II, published c.1820 (litho) / Public domain..

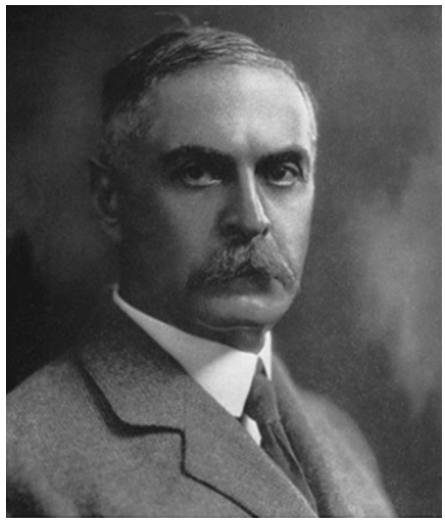

Figure 1.2 Karl Landsteiner. *Source:* VladiMens / Wikimedia Commons / Public domain..

Blood Donation Worldwide

Each year, approximately 100 million blood donations are made worldwide (Figure 1.5). A safe and adequate blood supply is now an essential infrastructure requirement of any modern national healthcare system. The

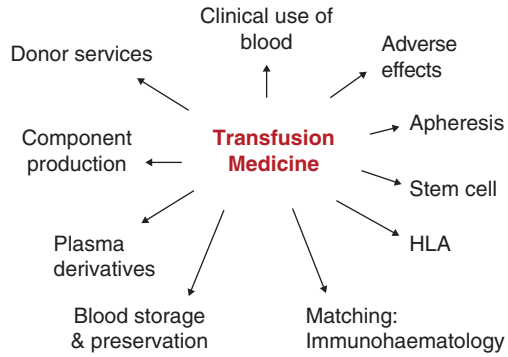

Figure 1.3 The range of transfusion medicine.

Figure 1.4 Patrick Mollison. *Source:* Garratty, Transfusion 2012;**52**:684–85. Reproduced with permission of John Wiley & Sons.

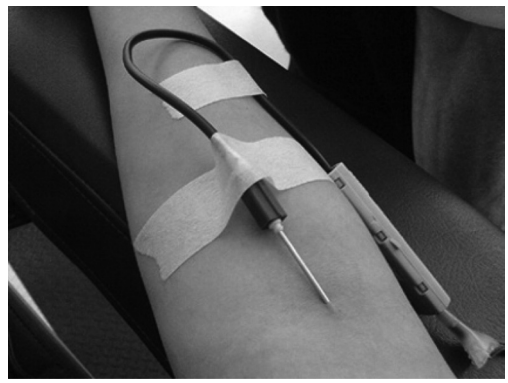

Figure 1.5 Blood donation.

recruitment and retention of healthy blood donors are vital activities of the field and the challenges and responsibilities faced by stewards of the blood supply were highlighted during the first year of the global COVID-19 pandemic, when routine blood collections were placed under great strain and when blood collecting agencies took on the added responsibility of collecting convalescent plasma to treat COVID-19 infection. While the economically advantaged nations of the world have established all-volunteer donor programmes with great success, data from the World Health Organization presented in Chapter 27 document that blood donation rates per capita in many low-income nations are insufficient to meet their needs. More research and investment are required so that all regions of the world can rely upon an adequate supply of safe blood.

Changing Landscape of Transfusion Risks

During the final two decades of the twentieth century, intense focus on screening blood donations for infectious diseases led to substantial progress in blood safety and a significant reduction in the risk of transfusion-transmitted diseases (Figure 1.6). Chapters 17–19 present an authoritative summary of this success. We currently enjoy a grace period when the risk of transfusion-transmitted infections is at an all-time low. One of the great successes of recent decades was the identification and screening of donors for hepatitis – a landmark effort that resulted in another Nobel Prize in our field, this time awarded to Harvey Alter (Figure 1.7) of the US National Institutes of Health (NIH) [2].

