The Pediatric and Adolescent Hip

Essentials and Evidence

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To Gavin De Kiewiet, an inspiring surgeon, mentor, and friend
And to all my other trainers who taught me to treat the whole child and not just the hip.

Sattar Alshryda

To my friend and teacher, Dr. Gerry Kiefer, who first introduced me to the beauty of pediatric hip surgery.
And to my wife, Rhonda, and children, Seamus and Cara, for your love and support during projects like this that steal away our precious time together.

Jason J. Howard

To my beautiful wife and children, in case you were wondering what I was doing.

James S. Huntley

To my father Perry for his inspiration to make the world a better place as a pediatric orthopedic surgeon, my mother Sally for inspiring me to communicate through art, and Susan, Tyler, and Abby for encouraging me to chase my dreams.

Jonathan G. Schoenecker

Foreword

Disease and deformity of the pediatric and adolescent hip are among the most frequent, challenging, and perplexing conditions faced by orthopedic surgeons treating this age group. Our understanding of the natural history of significant hip deformity has been slow in development because the time over which this evolves is protracted and may be longer than the career of an individual pediatric orthopedic surgeon, thus reducing the validity of experience as the basis for sound clinical decision-making. Similarly, the time from surgical intervention until an outcome can be accurately determined may extend almost two decades, making experience a matter of "too little, too late" in many instances. Evidence accumulated over more than one generation of surgeons in a particular institution is seldom recorded, with a few notable exceptions. Unless a surgeon is very subspecialized, experience with any hip problem, given the inherent variability, is most often very limited. Thus, there is a need for a reference source with a strong evidence-based focus, written by experts with both extensive clinical experience and a familiarization with what constitutes legitimate evidence.

A reasonable question for the editors is: Why a textbook, stationary in time, when new information is immediately available online from multiple websites and open-access journals, or from a collaborative wiki that updates information as it is received? This dilemma may be resolved by distinguishing between isolated "information" and comprehensive "knowledge." Potentially disruptive technology requires careful assessment, contextual reality, and profound understanding to ensure proper application. I believe this book does provide comprehensive and valid knowledge while at the same time utilizing sensible structure within an electronic platform. The consistent format for all chapters, combined with the authors' genuine expertise, accomplishes a valuable evidence-based approach to complex and often rare clinical conditions seen with pediatric and adolescent hip disease and deformity.

Each chapter distills topics having voluminous prior literature into manageable, readable, and informative content emphasizing key classic papers, essential evidence, and take-home messages. The editors have achieved an appropriate balance between more common conditions, such as developmental dysplasia of the hip (DDH), Legg-Calve-Perthes disease, and slipped capital femoral epiphysis, and more rare entities such as: the hip manifestations of Down Syndrome, bladder exstrophy, proximal femoral focal deficiency, and Larsen syndrome. The sections on poliomyelitis and tuberculosis are important inclusions for those working in developing countries.

I congratulate Drs. Alshryda, Howard, Huntley, and Schoenecker for producing what should be an essential reference source and practical guide for those managing pediatric and adolescent hip conditions.

John H. Wedge O.C., MD, FRCSC, FACS
Toronto, ON, Canada

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Dennis R. Wenger and James D. Bomar

Scientific Developments That Have Allowed Childhood Hip Surgery to Advance

Key nineteenth and twentieth century inventions revolutionized surgical care of musculoskeletal disease and led to the modern era which allows safe, generally predictable childhood hip surgery. Mercer Rang listed the following important scientific achievements that allowed modern surgery to evolve.

- Discovery of general anesthesia—1846
- Sterilization—discovery of bacterial origin of sepsis (Pasteur) and application to surgery (Lister—1860–1880s)
- Discovery of X-ray (Röntgen)—1895
- Discovery of stainless steel (for implants)—1920s
- Discovery of antibiotics—1930s

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Anesthesia

Surgery has been performed since the Stone Age including trephining of skulls, primitive draining of abscesses, as well as amputations. The stress and pain of having surgery remained almost intolerable until 1846, when William T.G. Morton (Fig. 1.1), a dentist at the Massachusetts General Hospital in Boston, demonstrated the first use of ether as a general anesthetic. Morton's method revolutionized surgical care and was quickly adopted by surgeons in the Boston area and then throughout North America. The understanding of the bacterial causation of surgical wound sepsis remained to be discovered.

Bacterial Basis for Surgical Infection

In the late 1850s, Louis Pasteur, a non-MD French scientist whose main interest was wine fermentation, developed an understanding of bacteria and studied them under the microscope. His research clarified the bacterial basis for infections (Fig. 1.2). While searching for an answer to surgical infection,

> ***…Joseph Lister, a Glasgow surgeon (Fig. 1.3) was told by a chemistry professor to read an obscure French paper by Pasteur, which had been written several years earlier…***

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Fig. 1.1 William T. G. Morten of Boston demonstrating the use of ether as a general anesthetic

Fig. 1.2 Louis Pasteur, a French chemist, proved that bacteria were the cause of infections (late 1850s—Paris)

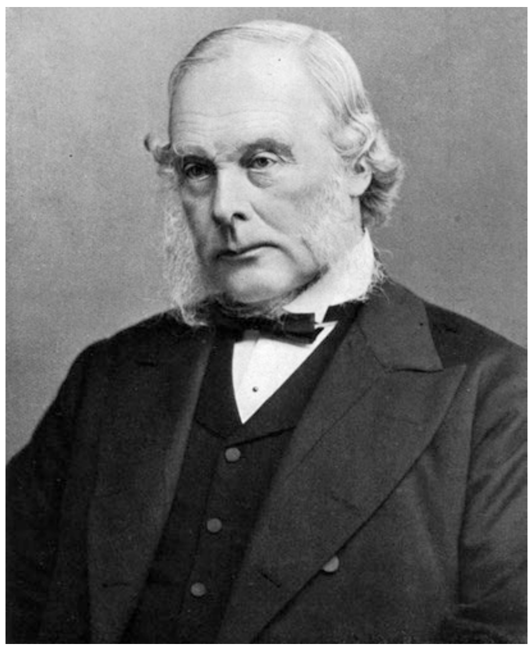


Fig. 1.3 Joseph Lister, a Glasgow surgeon, read Pasteur's paper and then visited Pasteur in Paris. He took the ideas back to Scotland and established a method to minimize operating room infections (carbolic acid soaked bandages and spray)

Lister visited Pasteur in the 1860s and took his ideas back to Glasgow where he applied them to the prevention of surgical infection.

Lister traveled to North America and startled a Philadelphia surgical audience in 1876, when he stated that "I can open a joint with absolute certainty that no infection will occur." Lister's concepts were critical in allowing safe childhood musculoskeletal surgery.

Unfortunate Timing: Discovery of Anesthesia vs. Discovery of Antiseptic Technologies

As Ponseti noted in his 1988 Presidential Guest Speaker Address at the Colorado Springs POSNA meeting,

> ***…the world would have been better off if understanding the bacterial cause of infections (about 1870) had occurred prior to the development of general anesthesia (about 1840)…***

so that methods for prevention of surgical wound sepsis would have been mastered before surgery was performed on a large scale.

For example, the American Civil War (1861–1865) occurred in a period after general anesthesia was available but before antisepsis principles were understood. The loss of life and limb in this war was greater than in any war before or since because surgeons could now operate on almost anyone (without pain)—but with no sterile gloves or sterile methods. Routine complete closure of contaminated gunshot/cannon wounds to limbs also greatly contributed to morbidity/death because many patients became septic and died.

Röntgen and Radiographs (X-Rays)

Wilhelm Conrad Röntgen (1845–1923—Fig. 1.4), a non-MD physicist in Würzburg, Germany (who lived with his wife above their scientific laboratory) developed the X-ray with the first known film performed on his wife's hand in 1895. Röntgen subsequently received the first Nobel Prize in physics for his discovery (well deserved, we might add).

Prior to Röntgen, many orthopaedic diseases were poorly understood, particularly childhood hip disorders. Differentiating between synovitis of the hip, sepsis, tuberculosis, Legg-Calvé-Perthes disease (only defined later), and slipped capital femo-

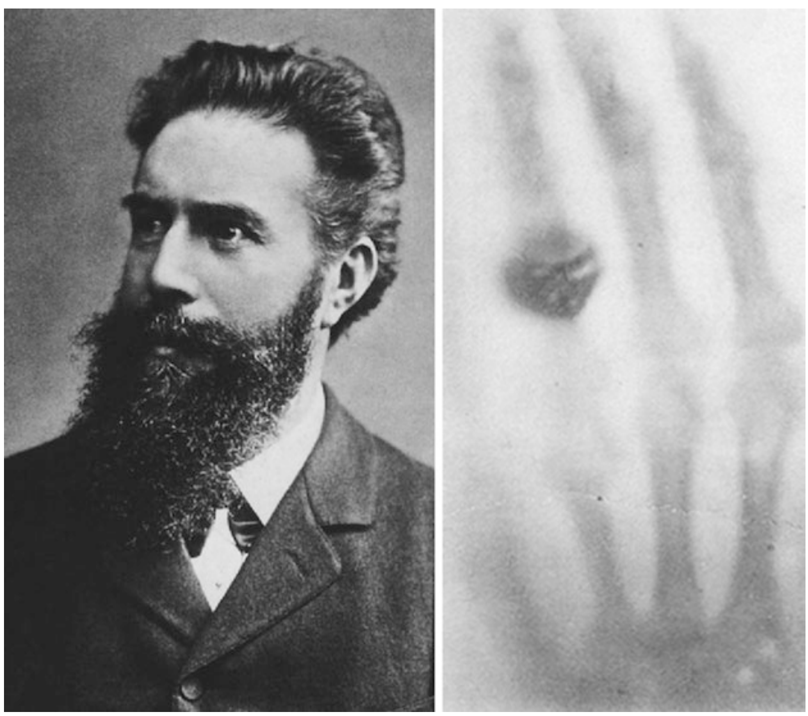


Fig. 1.4 Wilhelm Conrad Röntgen, a Würzburg physicist who lived above his laboratory, discovered the X-ray in 1895. The first image was of his wife's hand, including her wedding ring!

ral epiphysis (SCFE) was impossible. The X-ray changed everything. Röntgen first announced his discovery in December, 1895 and within 3 months, X-ray units were available throughout the leading teaching hospitals in Europe and London and soon thereafter, throughout the world.

> ***"Skeletal imaging radically improved the understanding of hip disease in childhood and provided a framework for the development of corrective operations."***

Stainless Steel Implants

Transition to the twentieth century brought with it many new ideas in culture, science, and surgery. Metallic implants had occasionally been used to fix fractures in the late nineteenth century, however the twentieth century brought more mechanically effective plates and screws. Bérenger-Féraud (France), who wrote on the topic in 1870, and Sir William Arbuthnot Lane (1856–1938—London), were among the first to use metal plates to treat fractures. William Sherman (1880–1979), popularized bone plating (Fig. 1.5) in the U.S.

Early bone plates suffered from poor quality and corrosion thus internal fixation remained problematic until the 1920s when stainless steel was invented and used to make non-corrosive implants. This revolutionized implant predictability, setting the foundation for the A-O methods (1960s—Fig. 1.6) and development of the proximal femoral blade plate, which greatly improved modern childhood hip surgery.

Antibiotics

The discovery of streptomycin, sulfa (Germany) and penicillin (Florey, Fleming—England) made childhood hip surgery safer. Also, streptomycin allowed medical treatment of tuberculosis, which had until this time been a major cause of destructive childhood hip disease.

In 1928, Alexander Fleming (1888–1955—Fig. 1.7), a Scottish bacteriologist working at St. Mary's Hospital, London identified penicillin, a bread mould which readily lysed staphylococci. Penicillin was hard to produce and the scientific community paid little attention.

