EXTERNAL SKELETAL FIXATION

DANA C. MEARS

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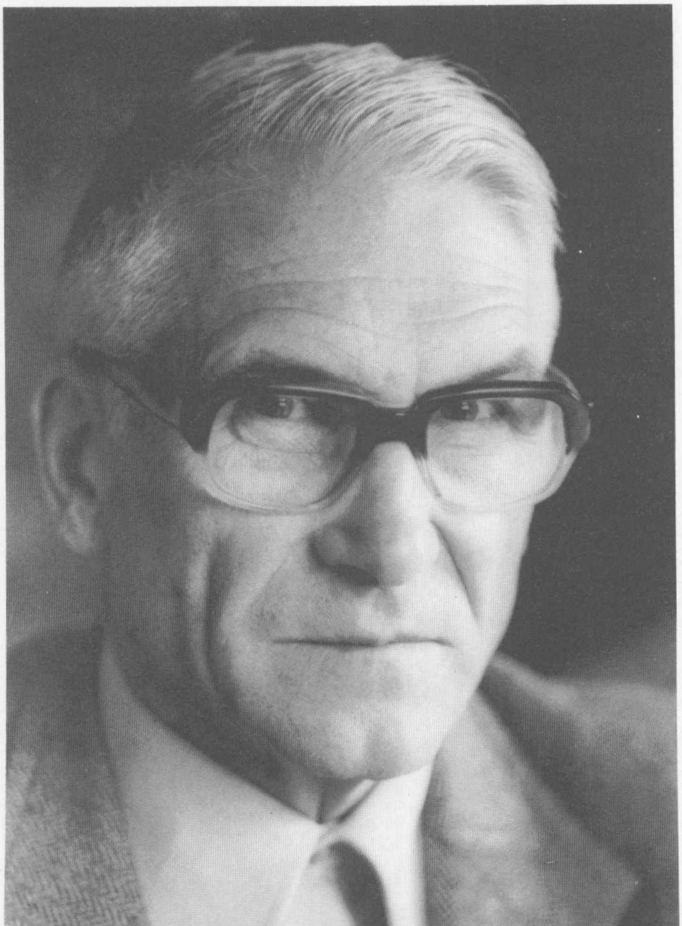
Dedication to Hans Willenegger



In Hans Willenegger I honor a surgeon who has been my teacher in the management of complex open and infected fractures. Many of his more than 200 technical papers and 9 books have focused upon the pathophysiology of open and infected fractures, the role of adequate stabilization and the use of bone graft. He is a masterful surgeon and an outstanding instructor in the diverse techniques of internal and external fixation of fractures. His patients remember him for his sound clinical judgment and surgical skill, his succinct appraisal of a complicated clinical problem and, not the least, for his personal warmth. He is able to relate to them emphatically and yet with a wry sense of humor that eases their burden considerably. On more than one occasion he came to

Pittsburgh to instruct me in the surgical management of difficult fracture problems. Ultimately, his didactic and clinical guidance encouraged me to prepare this manuscript.

As a former Professor of Surgery at the University of Basel, a former Chairman of the Department of Surgery at Kantonsspital Liestal, Basel, Switzerland, and more recently as the President of AO-International (Swiss Association for the Study of Osteosynthesis) he has traveled to virtually all parts of the world to supervise the instruction of thousands of surgeons in the acute management and the surgical reconstruction of the trauma patient. Hans has vigorously encouraged junior surgeons of many disciplines to undertake basic and clinical research in an attempt to develop superior methods of treatment. Justifiably he has been recognized as one of the pioneers who inspired appropriate recognition of trauma as one of the foremost medical problems in modern society. It is a great pleasure to dedicate this work to him.

DANA C. MEARS

Foreword

About 20 years ago during the formative period of the AO* Group, they developed a threaded external fixator to immobilize short fractures. The device was intended to neutralize a comminuted fracture by the provision of interfragmentary compression. The potential soft tissue problems associated with the alternative method of stabilization, open reduction and internal fixation, were the motivating force behind this effort. We were surprised and disappointed to observe that, even with the maximum "macroscopic stability" provided by external fixation, bone healing occurred at a very slow pace. External fixation used alone did not provide enough stability to permit primary cortical bone healing but it provided too much stability to elicit classical callus formation.

Subsequently, an improved armamentarium of internal fixation devices and superior knowledge of techniques of fracture stabilization by resort to interfragmentary compression resulted in a very high percentage of rapidly healing fractures. Undoubtedly the good results of rigid internal fixation or of medullary splinting by the use of an intramedullary nail reduced our interest and need to apply external fixation. In the late 1950s the major AO centers managed a relatively large number of low velocity injuries derived from sport accidents and a small number of victims of high velocity motor vehicular or industrial accidents.