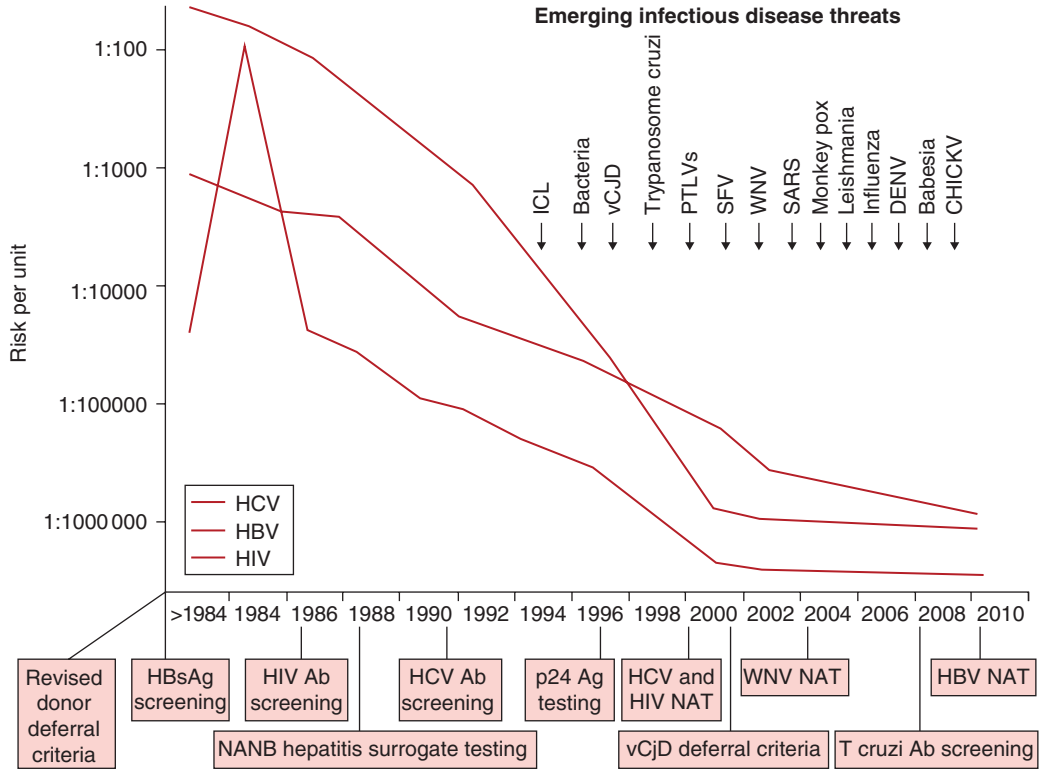

Figure 1.6 Risks of transfusion-transmitted infections over time. Ab, antibody; Ag, antigen; CHICKV, chikungunya virus; DENV, dengue virus; HBsAg, hepatitis B virus surface antigen; HBV, hepatitis B virus; HCV, hepatitis C virus; HIV, human immunodeficiency virus; ICL, idiopathic CD4-positive T-lymphocytopenia; NANB, non-A non-B hepatitis; NAT, nucleic acid testing; PTLVs, primate T-lymphotropic viruses; SARS, severe acute respiratory syndrome; SFV, Semliki Forest virus; T cruzi, *Trypanosoma cruzi*; vCJD, variant Creutzfeldt–Jakob disease; WNV, West Nile virus.

Despite this achievement, progressive encroachment of humans upon the animal kingdom is expected to result in the emergence of new infections that cross species barriers. Haemovigilance, robust screening technologies and chemical pathogen inactivation are all being applied to address this concern and are reviewed within the text. With the advent of the twenty-first century, the landscape of transfusion risk shifted its emphasis towards non-infectious hazards (Figure 1.8). Recent years have focused on improved understanding and prevention of transfusion-related acute lung injury, a topic covered in detail in Chapter 11. More recently, we have learned that circulatory overload from excessive transfusion is far more common than previously recognised, as described in Chapter 10. Yet Blundell himself specifically warned of it in his first description of transfusion: 'to observe with attention the