Ten years later, a group of Oxford scientists led by Howard Florey (1898–1968—Fig. 1.8), an Australian working at Oxford, found Fleming's report, developed more efficient methods for penicillin production, and in 1940 successfully treated infected mice. Human application soon followed and both British and American laboratories began mass production so that penicillin was available in World War II. Fleming, Florey, and Ernst Boris Chain (a German biochemist on the Oxford team) received the Nobel Prize for their work in 1945.

Hospitals and Children's Orthopedic Hip Surgery

The transfer of orthopedic concepts and methods from Europe to North America in the nineteenth century laid a foundation for the development of children's orthopedic sub-specialization in the mid twentieth century. This paralleled the development of major urban children's hospitals in North America, as well as the Shrine Hospital system.

The large urban North American children's hospitals included orthopedic units that allowed a focus on children's care. Out of this milieu, a group of skilled orthopedic surgeons, dedicated to the care of children's problems, arose and provided the nidus for the establishment of the new sub-specialty of children's orthopaedics.

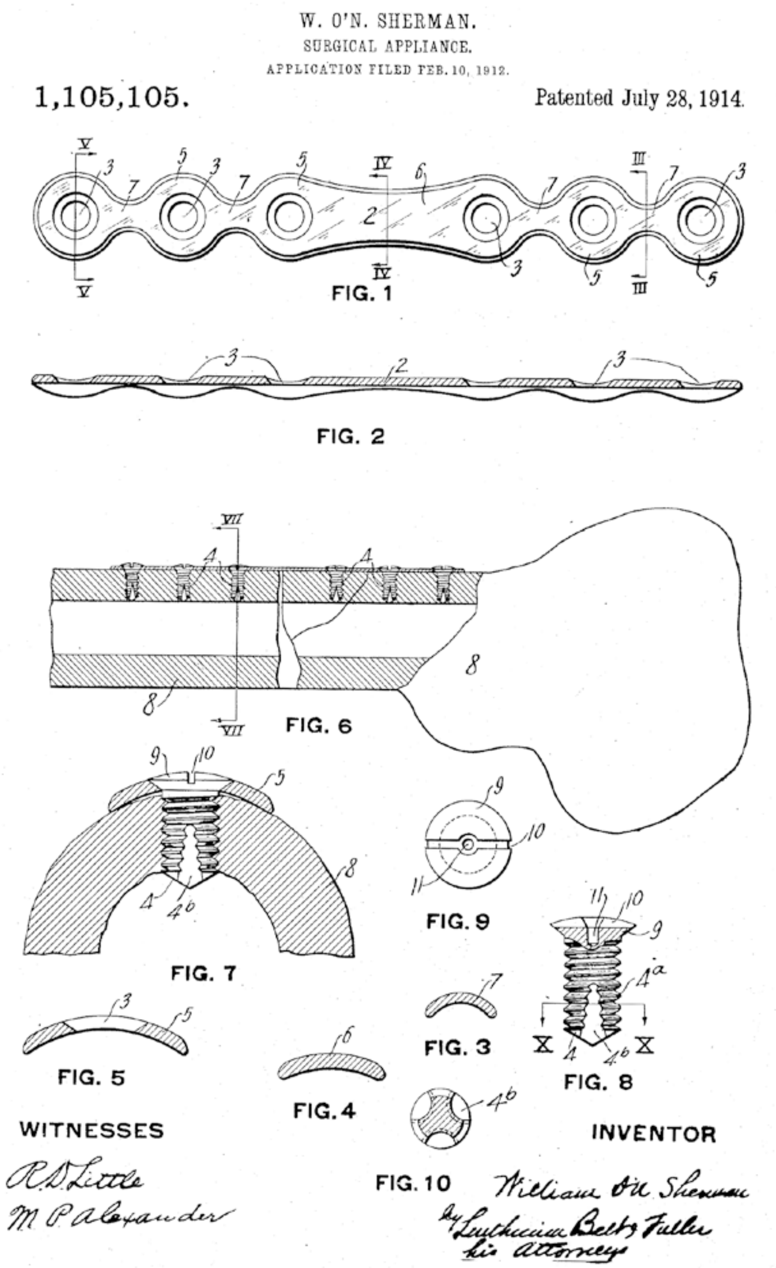


Fig. 1.5 Metal plates to stabilize fractures were first used in the late eighteenth and early nineteenth centuries. This drawing demonstrates William Sherman's surgical appliance application for his plate and self-tapping screw (1912—USA) (From: *The Story of Orthopedics*. Philadelphia: W.B. Saunders Company; 2000)

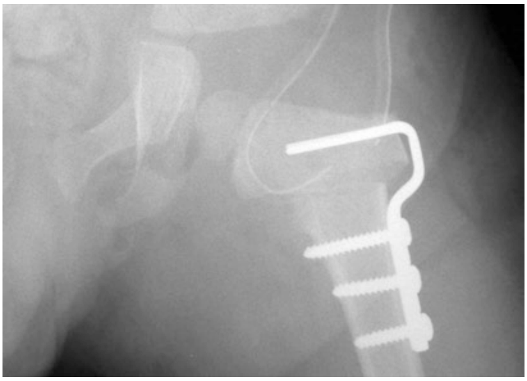


Fig. 1.6 The invention of stainless steel greatly improved bone plate efficacy The A-O blade plate (illustrated here) made childhood hip surgery more predictable (circa 1970)

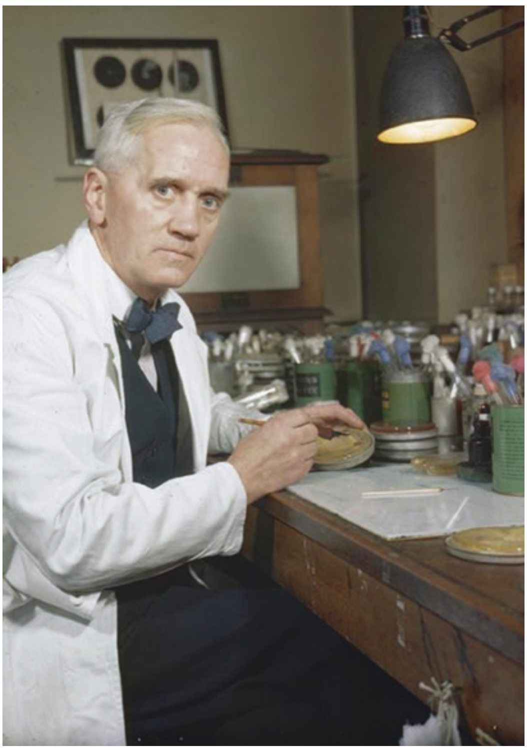


Fig. 1.7 Alexander Fleming (Scotland, London—1920s) identified a bread mould (penicillin), which lysed staphylococci. The scientific community paid little attention

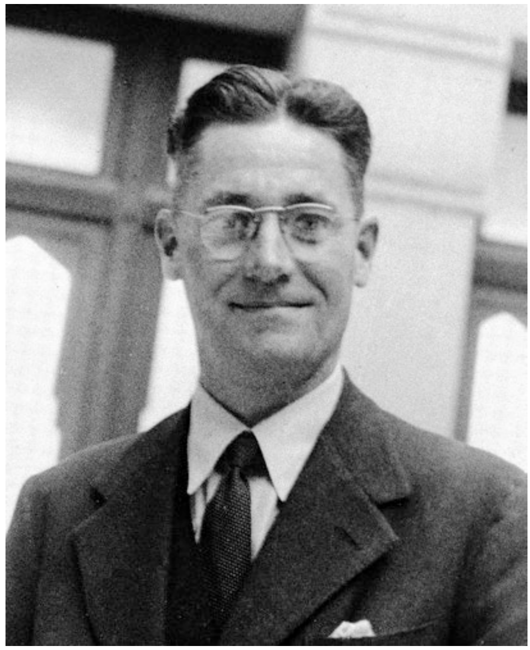


Fig. 1.8 Howard Florey (Oxford) led the scientific team that performed animal and human research proving the life-saving efficacy of penicillin. Their team was awarded the Nobel Prize for their efforts (1945). Licensed under the Creative Commons Attribution 4.0 International license—Author Brigadier Sidney Smith

The North American cities that developed powerful children's orthopaedic traditions include Toronto (Fig. 1.9) and Montreal (in Canada), Boston, New York City, Philadelphia, Wilmington, Atlanta, Chicago, Cincinnati, Memphis, New Orleans and others. Further west, Minneapolis, Iowa City, St. Louis, Dallas, Houston, Denver, Salt Lake City, Seattle, Portland, San Francisco, Los Angeles, and San Diego became important centers for children's orthopaedic surgery. Similar developments were also occurring in Europe and elsewhere.

These advances set the stage for the monumental advances in childhood hip surgery that have been made over the last 100 years. Our focus will be on the history of surgical advances in three common childhood hip conditions, namely developmental dysplasia of the hip (DDH), Perthes disease, and slipped capital femoral epiphysis. Our focus is on European and North America developments which we know the most about. Many parallel developments were occurring elsewhere in the world but we cannot cover everything in one chapter.

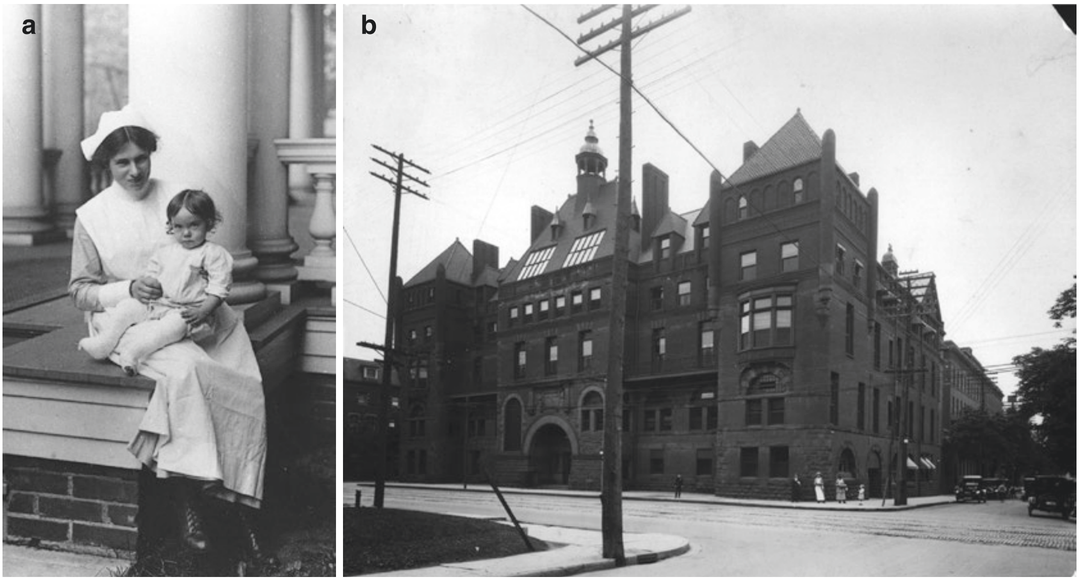


Fig. 1.9 (**a**, **b**) The Hospital for Sick Children—Toronto (late nineteenth century) was typical of the urban children's hospital movement in North America that helped to establish children's orthopaedics as a specialty. The nurse/child image shows an orthopaedic patient (note leg casts)

Congenital Dysplasia of the Hip 'First CDH–Now DDH'

We will frequently use the classic CDH description since only recently has the term been changed to DDH (developmental dysplasia of the hip), for technical/legal and other reasons. We will use CDH when quoting from historic documents and DDH for contemporary references.

> ***…Interestingly Adolf Lorenz, of Vienna, in a classic 1920 treatise, used the title "So-Called Congenital Dislocation of the Hip" to express his conviction that CDH is not truly congenital…***

but instead a "preliminary phase" that can lead to subsequent upward displacement of the femoral head. He didn't state what might alter the "preliminary phase" but clearly they could arise in the pre- or perinatal periods, or later.

Anatomy

The anatomy of hip dislocation was poorly understood until Giovanni Batista Palletta (1747–1832), who preceded Monteggia as the chief surgeon at the Ospedale Maggiore in Milan, gave the first anatomical description of a congenital dislocation of the hip discovered during the post-mortem exam of a 15-day-old boy.