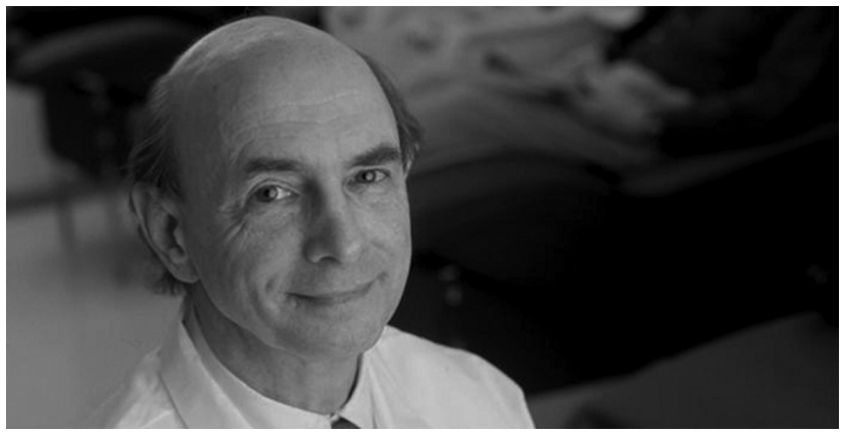

Figure 1.7 Harvey Alter. *Source:* Clinicalcenter.nih.gov

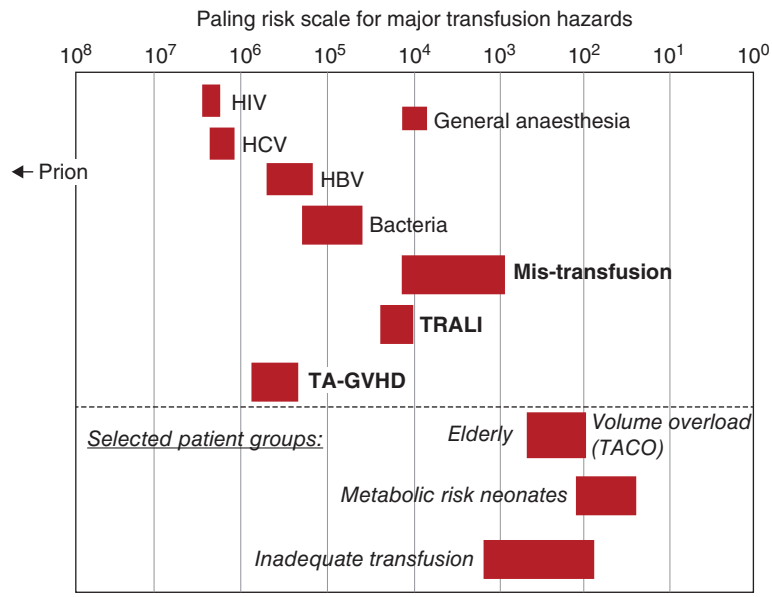

Figure 1.8 Paling scale of transfusion risk. HBV, hepatitis B virus; HCV, hepatitis C virus; HIV, human immunodeficiency virus; TACO, transfusion-associated circulatory overload; TA-GVHD, transfusion-associated graft-versus-host disease; TRALI, transfusion-related acute lung injury.

countenance of the patient, and to guard . . . against an overcharge of the heart' [1]. In addition, haemolytic reactions remain a serious hazard of transfusion. It is quite surprising that despite unimagined advances in internet connectivity, most nations still do not have a system for sharing patient blood group results or antibody profiles between hospitals, and are thereby failing to share information that would prevent acute and delayed reactions. Much can still be done to further reduce non-infectious hazards of transfusion. Readers will find that Chapters 7–19 provide state-of-the-art summaries of our current understanding regarding the full range of adverse effects and complications of transfusion.

Immunohaematology

Knowledge of the location and functional role of red cell surface proteins that display blood group epitopes has brought order out of what was once a chaotic assembly of information in blood group serology (Figure 1.9). Readers will enjoy an up-to-date treatment of this topic in Chapters 2–6.

Today, red cell genomics has become a practical clinical tool and DNA diagnostics in immunohaematology extends far beyond the reach of erythrocyte blood groups. Genotyping has always been the preferred method for defining members of the human platelet antigen system and is well established for HLA genes in the field of histocompatibility (Figure 1.10). The clinical practice of transfusion medicine is now supported by DNA diagnostics targeting a wide range of genes, including not only the increased use of DNA sequences that encode blood group antigens, but also those encoding complement proteins, haemoglobin polymorphisms and coagulation factors.