> ***…Dupuytren in Paris (1777–1835) also gave an extensive report of the pathologic changes—after dissecting multiple specimens in older children—but stated that the condition could not be treated…***

Late diagnosed CDH in a child was extremely common in the past and is still occasionally seen in developed countries in the modern era (Fig. 1.10).

First Treatment: Pravaz, France

Charles Gabriel Pravaz (1791–1853), served in Napoleon's army at Waterloo and then studied medicine in Paris. Pravaz became associated with Jules Guerin (see below) in his Paris institute, and then founded his own institute in his hometown of Lyon.

Pravaz described a traction treatment method for CDH that allowed reduction in 19 patients (Fig. 1.11). Pravaz was the first to describe a successful reposition of CDH with a technique that combined continuous traction with increasing

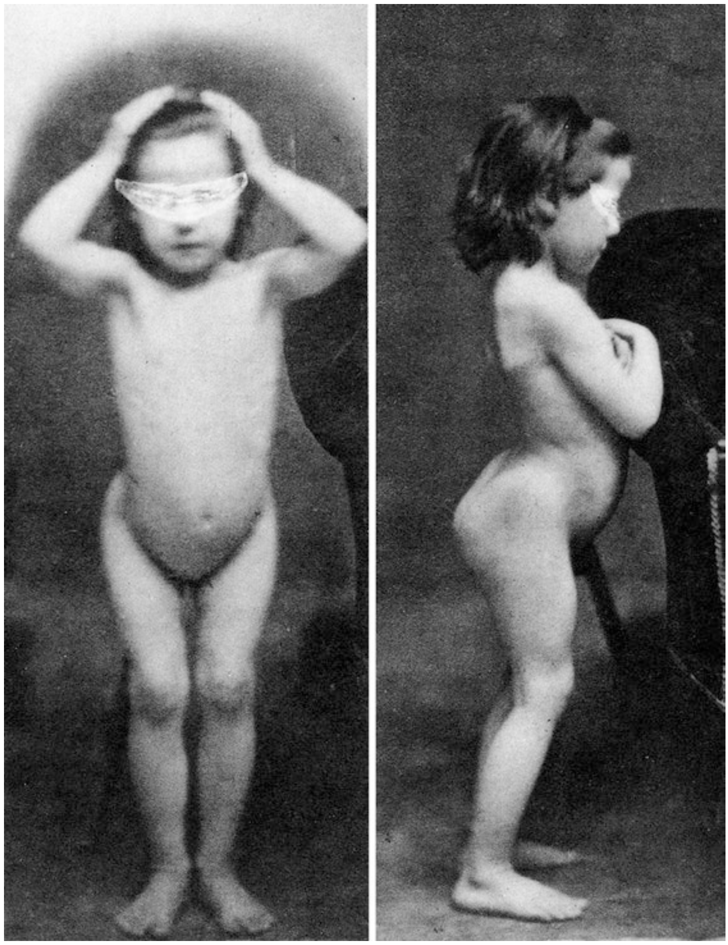


Fig. 1.10 Classic photograph depicting a 4-year-old child with bilateral CDH (Boston—1885). Note the typical increase in lumbar lordosis. (From Brown, *Double Congenital Displacement of the Hip: Description of a Case with Treatment Resulting in a Cure*. Boston Med Surg J 62(1885):541–46)

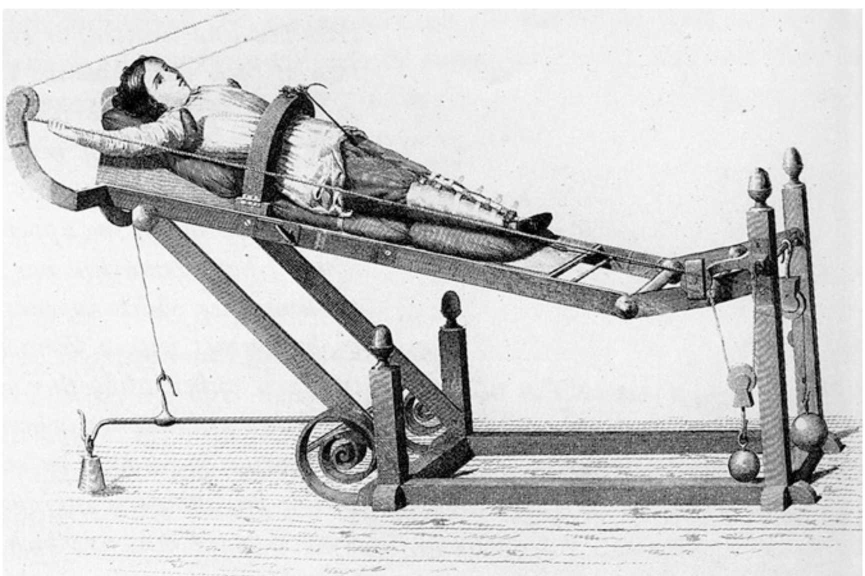


Fig. 1.11 Traction device for reduction of a dislocated hip designed by Charles Pravaz (Paris, Lyon) in the mid-nineteenth century. (From: *Orthopedics: A History and Iconography*. San Francisco: Norman Publishing; 1993)

abduction and pressure over the greater trochanter. These methods are almost identical to the gradual treatment methods used for CDH reduction at the Institute Calot in Berk, France, throughout much of the twentieth century (Georges Morel).

Surgical Methods

After learning of Pravaz's CDH reduction methods, Guerin in Paris immediately modified the method (as is characteristic of the competitive spirit of surgeons) by utilizing preliminary traction and a subcutaneous tenotomy (surgery) along with manipulative reduction. He also used his tenotomy knife to cut the superior capsule over the lateral wall of the ilium, creating adhesions in this area that he thought would encourage hip stability (rather like Hippocrates' "red-hot poker" inserted to prevent recurrent shoulder dislocation).

Agostino Paci (1845–1902), a surgeon from Pisa, was the first to advise a formal, acute method for manipulative reduction of CDH. Prior to that, all treatment had been by gradual traction methods such as that described by Pravaz and Guerin. Paci's method was later claimed by Lorenz in Austria, leading to some competition between the two.

Open Reduction for CDH

Alfonso Poggi (1848–1930) of Bologna described the first successful open reduction for CDH in a 12-year-old girl. Albert Hoffa (1859–1907) of Würzburg, Germany (later Berlin), then developed and standardized an anterior open reduction for CDH that was soon used throughout Europe.

The developments allowing safer surgery led to increasing conflict regarding whether or not a child with a dislocated hip should have a surgical open reduction versus a closed reduction. Adolf Lorenz [1] (1854–1946), the famous Austrian surgeon (Fig. 1.12), was a leader in the conflict related to these issues. He initially favored open reduction, but then developed an allergy to carbolic acid (the new mandatory intraoperative "system" to prevent infection). As a result, Lorenz could no longer operate! He then changed his indications and decided that all children with a dislocated hip could be treated by closed reduction even up to age 7 or 8 years of age and became an international celebrity, traveling throughout the world demonstrating his technique.

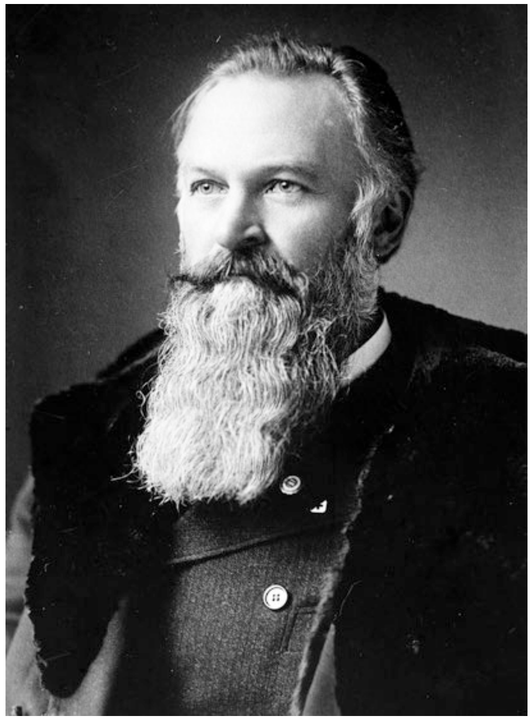


Fig. 1.12 Adolf Lorenz, the famous Austrian surgeon, first used open methods to reduce DDH but then reverted to closed methods due to his allergy to carbolic acid antisepsis. He traveled the world extolling his hip reduction technique

Other European surgeons found that the uniformly positive results reported by the famous Lorenz were not reproducible when they attempted his aggressive manipulative reduction methods and casting. Many children had capsular injury, nerve injury, fractured femurs, etc. Also Lorenz seemed blissfully unaware of the high incidence of avascular necrosis (AVN) that followed his methods (Fig. 1.13).

Lorenz had a great influence on North American surgeons including training Arthur Steindler, who later became Chairman of Orthopedic Surgery at the University of Iowa in 1913. Steindler served as a mentor to I.V. Ponseti whose intellect and influence have helped define

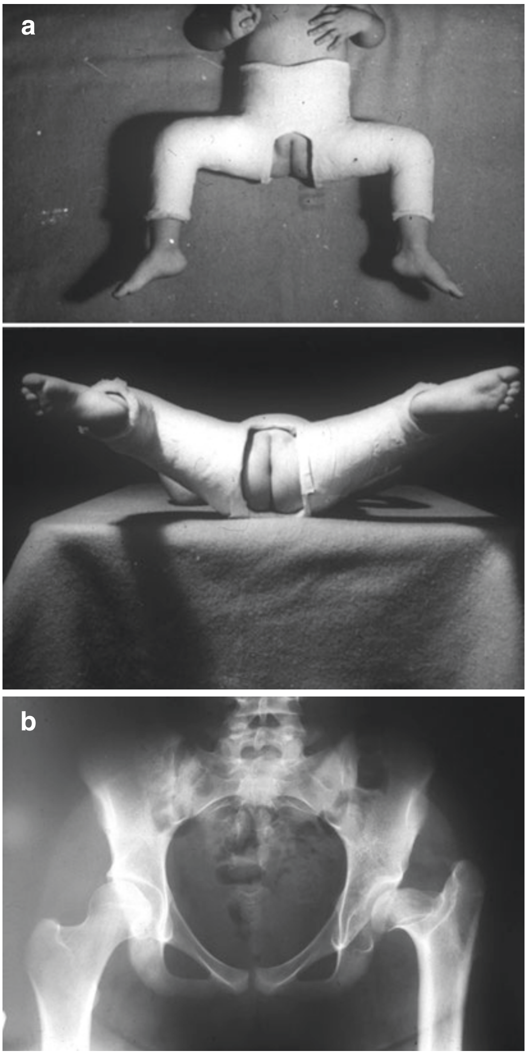


Fig. 1.13 (**a**) The somewhat extreme abduction hip spica position utilized in a Lorenz-style hip reduction. (**b**) Resulting AVN of the left hip noted at late follow-up of a CDH patient treated by the Lorenz method

CDH treatment in North America (subsequent trainees include Stuart Weinstein, Dennis Wenger, and many others) (Fig. 1.14).

Boston Contributions

Buckminster Brown (1819–1891) of Boston spent a period of time in Paris working with Guerin and took his CDH treatment methods back to Boston. These concepts have evolved in Boston through Bradford, Sever, Green, Tachdjian, and other subsequent surgeons of the "Boston School".

Henry Jacob Bigelow of Boston (1818–1890) made an important contribution to CDH treatment by studying the hip capsule (the anterior Y ligament now bears his name) and then publishing a book entitled "*The Mechanism of Dislocation and Fracture of the Hip: with the Reduction of the Dislocations by the Flexion Method*". Bigelow's reduction concepts were used by Lorenz as well as subsequent surgeons who performed manipulative closed reduction for DDH.

Medial vs. Anterior Approach for Hip Reduction

> ***"In the early twentieth century, Ludloff in Germany described a medial approach for open reduction of the hip that was relatively blood-free and very effective for young children (up to age 2 years)."***

A capsulorrhaphy was not performed and thus excellent casting techniques were required to maintain reduction. Other surgeons, including Hey-Groves of Bristol, U.K., preferred a typical anterior open reduction which allowed some capsular repair. Bony surgery was not typically performed with open reduction in younger children; however, several experts developed wedge osteotomies performed above the acetabulum to improve the stability of the hip that had been surgically reduced.

Osteotomies to Stabilize Reduction

As the twentieth century evolved, change occurred in DDH management, with younger children treated by closed reductions and older children treated with open reduction; often not effective, with many children having residual subluxation or re-dislocation. The need for simultaneous bony osteotomies became apparent.

Two somewhat different concepts for reduction evolved in the U.K. versus North America.

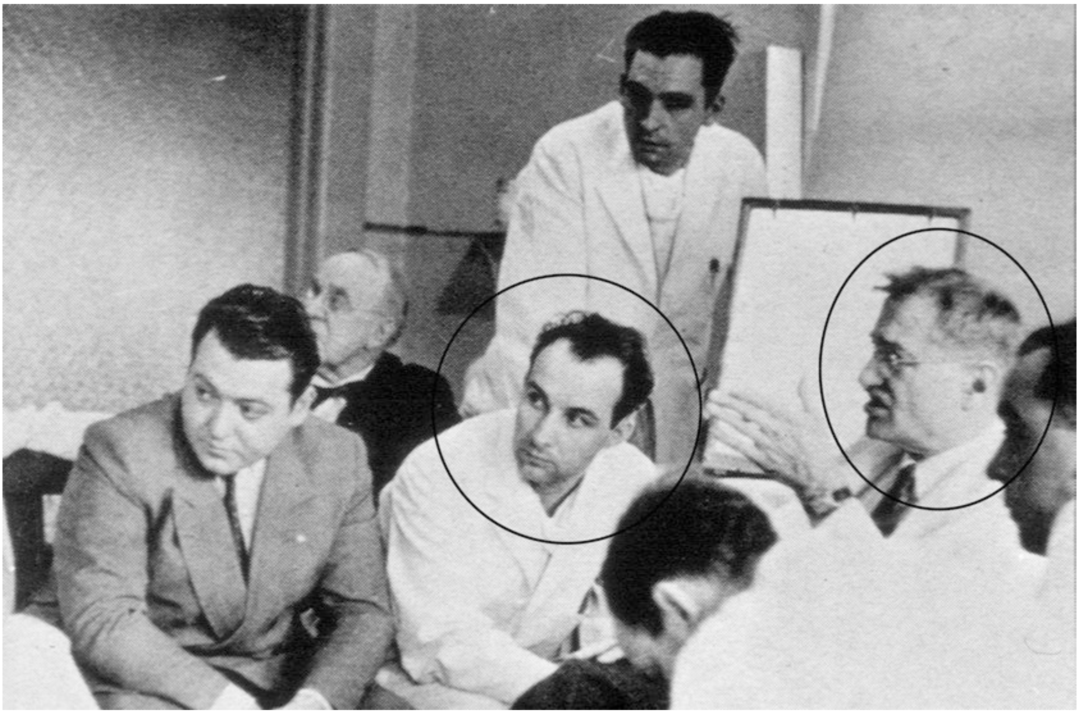


Fig. 1.14 The evolution of childhood hip knowledge (Univ. of Iowa—circa 1940). Professor Arthur Steindler (right circle) instructs orthopedic resident I.V. Ponseti (left circle)

Edgar Somerville (Fig. 1.15) at Oxford demonstrated that one could readily reduce a dislocated hip, even in an older child, if the labrum was excised along with an appropriate derotation, varus, and perhaps shortening femoral osteotomy [2]. Robert Salter (Fig. 1.16) in Toronto developed a quite different approach where he emphasized the importance of maintaining the labrum and the acetabular growth centers when he performed open reduction plus capsular repair plus innominate osteotomy [3] (now known as the Salter osteotomy) (Fig. 1.17). Salter's very rigorous capsular excision/repair provided a very low incidence of re-dislocation (although occasionally the child was left with an internal rotation contracture).

Ponseti in Iowa (Fig. 1.18) did important histologic work documenting the importance of the cartilage growth centers in the acetabulum [4] and both he and Salter realized that these centers, as well as the labrum, should not be excised as they contributed to subsequent acetabular growth. Ponseti and Weinstein (Iowa) also performed important studies to confirm the value of the medial open reduction for DDH.

Fig. 1.15 Edgar Somerville (Oxford) promoted open reduction for DDH that included labrum excision and often a femoral osteotomy (photo courtesy of Professor Michael Benson, Oxford UK)

Fig. 1.16 Robert Salter (Toronto) promoted open reduction for DDH that preserved the labrum and included a secure capsulorrhaphy plus an innominate (acetabular) osteotomy

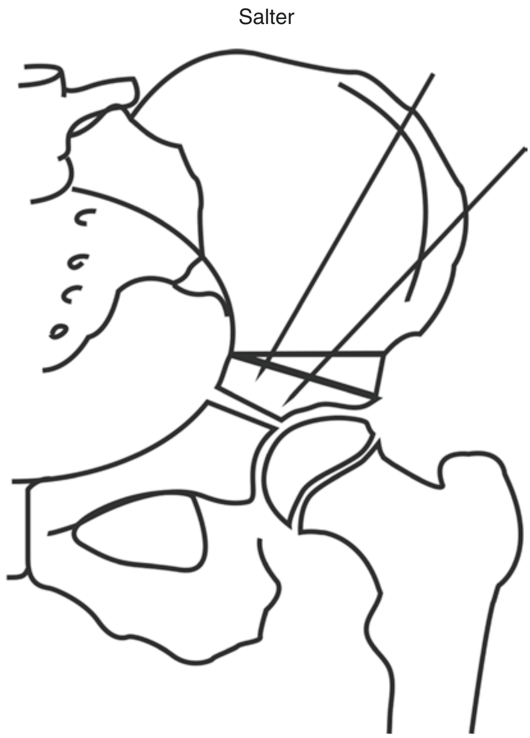


Fig. 1.17 Depiction of Salter's supra-acetabular osteotomy that re-directs the acetabulum to provide improved anterolateral femoral head coverage

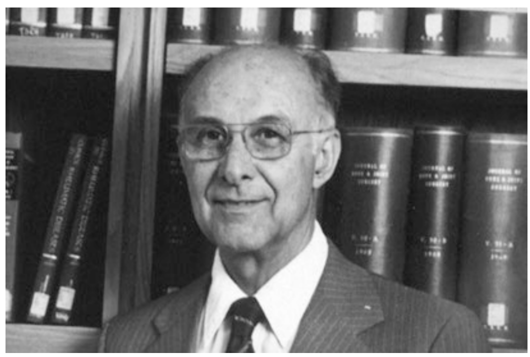


Fig. 1.18 Professor I.V. Ponseti of the University of Iowa published multiple papers that have clarified the histology and later clinical course of acetabular development after DDH reduction

Surgical Improvements: Deepening the Acetabulum Along with Open Reduction

Alfonso Poggi (1848–1930) in 1880 wrote a historic paper describing the first deepening of the acetabulum for developmental dysplasia of the hip. The idea of extending or improving the acetabular roof over the femoral head was further advanced by Franz Koenig in 1871. Spitzy of Vienna, Albee of New York (Fig. 1.19), and Dega of Poland were early proponents of placing a bone graft over the acetabulum to encourage its growth.

Thus Salter's advice for a pelvic osteotomy was not new but was unique because it was a complete osteotomy that re-directed the acetabulum (without the risk of decreasing acetabular size—as can occur with bending osteotomies when performed with primary open reduction plus acetabular osteotomy).

Salter advised the re-directional acetabuloplasty that now bears his name. The combination of reduction, a corrective capsulorrhaphy, and then a Salter innominate osteotomy (without femoral surgery) became a North American stan-

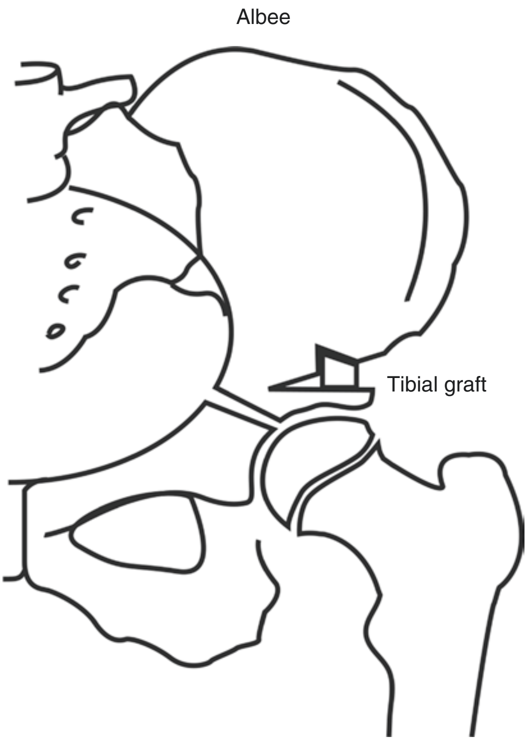


Fig. 1.19 Depiction of Albee's method for improving acetabular coverage of the femoral head (New York—early twentieth century)

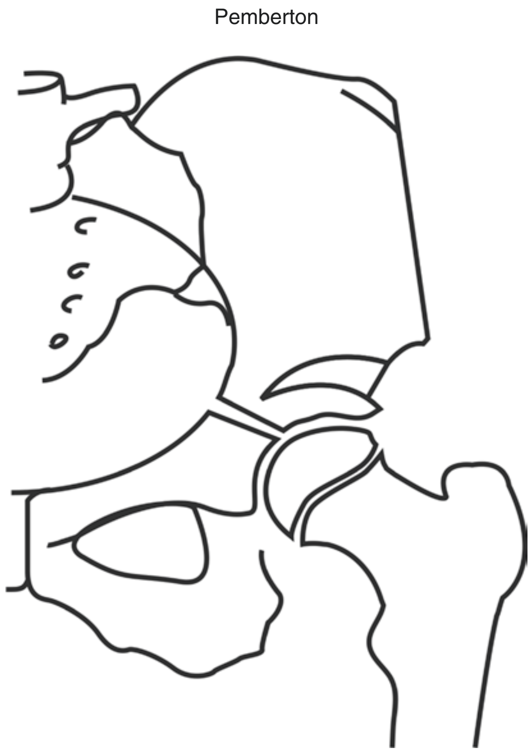


Fig. 1.20 Depiction of Pemberton's acetabular "bending" osteotomy, designed to improve femoral head coverage in DDH (Salt Lake City)

dard in the 1960s and 1970s. The Pemberton osteotomy [5] (1960s) was also commonly used in North America (Fig. 1.20).

Femoral Shortening for Older Children

Closed vs. open reduction for delayed diagnosis of CDH remained the orthopaedic standard throughout the late nineteenth and early twentieth century, but treatment in older children proved to be difficult. Hey-Groves of England may have been the first to mention femoral osteotomy to aid in reduction in 1928. Ombredanne (France) also described the concept of femoral shortening to help reduce the hip in the older child in 1932, with Klisic of Yugoslavia popularizing the method in the mid to late twentieth century (Fig. 1.21). Klisic also included an acetabular osteotomy.

Klisic's massive experience, presented to a North American orthopaedic audience at both the Tachdjian International Course and the landmark Royal Oak, Michigan Children's Hip Course (mid 1970s), showed American surgeons the clear efficacy of femoral shortening. Following his presentations, most American centers began to use femoral shortening in older CDH patients. Klisic's methods have stood the test of time and are now used widely throughout the world [6].