Despite advances in defining antigens, both clinical illness and blood group incompatibilities remain dominated by the patient's antibody responses. A robust form of antibody analysis and better control of the immune response remain important frontiers of our field. The ability to downregulate specific alloimmune responses would revolutionise the approach to solid organ transplantation, haemophilia complicated by inhibitors,

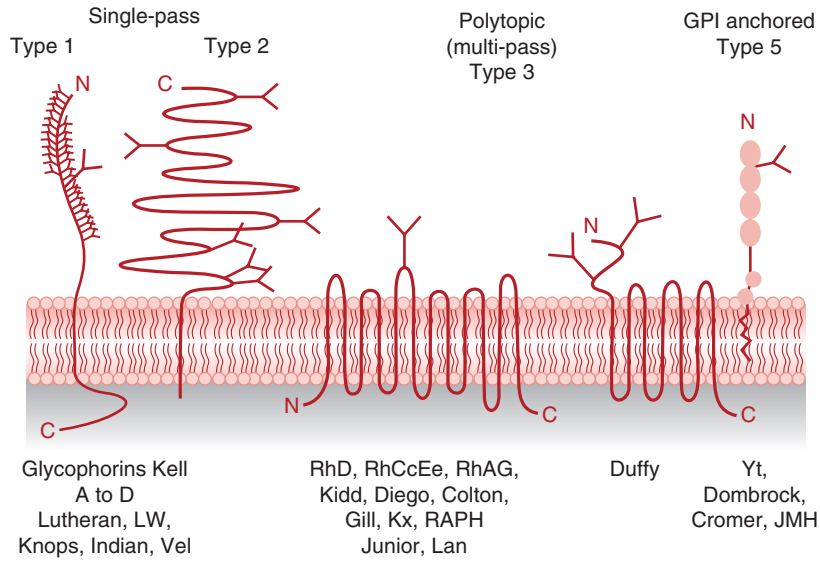

Figure 1.9 Red blood cell antigens. *Source:* Daniels G, Bromilow I. Essential Guide to Blood Groups, 3rd edn. Wiley: Chichester, 2014. Reproduced with permission of John Wiley & Sons.

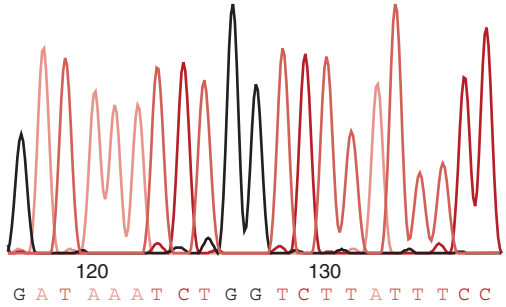

Figure 1.10 DNA sequence.

platelet refractoriness, red cell allosensitisation, haemolytic disease of the newborn and a host of other challenges that confront transfusion specialists every day.

In the meantime, we can offer patients powerful yet non-specific immune suppressants. And while the focus of many treatments is on reduction of pathological antibodies, it is increasingly clear that antibodies themselves do not injure tissues nearly as much as the complement proteins that antibodies attract. Complement is at the centre of a wide variety of disorders, including drug-mediated haemolysis or thrombocytopenia, severe alloimmune or autoimmune haemolysis, cryoglobulinaemic vasculitis, HLA antibody-mediated platelet refractoriness and organ rejection, paroxysmal nocturnal haemoglobinuria, atypical haemolytic-uremic syndrome, hereditary angioedema, glomerulonephritis and age-related macular degeneration. With the development in the future of better agents to suppress complement, it can be anticipated that the focus of treatment may shift from removal of pathological antibodies to control of their effect.

Clinical Use of Blood Components: Evolution Based on Evidence

Recent years have witnessed a growing body of evidence derived from clinical research and focused on the proper use of blood components. While such research has lagged for plasma products, progress has been made for both red cells and platelets. Ever since the landmark publication of the TRICC trial by Hebert and others [3], clinical investigators have repeatedly challenged the traditional 100 g/L haemoglobin threshold for red cell transfusion. There are now at least 13 well-designed, sufficiently powered randomised controlled trials documenting that a conservative haemoglobin threshold for red cell transfusion is as beneficial for patient outcomes as a more liberal threshold (Figure 1.11). These studies cut across a broad range of patient categories, from infants to the elderly. As a result, in hospitals worldwide, red cell use is more conservative and transfusions are now withheld in non-bleeding patients until the haemoglobin concentration falls to 70 g/L. Looking ahead, we anticipate that future clinical research will seek to further refine the indication for red cells by addressing the fact that the haemoglobin concentration is but one dimension of tissue oxygenation, and that the decision to transfuse red cells should include measures of both oxygen delivery and tissue oxygen consumption.