Initially, most North American surgeons used the Salter open reduction plus acetabuloplasty for children up to 4 or 5 years of age and avoided femoral osteotomy, except for older children. Over time, the age indications were lowered as surgeons recognized the great value of adding a derotational femoral shortening to the "Salter method" [7]. By the early twenty-first century, many (if not most) North American surgeons, faced with a completely dislocated hip in a 2 or 3-year-old child, will combine open reduction

Fig. 1.21 Predrag Klisic, an important Yugoslav (Serbian) orthopedic surgeon introduced North Americans to the importance of femoral shortening for treatment of DDH in older children (1970s) (photo courtesy of Darko Antonivich and Klisic family)

plus acetabuloplasty plus derotational femoral shortening.

Extreme Cases

During the period from the 1940s to the 1960s, there were also operations done for more severe hips that were perhaps considered untreatable by traditional methods. These included the Colonna procedure (Philadelphia), and the Chiari osteotomy (Vienna). Colonna utilized excised hip capsule to cover the femoral head, which was then placed into the acetabulum which had been reamed to a greater depth. Extreme stiffness was common and the procedure is now rarely used.

The Chiari procedure creates a shelf support via a complete "translational" pelvic osteotomy that places the femoral head below a "ledge" of bone, allowing the development of a fibrocartilaginous "roof". The Chiari osteotomy is still used in rare cases to treat residual dysplasia.

Traction Prior to Reduction Surgery

As noted earlier in this chapter, before the surgical era, traction methods were routine in reducing DDH. A dislocated hip, even in a 4 year old, could be routinely reduced with prolonged traction applied through skin traction with gradual abduction and then internal rotation. The method of Petit (Paris) and Morel (Institut François Calot—Berck) were typical of this methodology and were used even into the second half of the twentieth century [8]. The method was quite safe and effective, but is no longer widely used because of current concepts regarding the expense of a prolonged hospital stay.

> ***"The liberal use of femoral shortening as part of reduction surgery has also contributed to the non-traction era".***

Osteotomies for Residual Hip Dysplasia

Many patients who have treatment for early childhood hip dysplasia end up with inadequate femoral head coverage. The European and North American literature is filled with many types of osteotomies that have been developed by surgeons in differing countries and continents, all designed to improve acetabular coverage and thus forestall the early onset of hip arthritis that can occur in a hip that is poorly covered.

Although a varus femoral osteotomy can be selected, it can leave the child with a limp and the acetabular dysplasia may never fully correct. By the mid twentieth century in North America, most residual childhood hip dysplasia has been treated by relatively simple acetabular osteotomies (Salter, Pemberton) in younger children. As children get older, it becomes difficult to rotate the acetabulum with a single cut thus, procedures such as triple pelvic osteotomy (Steel [9] and others) (Fig. 1.22) and periacetabular osteotomy (Ganz) were developed and are commonly used.

Fig. 1.22 Depiction of triple pelvic osteotomy as described by Steel, Tonnis, Carlioz, and others. Making three bony cuts allows free rotation of the acetabulum

Perthes Disease 'Also Legg-Calvé-Perthes Disease'

The directions for creating this chapter were to cover the history of children's hip surgery over the last 100 years, and interestingly Perthes disease encompasses almost exactly that period. Radiographs were first discovered in 1895 by Röntgen, and in 1910, simultaneous publications were produced by Legg, Calve, Perthes and Waldenström (Fig. 1.23) describing this unusual condition of the hip in childhood.

Many different developmental bone disorders were described almost immediately following the invention of the radiograph (Sever, Kohler, Osgood, Schlatter, many others) providing a "golden era" for an orthopedic surgeon to become famous (via an eponym). These were broadly consolidated into a group known as the "osteochondroses".

Fig. 1.23 The "recent" (in 1895) discovery of X-rays made hip disease more understandable. In 1910, these four surgeons simultaneously reported the condition we now refer to as Perthes, Legg-Perthes, or Legg-Calvé-Perthes disease. Waldenström's name didn't make "the cut" but he is eponymically recognized for his chronological staging of Perthes disease

Perthes was recognized as a non-infectious sort of "coxitis" in children whose etiology was (and continues to be) enigmatic. The pathology of Perthes disease was defined in the mid-1920s when Phemister (University of Chicago) performed histologic studies clarifying that the peculiar radiographic findings were produced by AVN. Some prefer the term "aseptic necrosis" because in the earlier orthopedic era, most femoral head destruction was the result of tuberculosis or other type of bacterial infection.

Non-operative Treatment

Almost all Perthes treatment was non-operative during the first half of the twentieth century, utilizing devices that discouraged weight bearing on the affected limb. These included the stirrup crutch, as well as many types of braces. In the 1930s, A.O. Parker in Cardiff, Wales advised that femoral head deformation could be best prevented by femoral head "containment" which he achieved by applying so-called "broomstick plasters" (in the British tradition, two cylinder casts held separated by an attached broomstick/wooden dowel [10]). The method proved quite effective and was continued in the modern era by Petrie (Montreal) and more recently by Schoenecker, et al. in St. Louis.

Orthoses which matched the abduction cast model were then developed by European and North American experts. The goal of both the casts and the orthoses was to hold the thigh and leg abducted and internally rotated so that the femoral head was deeply contained within the acetabulum. The problem is that the femoral head revascularizes and reossifies slowly over a 1½ to 2-year period. Although abduction casting and bracing proved to be quite effective,

> ***…as the twentieth century evolved, and the psychology of childhood development became better understood, surgeons looked for better methods to avoid prolonged cast or brace wear.***

Surgical Containment

In the 1960s, early reports began to appear advising surgical methods to provide containment of the femoral head in Perthes disease. Axer (Israel) [11], and Lloyd-Roberts/Catterall (London) [12] (Fig. 1.24), and others reported that proximal femoral varus osteotomy would allow the femoral head to remain contained with the acetabulum during normal walking with the acetabulum serving as a "mold" to allow the femoral head to heal in a more normal shape (Fig. 1.25). Stulberg et al. noted that head shape (after treatment and healing) was predictive of early onset arthritis [13].

Soon thereafter, Salter (Toronto) decided that innominate osteotomy, which he had developed for the treatment of DDH, could also be applied to contain the femoral head, during healing, in Perthes disease [14].

As in any change from nonoperative to operative treatment, substantial disagreement occurs until a new paradigm is accepted. Such was the case for Perthes disease with many European and most North American, traditionalists continuing with abduction bracing for Perthes treatment. However, once it became clear that the femoral head can only be well-contained with a brace that extends from the hip, over the knees, and to the foot (to control hip rotation), more surgeons moved towards surgical containment as a more civilized treatment.

Although Lloyd-Roberts and Catterall strongly suggested that surgical containment provided a better radiographic and clinical outcome as compared to nonoperative treatment, their paper did not meet the highest standards because of the absence of matched controls. Recognizing this deficiency, in the 1980s, Dr. Tony Herring (Fig. 1.26) and colleagues at the Texas Scottish Rite Hospital—Dallas began a prospective, multi-center, randomized study that compared patients with Perthes disease who had the following treatment:

1. No specific treatment—stretching of adductors, possible physical therapy.
2. Brace containment methods.
3. Proximal femoral varus osteotomy.
4. Salter innominate osteotomy.

This well-funded and carefully performed prospective "surgeon choice" randomized study led to an important publication that clarified that Perthes patients have a better outcome if they are treated by surgical containment rather than minimal treatment or bracing [15, 16]. The study noted

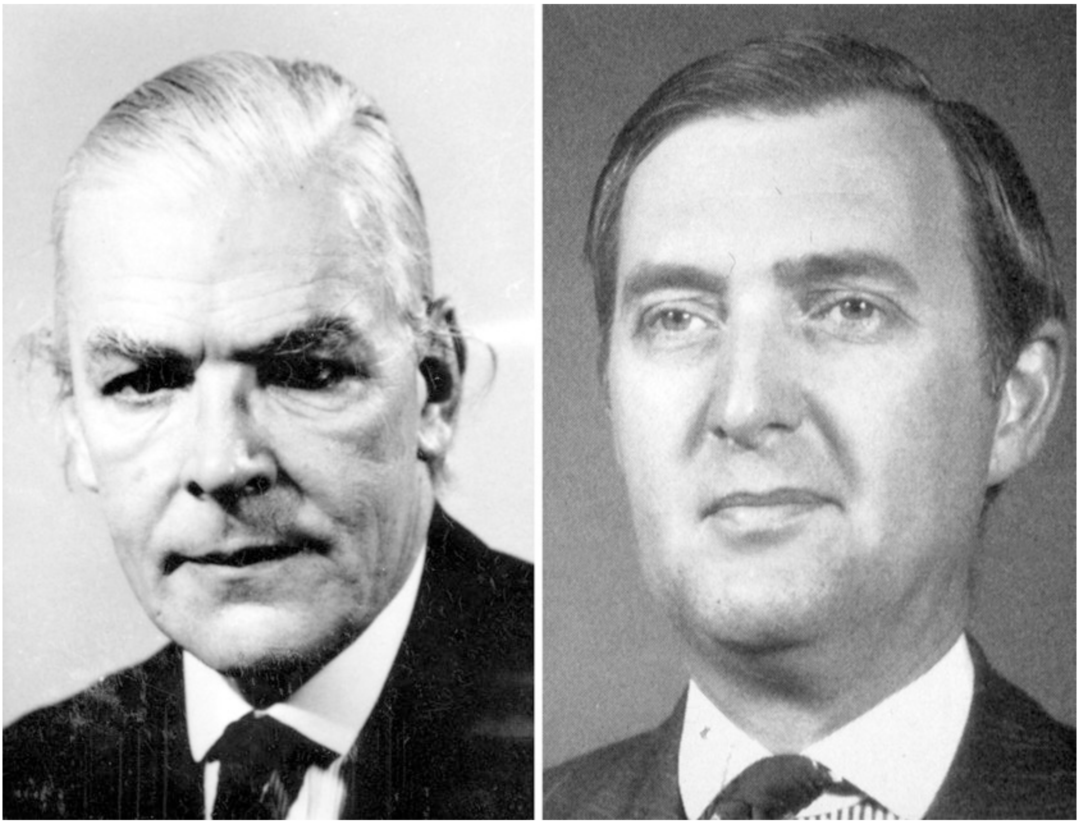
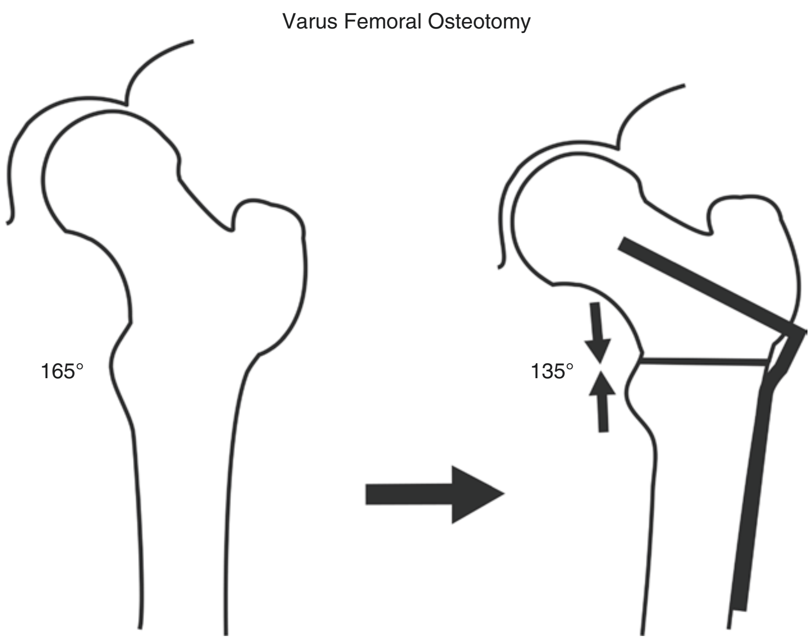


Fig. 1.24 George Lloyd-Roberts (left) and Anthony Catterall (right), both from London, provided an early understanding of the efficacy of varus femoral osteotomy in treating Perthes disease