The last decade has also witnessed evidence-based refinements in the indication for platelet transfusion. The modern era of evidence begins with the work of Rebulla et al. [4], who documented that a platelet threshold of 10×10^9/L was equivalent to 20×10^9/L for prophylactic platelet transfusions. Further advances came with the TRAP trial [5], demonstrating that reducing the number of leucocytes (and not the number of donors) was key to preventing HLA alloimmunisation, and the PLADO trial [6], which demonstrated that the traditional dose of platelets (approximately equivalent to that found in 4–6 units of whole blood) resulted in the same outcome as transfusion of 3 units, or 12 units as judged by the proportion of days with grade 2 or higher bleeding. Finally, the TOPPS trial [7] revealed that there was little value to prophylactic platelets among clinically stable patients undergoing

Randomized Trials of RBC transfusion threshold

Author	Name	Setting	Trigger	'n'
Hebert, 1999	TRIC	Adult ICU	7 vs 9	838
Kirpalami, 2006	PINT	Infants < 1 kg	10 vs 12	457
Lacroix, 2007	---	Pediatric ICU	7 vs 9.5	637
Hajjar, 2010	TRAC	Cardiac surgery	8 vs 10	502
Cooper, 2011	CRIT	Acute MI (pilot)	8 vs 10	45
Carson, 2011	FOCUS	Hip surgery elderly	8 vs 10	2,016
Villaneuva, 2013	---	UGI bleed	7 vs 9	921
Walsh, 2013	RELIEVE	Older patients in ICU	7 vs 9	100
Robertson, 2014	---	Traumatic brain	7 vs 10	200
Holst, 2014	TRISS	Septic shock	7 vs 9	998
Murphy, 2015	----	Cardiac surgery	7.5 vs 9	2,007
Mazer, 2017	TRICS-III	Cardiac surgery	7.5 vs 9	5,243
Franz AR, 2020	ETTNO	Infants < lkg	10 vs 12	1013
Ducrocq G, 2021	REALITY	Acute MI	8 vs 10	668

Figure 1.11 Trials examining the red blood cell (RBC) transfusion threshold. ICU, intensive care unit; MI, myocardial infarction; UGI, upper gastrointestinal.

autologous bone marrow transplantation. The goal now is to conduct more research on platelet transfusion outside the context of haematological malignancy. While we still have much more to do if we are to refine the clinical use of the traditional blood components, Chapters 37–40 on patient blood management and 47–48 in the section on developing the evidence base for transfusion should give readers a solid foundation upon which to improve clinical decisions regarding transfusion.

Urgent Transfusion

Care of the haemorrhaging patient has always been an essential aspect of transfusion practice. The tragedies of war and human conflict have repeatedly stimulated research focused on urgent transfusion during haemorrhage. Demand for knowledge in this area sadly continues and is also driven by trauma occurring in civilian life, for example due to firearms and automobile injury. This is an area of changing practice patterns, including a re-examination of products such as whole blood and cold-stored platelet concentrates that were used decades ago (Figure 1.12). Readers will welcome the up-to-date focus found in Chapter 30. With the advent of increasingly complex surgery and deployment of life support systems such as extracorporeal membrane oxygenators, massive transfusion is no longer restricted to trauma. In fact, recent studies document that the majority of massive transfusion episodes are associated with surgical and medical conditions unrelated to trauma [8]. More research in these patient groups is needed.