Fig. 1.25 Depiction of varus femoral osteotomy. Decreasing the neck-shaft angle allows the femoral head to be "contained" while the child is standing/walking



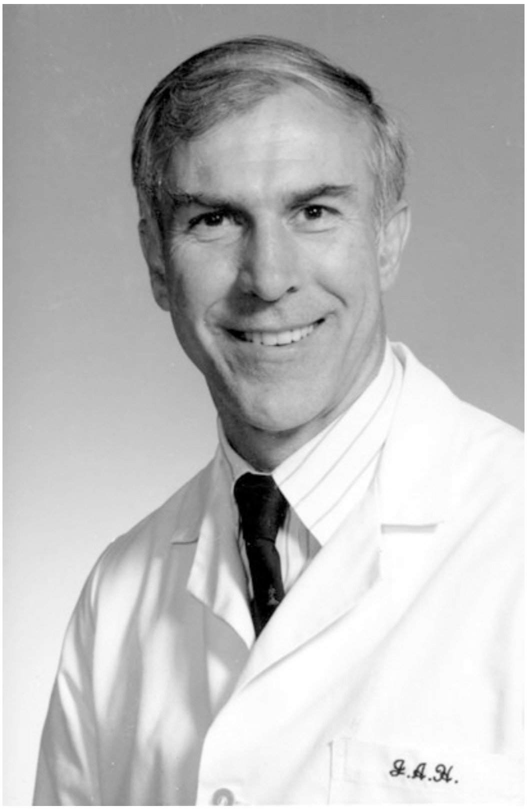


Fig. 1.26 John (Tony) Herring of the Texas Scottish Rite Hospital—Dallas led the prospective Perthes study group that more scientifically established the efficacy of surgical containment

that mild cases in younger children do not benefit from treatment and that severe cases in older children may not benefit from simple containment methods (femoral osteotomy or Salter procedure). Their study did not include surgical methods designed for severe cases where one might select "hyper containment" (Salter plus femoral osteotomy, triple innominate osteotomy, etc.).

Recognizing the need for more aggressive methods of containment for severe cases, methods were developed to treat such cases including combining proximal femoral and Salter osteotomy (Olney/Asher, Kansas City, also Staheli, Seattle) or the triple innominate osteotomy (Steel, Tonnis, Carlioz, others), which allows more complete coverage of almost any femoral head.

…Most orthopedic surgeons are happy to accept a surgical solution for a complex problem because they are trained for and enjoy performing operations…

Thus, following the studies by Herring et al., there has been a strong movement throughout the world toward surgical containment surgery for Perthes disease.

Two of the largest studies confirming the efficacy of surgery with femoral osteotomy are those of Wiig et al. (Oslo, Norway) [17], as well as the very large series published by Benjamin Joseph (Fig. 1.27) in Manipal, India. Joseph reported the results of surgical treatment in more than 600 patients, and also developed a sophisticated algorithm (designed for surgeons) that advises early surgical containment to minimize head lateralization and flattening that occur when a child is left untreated [18, 19]. These algorithms are sometimes difficult to follow, but most surgeons rather like Joseph's viewpoint since it appears to encourage an operative procedure when one is not certain whether to intervene (better to prevent head deformation than wait too long).

Newer Methods

The surgical community continues to search for improvements in surgical treatment. Nuno Craveiro Lopes (Portugal) has recommended serial penetration of the avascular epiphysis with small K-wire drill holes to improve vascularity between the metaphysis and the epiphysis (even in mild cases). This can also be combined with hip distraction via an external fixator. His method has been popularized elsewhere but with little scientific support of efficacy and no prospective randomized studies that we are aware of. It remains unclear as to whether the drill-hole channels remain open long enough to speed head revascularization. Medical treatment has also been pursued in several centers (bisphosphonates etc.) but as of yet not a standard addition or supplementation to surgical containment.

Despite all of the above, currently, straightforward surgical treatment remains highly effective

Fig. 1.27 Benjamin Joseph of Kasturba Medical College (Manipal, India) has the world's largest reported series of femoral osteotomy for Perthes disease. The right image shows him with his extensive (and beloved) X-ray research files. Dogged determination in maintaining all records and X-rays of 600 patients symbolizes the dedication of nineteenth and twentieth century researchers who have provided our knowledge base

and most children can lead a relatively normal life following surgical containment for Perthes disease.

Slipped Capital Femoral Epiphysis (SCFE)

> ***"Before the advent of X-ray, SCFE was likely just another cause of limp and likely considered a rather benign disease."***

Even after X-ray became available and the pathogenic process (slip) recognized, early diagnosis was rare and the main interest of surgical treatment during the early part of the twentieth century was to perform femoral osteotomies to correct late deformity.

The first specific literature reference to what is now known as SCFE was by Jean-Louis Petit who in 1723 wrote "decollement, that is separation of the head from the neck—in the sense that one says a criminal has been beheaded—can also be seen when one has separation of the epiphysis from the neck of the femur. One should consider that the cartilage between the epiphysis and the neck are a form of cement that joins both parts".

Later, Ernst Muller in Tubingen, Germany (1888), gave a more complete description of SCFE when he examined several autopsy specimens of patients with a pathologic process in the proximal femur. He noted that the condition was seen in healthy young individuals from 14 to 18 years of age with no known cause or prior injury, that symptoms developed slowly, that hip joint movement was usually free and without crepitus, and that the femoral head must be in a healthy joint. He then described the pathologic findings he had noted in an anatomic specimen and thought that the gradual bending at the head/neck junction was perhaps due to a rachitic condition.

Surgical Stabilization

As the century evolved and more patients were studied radiographically, the disease became better defined with an understanding that a slip could be progressive and that this could be prevented by surgical stabilization. Early methods used large diameter nails similar to those which had been invented to nail femoral neck fractures. Unfortunately, these large nails could cause further separation of the physis due to the blunt trauma of inserting them.

The availability of threaded Steinman pins greatly improved this circumstance. Two or three large threaded pins placed across the slip would stabilize the slip in a predictable manner. A better understanding of the clinical presentation of SCFE (chubby pre-adolescent—foot turned out—knee pain) allowed earlier diagnosis with in-situ pinning before a substantial slip had occurred.

> ***"Surgical pinning in this era was cumbersome because power K-wire drivers had not yet been invented."***

The surgeon had to use a manual drill plus large diameter threaded pins whose "tip position" had to be documented by serial plain radiographs (which required processing in an often distant X-ray development room between each pin "adjustment").

Early pinnings were plagued with an unfortunately high incidence of chondrolysis despite the surgeon feeling that the final X-ray showed good pin-tip position.

> ***…This chondrolysis was not fully understood until the brilliant radiographic and geometric studies of Walters and Simon (Boston Children's Hospital and MIT),…***

who documented that many patients who appeared to have the pin tips well within the femoral head, were actually penetrating the joint [20]. This "blind spot" was most commonly noted when the pin tips were in the lateral quadrants of the head (rather than central). Thus, the cause of chondrolysis proved not to be a mysterious immune condition, but instead was the result of pin tip joint penetration (Fig. 1.28).

This understanding, plus the development of cannulated screw systems, the recognition that a single large central screw could stabilize most slips, and the development of high quality image intensifiers, radically improved SCFE care in the last third of the twentieth century.

In-Situ Pinning vs. Reduction

In general, the prognosis for in-situ pinning slipped capital femoral epiphysis has been quite satisfactory. The landmark paper by Boyer and Ponseti (University of Iowa) [21] demonstrated that even more severe slips pinned in-situ could have good long-term function and would not require a total hip replacement until upper middle age. Similar papers demonstrating the efficacy of in-situ pinning also appeared in the Scandinavian literature.

Societal Change and Surgical Choices

The initial papers from the University of Iowa and other conservative centers were developed in communities where most patients were from farmer/laborer stock who likely did not pursue athletics in adult life. Also, the patients were often (but not always) of normal weight.

A rather rapid revolution then occurred in the late twentieth century in North America with a tremendous increase in the incidence of childhood obesity along with markedly less physical activity as the population left the farms for the city—plus access to TV watching/video games. In addition, city life and more leisure time allowed greater athletic activities in teenagers, with the associated increased stress on the sensitive proximal femoral physis.

Stable vs. Unstable Slip and Surgical Choices

It had been known for at least the last 75 years that acute slips had a very poor prognosis. Loder

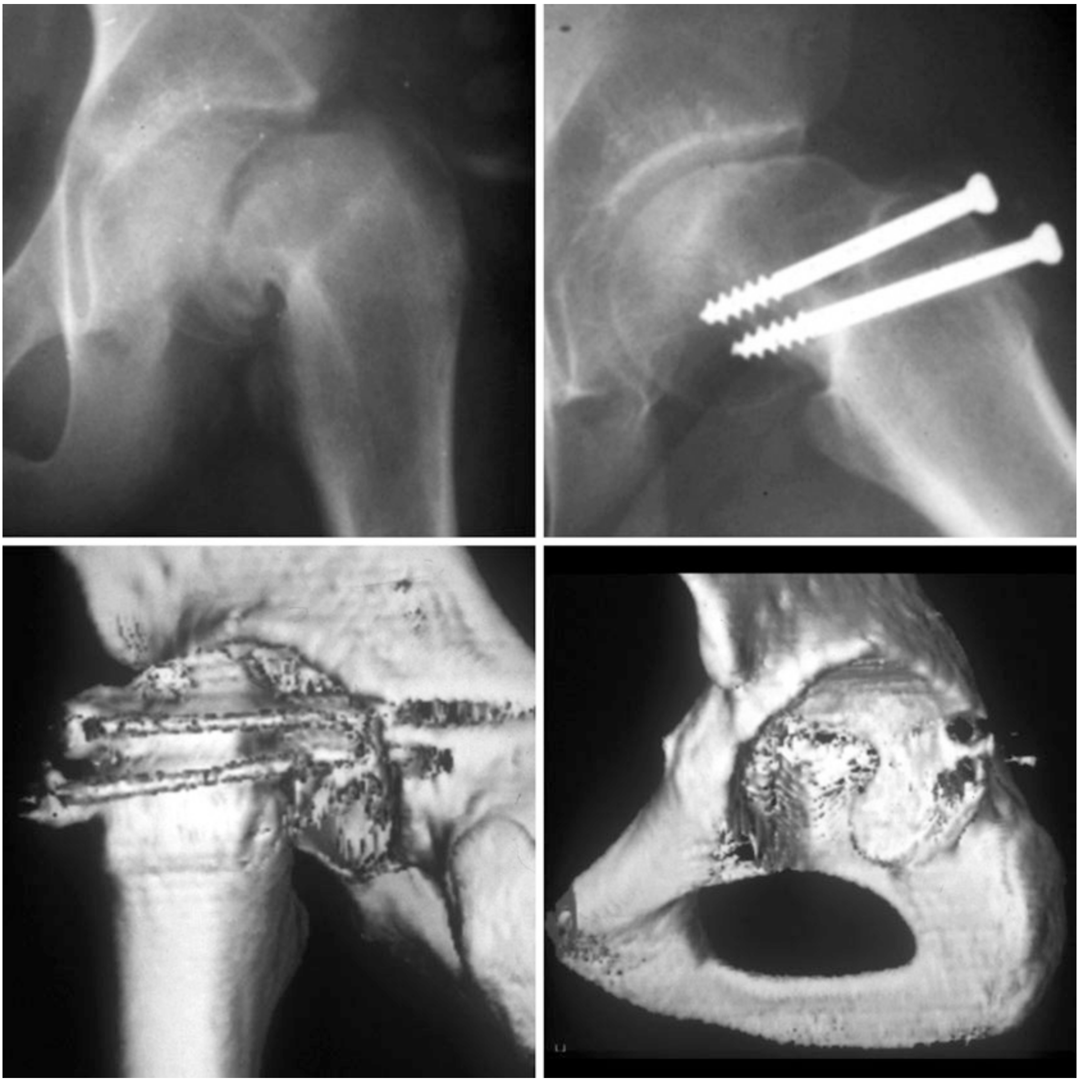


Fig. 1.28 Severe SCFE treated by in-situ pinning. The X-ray shows the pin tips far from the joint (top). But the hip was stiff and painful. The 3DCT study (lower) shows that the pin tips were in the acetabulum

and colleagues (Fig. 1.29) studied a large series of SCFE patients in the early 1990s and were able to divide slips into "stable" slips and those that were "unstable" due to an acute change in epiphyseal position [22]. Loder's logic and language were accepted almost immediately and led to clearer decision-making when a SCFE patient arrived—about 95% were stable and 5% unstable.