Patients Requiring Chronic Transfusion Support

Chapters 32, 33 and 34 address the needs of patients with benign and malignant haematological disorders and those with haemoglobinopathies such as sickle cell anaemia, who often require chronic transfusion support (Figure 1.13). Patients with haemoglobinopathies, thalassaemia, myelodysplastic syndromes,

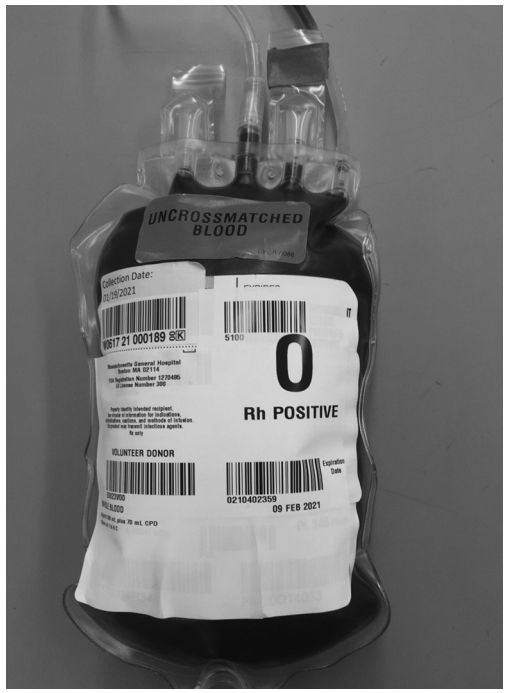

Figure 1.12 Unit of whole blood. *Source:* Sunny Dzik (Massachusetts General Hospital).

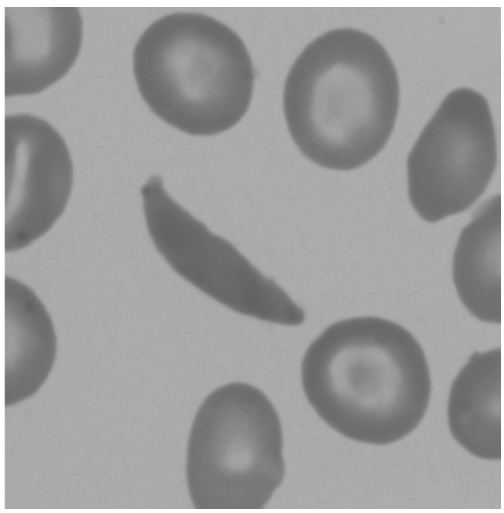

Figure 1.13 Sickle cell anaemia. *Source:* Gregory Kato / Wikimedia Commons.

aplastic anaemia, refractory anaemia, congenital and acquired haemolytic anaemia and those with chronic bleeding disorders such as hereditary haemorrhagic telangiectasia depend upon transfusion to sustain them. Worldwide, the numbers of individuals with severe uncorrectable anaemia are enormous. For these conditions, blood transfusion is seen at its raw, primal best: the sharing of blood from those in good health with those in need.

Obstetric, Neonatal and Paediatric Transfusion Medicine

Care of the low-birthweight, premature infant remains very challenging. Anaemia and thrombocytopenia result from physiology unique to these youngest of patients, as described in Chapter 35. Neonatal and paediatric transfusion medicine is filled with customary practices often based more on tradition than on evidence. We applaud those who have conducted the controlled trials that are summarised within the text, and look forward to additional clinical research designed to answer fundamental questions that confront the paediatric transfusion specialist.

Haemostasis and Transfusion

No area of transfusion medicine has seen such explosive recent innovation as the field of haemostasis. A wide range of anticoagulants is now available and the balance between anticoagulation, haemostasis and thrombophilia has become more complex. Transfusion therapy continues a long evolution from plasma replacement to the targeted use of a growing number of plasma-derived or recombinant products that influence haemostasis. Tools and treatments used in the past and then put aside, such as viscoelastic testing and antifibrinolytics, have made a strong resurgence and are finding new positions in the evaluation and treatment of bleeding. Additional haemostasis agents, which we will need to clinically master, are on the way. Chapters 28–30 address these

topics and will give readers new information on the important role of transfusion in the care of patients with disorders of haemostasis and thrombosis.

Cellular Therapies, Transplantation, Apheresis

Cellular therapy is a major growth area in transfusion medicine. The ability to mobilise haematopoietic progenitor cells, then harvest them safely in bulk numbers, process, freeze and successfully reinfuse them as a stem cell tissue transplant has completely revolutionised the field of bone marrow transplantation (Figure 1.14). Other therapeutic areas, such as treatment with harvested and manipulated dendritic cells, mesenchymal cells, T cells and antigen-presenting cells, have progressed far more slowly. Nevertheless, with advances in gene engineering, the potential to treat illnesses with autologous re-engineered cellular therapies is very bright. Chapters 41–46 present a detailed account of the current state of the art in cellular therapies as well as a glimpse of where this field is heading.