The conservative approach was to treat all stable slips with in-situ pinning with performance of a late osteotomy if the patient had an unacceptable limb deformity (external rotation, limited hip flexion). The late osteotomies were of the valgus-flexion type, as designed by Southwick and Imhauser, which corrected limb deformity (rotation) and better centered the femoral head in the acetabulum.

Fig. 1.29 Randall Loder (Indianapolis) studied and defined the concept of a stable vs. unstable SCFE in the early 1990s

Fig. 1.30 Reinhold Ganz (Bern, Switzerland) provided the intellectual drive, research studies, and surgical techniques that greatly improved our ability to anatomically reduce a severe SCFE

Unstable Slips

Unstable slips present with severe pain and are unable to walk, with an ultrasound study demonstrating fluid in the joint. These patients had a poor prognosis and if they were surgically reduced, very commonly developed avascular necrosis (AVN).

The treatment of the unstable slip remained problematic. If the hip was pinned in-situ, in a very displaced position, a large anterior metaphyseal "bump" impinged on the acetabulum with significant risk of early arthritis. If they were manipulated and reduced, and then pinned, the risk of avascular necrosis was high. Thus, the hip seemed doomed.

The Move Towards Anatomic Reduction

The 1990s and the first 20 years of the twenty-first Century brought significant (some would say radical) re-thinking about significantly displaced slips.

…Ganz (Fig. 1.30) and colleagues in Bern, Switzerland, recognized that not every slip patient had a good clinical result after in-situ pinning and began to advise anatomic reduction…

of SCFE, first in unstable and severe slips and later even mild slips [23].

This was not an entirely new idea since Herndon in Cleveland (1950s) had recommended removal of the anterior femoral head bump at the time of an in-situ pinning [24]. Also, Dunn in the U.K. had recommended anatomic reduction at the epiphyseal level for significant slips. Fish in the U.S.A. similarly promoted anatomic reduction for severely displaced slips.

Ganz et al. performed careful anatomic studies to better understand the blood supply to the femoral head epiphysis and also defined the location and nature of callus that forms subperiosteally in patients with a more severe slip [25]. They then developed a trans-trochanteric surgical hip dislocation approach which allows removal of the callous and careful anatomic reduction of both stable and unstable slips. Ganz described his operation as a modified Dunn procedure, thus crediting the prior work by Dunn in the UK [26].

The Ganz method was demanding, but when done carefully, with Swiss detail and proper training, yielded favorable results. The complexity of the surgery, however, kept the method from providing uniformly positive results worldwide. Many major hip centers in North America and Europe now use the surgical hip dislocation/modified Dunn method for acute unstable slips because the risk of AVN is so high in this patient group. There is much less tendency to use this method on a stable severe slip since the incidence of AVN is negligible after in-situ pinning plus later corrective osteotomy.

Less Complete Reduction/Monitoring Blood Supply

Parsch (Germany) has described a likely safer method of treating the acute, unstable, SCFE that includes an open anterior capsulotomy, hematoma evacuation, and partial reduction plus k-wire stabilization of the slip. The AVN rate with this method is reported as less than 10% [27].

In an attempt to improve results in unstable slips, a great deal of current research focuses on intraoperative maintenance of femoral head blood flow. Schrader and colleagues in Atlanta have developed a method of measuring the oxygen tension within the femoral head by placing a catheter through a threaded screw [28]. Also with the surgical dislocation approach, a catheter can be inserted into the femoral head and attached to a pressure monitor, allowing minute-by-minute monitoring of blood flow.

The "Athletic Hip": Deformity Due to Extreme Training

Another contemporary interest of Ganz and the Swiss group relates to the "translational deformity" at the proximal head/neck junction that develops in individuals who have participated in rigorous sports training during childhood/adolescence [29]. It appears that with vigorous physical training throughout this period, in pre-disposed individuals, a subtle deformity evolves at the head-neck junction (physeal level), producing an anterolateral bump (Fig. 1.31). The so-called "lack of offset" hip impinges on the acetabular rim, leading to labral injury, cartilage delamination, and early arthritis. Corrective surgery to remove the "bump" can be performed via open or arthroscopic approaches.

Hip Preservation Surgery

The tremendous knowledge advances that have been made to manage hip deformities whether due to DDH, Perthes, SCFE, the "athletic hip", or other causes has led to an entirely new specialty described as "hip preservation surgery", which is surgery to postpone or prevent total hip replacement. Freeman questions the hypothesis that surgery can preserve a hip and prevent the need for arthroplasty [30], which currently remains unproven. The bi-annual Bernese Hip Symposium and the North American based Academic Network of Conservational Hip Outcomes Research (ANCHOR) study group keep interested experts updated on this new surgical subspecialty.

Despite a growing understanding of the origin and nature of the athletic hip impingement syndrome, there is little common understanding or agreement regarding what sports children should be limited from, numbers of hours that they should practice, and whether or not children with differing biology and/or genetic make-up may have a different risk level for developing hip deformity when participating in "cutting sports", such as soccer, basketball, hockey, etc.

The “Athletic Hip”

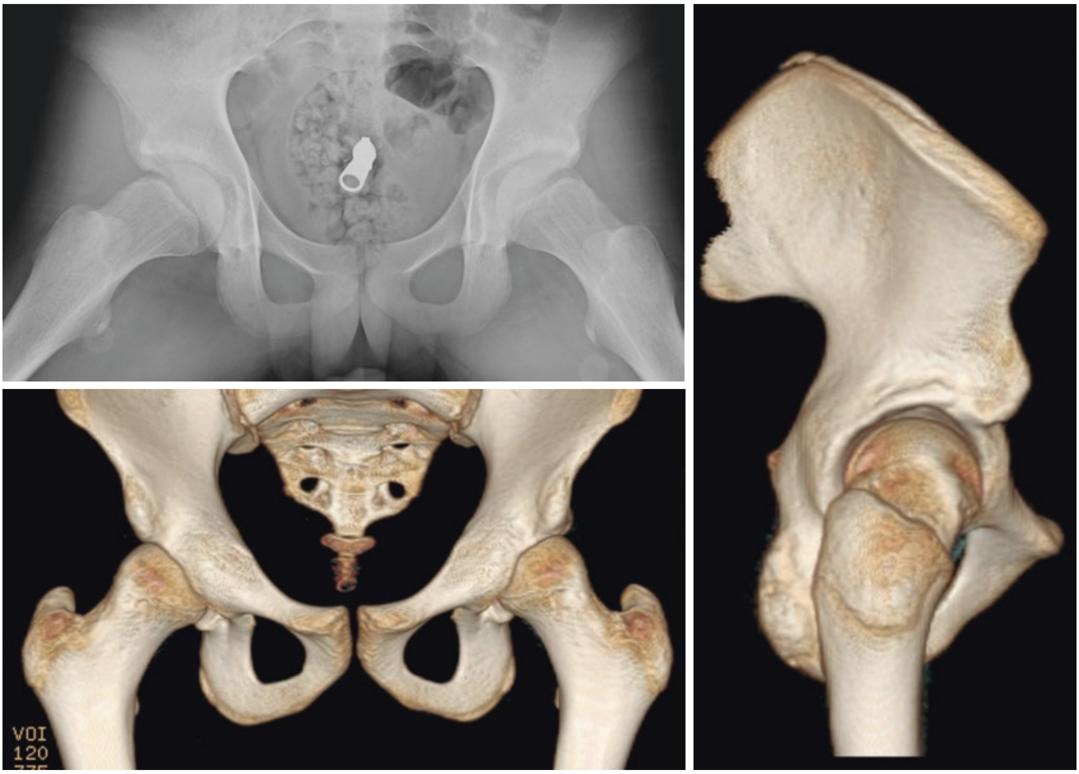


Fig. 1.31 Radiographs and 3D-CT study shows the antero-lateral prominence at the head-neck junction noted in a very athletic teenage male who presented with hip pain

Summary

The history of hip surgery in childhood is complex and likely was not very interesting until the radiograph was invented in 1895. Further “inventions” have made modern surgery safe. High level imaging, with image intensifiers and then CT scans, as well as MRI studies, and then three dimensional imaging have revolutionized our understanding of how children’s hips become deformed and whether corrective surgery can be beneficial.

Finally, the development of academic centers that focus on childhood hip disorders, as well as a growing number of centers that focus on hip problems in adolescents and young adults, assure a continuous and changing “history” of childhood hip disease. The rapid appearance of new concepts, implants, and operations, fueled by the digital revolution, will continue to outpace our ability to carefully study the results of new operations. Internet savvy, subspecialty oriented, “advertising clinics” will continue to jeopardize sensible progress. Future historians will revel at our amazing advances—and perhaps despair from our occasional/frequent mis-steps.

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2 Anatomy and Physiology of the Pediatric Hip

Emily K. Schaeffer and Kishore Mulpuri

Introduction

The hip joint is an articulating "ball-and-socket" joint that is formed by the head of the proximal femur and the acetabulum. The proximal femur consists of the approximately spherical femoral head, the femoral neck, and the greater and lesser trochanters (Fig. 2.1). The femoral head joins the neck at the subcapital sulcus—a deep groove containing the intra-articular subsynovial vascular ring (Fig. 2.1). The acetabulum is a semi-spherical concavity formed by three major components of innominate bone: the ilium, ischium and pubis. During development and maturation, these three separate bones unite at the centre of the acetabulum, known as the tri-radiate cartilage (Fig. 2.2). The femoral head and the acetabulum come into closest contact during maximum weight-bearing and extremes of range of motion, for example flexion and internal rotation [1].

The anatomy of the pediatric hip represents a changing landscape throughout all stages of growth and development, from birth until skeletal maturity. Abnormalities during different developmental stages can cause a number of debilitating hip conditions that can have lasting ramifications into adulthood. Hip joint development begins in the embryonic phase of life, and is a progressive, dynamic process that continues throughout fetal development, infancy and childhood. The relatively rapid hip development that occurs during the prenatal and neonatal phases can have an impact on the different surgical and non-surgical management options used in the treatment of

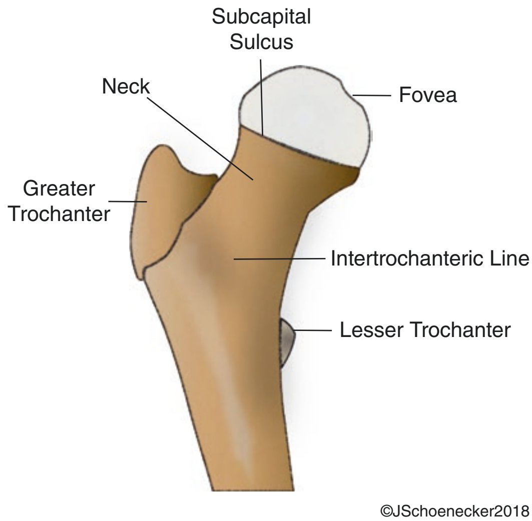

Fig. 2.1 The proximal femur. The bony proximal femur consists of the femoral head and neck, separated by the subcapital sulcus. The greater and lesser trochanters are non-articular traction apophysis, providing attachment points for muscles, ligaments and tendons of the hip joint. The trochanters are connected by the intertrochanteric line

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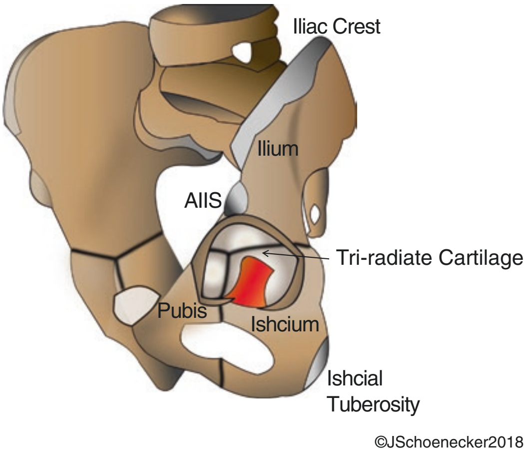

Fig. 2.2 The bony acetabulum. The acetabulum is a semi-spherical cavity formed by three components of innominate bone. The ilium (2/5), ischium (2/5) and pubis (1/5) unite during development at the tri-radiate cartilage in the centre of the acetabulum

pediatric hip disorders. In particular, the unique anatomical and physiological features of the developing pediatric hip merit the surgeon's consideration before deciding on the most appropriate treatment for common disorders such as developmental dysplasia of the hip (DDH), slipped capital femoral epiphysis (SCFE), Perthes disease, and hip displacement in cerebral palsy.