Figure 1.14 Cryopreservation in liquid nitrogen.

The Future

This sixth edition of this textbook concludes, as have previous editions, with reflections on the future of the field. While speculation on the future is never easy, our own view is that the ability to perform targeted gene editing is one of the most promising current research endeavours. CRISPR (clustered regularly interspaced short palindromic repeats) technology allows for the targeted excision of DNA at any known sequence (Figure 1.15).

Figure 1.15 CRISPR technology allows targeted excision of DNA. *Source:* Tobias Arhelger / Adobe Stock.

Short tandem repeat DNA sequences (eventually renamed CRISPR) were originally discovered as part of the normal bacterial defence against viruses. Several genes in bacteria, called CRISPR-associated genes (cas), were found to code for nucleases specific for these repeat sequences, thereby disrupting viral genomes within bacteria.

One of these cas genes, *Cas9*, was found to work efficiently within eukaryotic cells as a nuclease that could be guided by RNA to a specific DNA target. This RNA guide can be synthesised to match the cellular DNA area of choice. By delivering the *Cas9* nuclease and the guiding RNA into a cell, the genome of that cell can be disrupted or edited in a controlled manner. The development of this remarkable technology resulted in the award of the 2020 Nobel Prize in Chemistry to Emmanuelle Charpentier and Jennifer Doudna.

One example of the application of CRISPR technology has focused on haemoglobin F production [9]. The *BCL11A* gene is the natural suppressor of haemoglobin F. *BCL11A* is turned on after birth, resulting in active downregulation of haemoglobin F transcription. CRISPR technology has been used to disrupt the promoter region of the *BCL11A* gene, thus removing its suppression, with a resulting increase in haemoglobin F production. In 2021, this approach was successfully applied to patients with sickle cell disease and beta-thalassemia, resulting in a dramatic decrease in painful crises in sickle cell patients and a decrease in transfusion dependence among those with thalassemia. The stunning application of the technology resulted in a phenotype cure previously unimaginable among patients with these lethal haematological disorders.

Conclusion

James Blundell would immediately recognise a red cell transfusion if he saw one today. However, the great part of what we do would be incomprehensibly advanced and far beyond his understanding. In a similar way, the technologies of the future will revolutionise medical care in ways we can hardly imagine. Let us look forward to a time when we can reflect back on non-specific immune suppression, apheresis therapy, blood group incompatibilities and one-dimensional laboratory triggers for transfusion care as practices that we needed to understand today so that we could achieve the promise of tomorrow.

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2 Essential Immunology for Transfusion Medicine

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Cellular Basis of the Immune Response

Leucocytes from the myeloid and lymphoid lineage form the innate and adaptive arms of the immune system. Each cell type has its own unique functions.

Innate Immune Cells

Phagocytes and Antigen-Presenting Cells

The innate immune system comprises the skin (epithelial) and mucous membrane barrier, lysozymes such as in the eye, phagocytic cells and inflammatory-related proteins (complement, C-reactive protein and lectins). The innate immune system has evolved to be the first line of defence to pathogens, to eliminate pathogens directly via lysozymes, by phagocytosis or direct complement lysis, and to stimulate the adaptive immune system to respond [1].

Monocyte-derived macrophages, neutrophils (polymorphonuclear neutrophils, PMNs) and dendritic cells (DCs) function as phagocytes that remove dead cells and cell debris or immune complexes. In addition, these cells act as the first line of innate defence, ingesting and clearing pathogens. The first step as an infectious agent breaks the skin barrier through a wound or otherwise is the recognition of pathogen-derived signals via the expression of pathogen-associated molecular patterns (PAMPs) or danger-associated molecular pattern (DAMP) signals from inflamed tissues via pattern recognition receptors (PRRs) [2]. In humans, pathogen recognition receptors detect distinct evolutionarily conserved moieties on pathogens. Recognition by these receptors triggers cell differentiation and expression or secretion of signalling proteins. Some of these proteins, termed cytokines, such as interleukin (IL)-1, IL-6 and tumour necrosis factor (TNF), signal the body to increase acute-phase proteins that activate complement, while other chemokines attract circulating immune cells to the site of infection. The complement system can be activated by innate mechanisms via the expression of conserved pathogen carbohydrate motifs (PAMP recognition) or by the alternative pathway.

DCs and macrophages response to these cytokine signals and serve as antigen-presenting cells (APCs) that present digested linear protein peptide as antigen to specific T cells of the lymphoid lineage. PRR ligation of DCs and macrophages in this setting induces maturation of these cells into APCs with the acquisition of chemokine receptors that trigger their migration to lymph nodes where resting T cells reside. Simultaneously, mature APCs acquire co-stimulatory molecules and secrete other cytokines. These cellular changes are needed for T-cell activation and differentiation and eventually the immune

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response, including cytotoxic T cell and B cell antibody production in response to specific pathogens. The type of PRR ligation determines the cytokines produced, which in turn induces the optimal pathogen class-specific immune response.

Adaptive Immune Cells

T Lymphocytes

Specific cells of the immune system are involved in the adaptive immune response [3]. T cells are formed in the thymus. Through gene recombination, billions of different antigen receptor variations form. Each lymphocyte expresses a unique T-cell receptor (TCR). Immature T cells initially express a TCR in complex with CD4 or CD8 molecules, which respectively interact with major histocompatibility complex (MHC) class II or class I molecules on APCs. The presentation of self-antigens within such MHC molecules on thymic stromal cells determines the fate of the immature T cells. Interaction of T cells with APCs presenting self-antigens in the thymus results in the removal of T cells that have a TCR with high binding affinity for a self-antigen MHC. The T cells that survive this so-called negative selection process migrate to the secondary lymphoid organs, and are available to respond to foreign antigen peptides. There, TCR-specific binding to complexes of MHC can activate them with non-self (e.g. pathogen-derived) antigens on matured APCs. Interactions between the co-stimulatory molecules CD80 and CD86 on the APC with CD28 on the T cell subsequently drive the activated T cells into proliferation. Without co-stimulation (e.g. by not fully differentiated APCs or by insufficient or absent PRR ligation), T cells become non-functional (anergised). The requirement of PRR-induced danger signals thus forms a second checkpoint of T-cell activation to prevent reactivity to self-antigens. Hence, the normal removal of autologous apoptotic or dead cells and cell debris by phagocytes will not lead to alloimmunisation, since the PRR-induced signal is absent.

While immunoglobulins bind to amino acids in the context of the tertiary structure of the antigen, the TCR recognises linear amino acids of the antigen in the context of a foreign peptide bound to an MHC molecule. MHC characteristics ensure near-endless protein/peptide binding capacities and thus can continually respond to new and rapidly evolving pathogens. MHC class I is expressed on all nucleated cells and presents so-called endogenous antigen-constituting self-antigens, thus maintaining tolerance to self while also presenting antigens from viruses and other pathogens that use the replication machinery of eukaryotic cells for their propagation. The exceptions are viruses and parasites (like *Plasmodium falciparum*) that hide in red blood cells (RBCs), because the latter lack MHC. Fortunately, RBCs also lack the DNA replication machinery for such pathogens.

MHC class II molecules of APCs present antigenic proteins that are ingested or endocytosed from the extracellular milieu. The described antigen expression routes, however, are not absolute. Specialised DCs in this respect can also express pathogen-derived proteins that have been taken up by the DCs via the endocytic route and other extracellular-derived proteins on MHC class I to CD8+ cytotoxic T lymphocytes (CTLs). Conversely, cytosolic proteins can become localised in the endocytic system via the process of autophagy and become expressed in MHC class II.

Paradoxically, the fact that T cells become activated only when the specific TCR recognises non-self-antigens in the context of its own MHC (termed MHC restriction) seems to refute the condition whereby MHC/HLA-mismatched tissue transplants are rejected. However, upwards of 10% of T cells can be activated by donor-specific MHC; an additional alloantigen is not needed for this. This large circulating pool of T cells reacting with non-self MHC is usually present and explains the acute CD8-dependent rejection of non-self MHC in transplant rejection that occurs without previous immunisation.