Prenatal Development of the Hip Joint

The Embryonic Phase of Hip Joint Development

Primary tissue differentiation occurs in the embryonic phase of pre-natal development, weeks two through eight post-conception. It is in this phase that the entirety of the musculoskeletal system develops, including the immature origins of the hip joint [2]. All the elements comprising the pelvis and the hip joint arise from a single mass of mesoderm, transitioning sequentially to blastemic tissue, precartilage, and cartilage in the early embryonic stages [3]. Appearance of the lower limb buds occurs by 28 days post-conception, and the first recognizable structure of the hip joint—the cartilage model of the femoral diaphysis—appears during the sixth week [2]. At this point, the hip joint is nonarticulating, the precartilage that will eventually form the femoral head being contiguous with the cartilaginous acetabulum. Primitive chondroblasts in this area begin to undergo differentiation and, as their nuclei separate, matrix material is secreted into the cytoplasm and a club-shaped femur begins to form [4]. Undifferentiated mesenchymal cells—blastemal cells—make up the trochanteric projection from the femur that will subsequently form an apophysis with its associated muscle attachments. The precartilage covers the long bone articulations and the cartilage model will form the basis for the development of osseous structures. During the seventh week, a precartilaginous centre develops in the middle of the femoral shaft and the acetabulum begins to distinguish itself from the femoral head, starting as a shallow depression of approximately 65 of the arc of a circle that eventually deepens to 180 over the course of development [2]. There is evidence to suggest that movement is necessary for appropriate joint cavity formation during this period, as studies using neuromuscular blockers in chick embryos resulted in failed hip joint cavitation, failed development of intra-articular ligaments, and replacement of muscle with fat [5].

Concurrent to joint cavity development, the femoral head and articular cartilage are forming, with apoptotic cell death occurring in the interzone to create the joint space [4]. Due to the development of a discernable joint space, this stage is notable as the first time during development that it would be hypothetically possible to "dislocate" the hip. Should that occur, said dislocation would most likely be inferior as a result of poor definition of the transverse acetabular ligament [2]. Differentiation begins in the ilium just above the acetabulum. The deepening of the acetabular cavity throughout the embryonic phase is influenced by pressure from the femoral head, and during this time, differentiation of the ligamentum teres femoris and other protective capsular structures begin [2]. From here, the cartilage of the ilium with attached labrum grows over the femoral head. By the eighth week, at the end of the embryonic phase, both primary and secondary ossification centres in the ilium appear, in addition to early formation of the synovial tissue, liga-

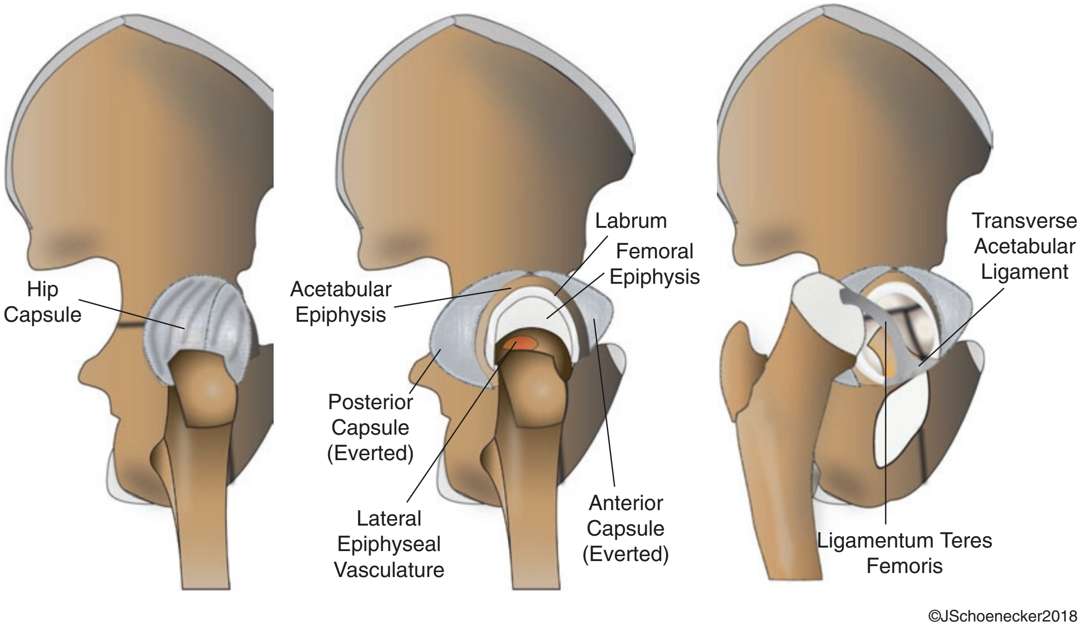

Fig. 2.3 Structures and features of the hip joint. The hip capsule encompasses the articulating components of the acetabulum and femoral head. The cartilaginous labrum encircles the femoral head, and the ligamentum teres femoris attaches at the fovea of the femoral head and blends with transverse acetabular ligament

mentum teres and the acetabular labrum (Fig. 2.3). While the neck of the femur is now elongated, unlike the ilium, the femur has not yet developed a secondary centre of ossification [1, 6].

The Fetal Phase of Hip Joint Development

Ossification, vascularization and maturation of both the proximal femur and acetabulum occur in the fetal phase, which represents week 8 post-conception through to birth. Femoral ossification proceeds from the centre of the diaphysis in both proximal and distal directions while the lower limb bud internally rotates [7]. By the 11th week, the spherical femoral head has reached 2 mm in size and the femur has 5–10° of anteversion [8]. This anteversion will continue to increase throughout fetal development, reaching a maximum of 45° at 36 weeks.

Throughout the fetal phase, the femoral head is also changing shape. During the embryonic phase, an anatomical study of 44 hip joints in fetuses and children reported that the femoral head represents 80% of a complete sphere however, femoral sphericity decreases throughout the fetal phase, resulting in a 50% spherical head at the time of birth [1, 9]. The femoral head gradually regains some sphericity in the postnatal period. As a consequence of this dynamic sphericity, acetabular coverage of the femoral head is at its lowest at birth, before again increasing through infancy and childhood [1, 9].

In the acetabulum, the primary ossification centre appears in the ilium during the early fetal period at 9 weeks. Between the 11th and 16th weeks of fetal development, the muscles form around the hip joint and capsule, the capsule joins with the femoral perichondrium and the acetabular labrum, the ligamentum teres and transverse acetabular ligament form within the capsule, and the articulating surfaces of the femoral head and acetabulum are covered by hyaline cartilage (Fig. 2.3). By the end of the 16th week, the ischial ossification centre of the acetabulum has appeared and the femoral shaft has fully ossified [6]. Following delineation of the three main acetabular epiphyseal centres delineated by the triradiate cartilage, ossification of the ischium begins in the fourth gestational month, and then a few weeks later in the pubis [10]. During iliac ossification, the lateral cortex of the ilium is persistently thicker than the medial cortex, possibly due to asymmetric mechanical stresses imposed by the gluteal muscles. Iliac ossification is also marked by haversian bone remodelling, becoming visible in the 28th week [3]. By 32 weeks post-conception, femoral shaft ossification reaches the greater trochanter and ilial and ischial ossification are complete [6].

Additionally, the vascular supply both to the femoral head and acetabulum matures throughout this time. The nutrient proximal femur artery, extracapsular circumflex arteries and the acetabular artery enter the acetabular fossa in the early fetal period (2 months). Between the second and third month, femoral vascularization also begins to develop distinct metaphyseal and epiphyseal supplies, while retinacular vessels perforate the femoral head and neck [11].

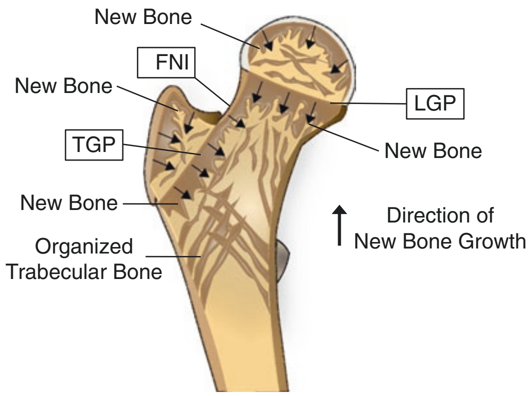

Fig. 2.4 The growth plates of the proximal femur. During postnatal development, three growth plates promote ossification of the femoral head and neck: the longitudinal growth plate of the femoral neck (LGP), the growth plates of the greater trochanter (TGP) and the femoral neck isthmus (FNI). Both the LGP and TGP provide longitudinal growth (black arrows), with the FNI connecting the two growth plates at the lateral neck

Postnatal Development of the Hip Joint

Acetabulum

The acetabulum remains immature at birth, primarily consisting of a cartilaginous ring around the femoral head, with the tri-radiate cartilage at its deepest, central point. The ischial, ilial and pubic arms of the tri-radiate cartilage eventually fuse to form the non-articulating portion of the acetabulum during the pubescent period [10]. Simultaneously, the cartilage ring grows along with the femoral head to create the load-bearing, articular surface. Three primary ossification centres—ilial, ischial and pubic—help to define the Y-shaped tri-radiate cartilage as ossification occurs (Fig. 2.2). The largest ossification centre is the os acetabuli from the pubis, forming the anterior acetabular wall by maturity. The ilial centre forms the superior acetabular dome, while the ischial centre forms the posterior acetabular wall. These ossification centres typically completely fuse to the body of the acetabulum between 17 and 18 years of age [12, 13].

Femur

At birth, femoral ossification has reached the greater trochanter and femoral neck, while the proximal femur remains cartilaginous. Three separate growth plates contribute to the growth and morphology of the proximal femur throughout postnatal development: the longitudinal growth plate (LGP) of the femoral neck, the growth plate of the greater trochanter (TGP) and femoral neck isthmus (FNI) that connects the two on the lateral neck. The LGP and TGP provide longitudinal growth [1, 14, 15]. LGP activity is influenced by acetabular pressure (Fig. 2.4) [1, 14, 15].

The ultimate shapes of both the femoral head and acetabulum at skeletal maturity are intimately connected and depend upon their dynamic interaction throughout development. An anteroposterior view of the pelvis demonstrating the relationship between the acetabulum and proximal femur is depicted in Fig. 2.5. Disruptions in their contact relationship or growth progression can result in angular deformities, shallow acetabuli, or otherwise imperfect hip joint formation. Despite their interconnected nature, few studies have focused on the development of the femur and acetabulum in parallel, instead focusing on one or the other in near isolation. To address this, Birkenmaier and colleagues undertook a geometrical analysis of their parallel development based on plain radiographs [16]. Studying 675 hips ranging in age from