In the last two decades, this picture has changed radically as high velocity injuries with large third-degree tissue destruction accelerated on a worldwide basis. In such cases, stabilization of the comminuted bony fragments was essential to salvage the traumatized soft tissues of the injured limb. With the precarious blood supply of the adjacent soft tissues, extensive surgical dissection to approach the fracture was extremely likely to jeopardize the viability of the traumatized tissues. A recurrent interest followed for the use of external fixation to provide adequate stability and better visualization of an open wound than would be achieved by the use of a suitable plaster cast.

In the past decade with the renaissance of the external fixator, particularly in North America, a comprehensive book on this topic is long overdue. A whole generation of North American surgeons were biased when the use of external fixation was banned by the United States Surgeon General during most of World War II. Unfortunately, the resurgence of interest in external fixation has been complicated by a plethora of new devices and diverse philosophies of managements. This situation has led to confusion for practicing fracture surgeons. With his many contacts throughout the world, his clinical experience coupled with his background in biomechanics, metallurgy and an interest in teaching, Dana Mears is an excellent candidate to author this timely book for anyone who has experienced the dilemma of when and how to use external fixation. Numerous international authorities have contributed their expertise to make this book an essential ingredient of any surgeon's library. Upon study of this volume the experienced surgeon should be well aware of the various ways of treating difficult traumatic and reconstructive problems, while the resident will begin to develop an understanding of external fixation and its potential benefits and liabilities in the care of complex fractures. Unquestionably, this book represents the "state of the art" of external fixation. It is not the author's fault that engineering sophistication in this field has blossomed "excessively" to flood the market place with a plethora of expensive and excessively complicated fixation devices. With present techniques a few mechanical elements provided by several external fixation systems suffice to cope with most of the clinical problems in which external fixation is employed.

In recent years, the concept of rigidity and external fixation has evolved in two different

* AO, Arbeitsgemeinschaft für Osteosynthesefragen; or ASIF (Swiss) Association for the Study of Internal Fixation.

directions. In most cases external fixation serves primarily to neutralize an unstable fracture and it provides the optimal enviroment for the soft tissues to resist infection and to heal. Usually, solid bone healing and normalization of the entire injured limb is optimally achieved by a secondary stabilizing operation when external fixation is replaced by a suitable technique of internal fixation. In such instances it is advisable to insert the transfixing pins remote from the fracture focus even at the cost of some decrease in fracture stabilization. On the other hand, in the presence of a segmental bone defect in which autologous cancellous bone graft is employed to restore lost diaphyseal bone, external fixation provides the optimal method of stabilization. Less rigid external fixation is required to reconstruct a typical diaphyseal fracture than would be needed if one of the presently available techniques of internal fixation were employed. In such a case one of the two transfixing pins applied to either principal bone fragment is inserted close to the fracture and the other is positioned remote from the fracture. About 6 to 12 weeks after presentation the medial or lateral part of the frame is removed. Six to 12 weeks later the remainder of the frame is replaced with a suitable cast or cast brace which is employed until the bone is solidly united. Both of these valuable concepts of external fixation are well documented here.

In the author's discussion of the long-term stability of unilateral and transfixing pins he describes the application of a "preload" whereby the free ends of pins are deformed elastically towards each other. By the use of this simple technique, the degree of stability is greatly increased and the duration of effective fixation is considerably prolonged. If a comminuted tibial shaft is provisionally reconstructed by the use of lag screws, subsequently during the application of an external frame for neutralization of the fracture zone the preloading concept can be favorably employed to further augment stability. Undoubtedly an increase in the number of pins and the application of threaded pins are other ways to increase the "life-span" of stable external fixation. In this book these methods are presented in many well illustrated cases. Both for the present and the future, simplification of external frames by resort to the principle of preloading of transfixing pins and of other comparable methods is a major goal.

Many positive aspects of this monumental documentation deserve mention. Despite the emphasis on external fixation (primarily for application to segmental defects and extensive zonal comminution), Dana Mears repeatedly cites the proper role of internal fixation. External fixation is recommended for application primarily in those situations where the use of internal fixation is contraindicated by the presence of a major soft tissue defect. A principal emphasis of the text is a detailed description of the various techniques of soft tissue reconstruction for use in such cases. The author's statement that adequate internal fixation, combined with any appropriate correction in axial alignment, is a much more reliable treatment of nonunions of all types than cast immobilization, external fixation or electrical stimulation deserves emphasis. The role of antibiotics is well described particularly with reference to the management of cellulitis. Likewise, the primary role of surgical debridement of established infection in bone is highlighted. Any surgeon with an interest in the traumatized locomotor system will feel privileged to possess this extensive documentation. To have an opportunity to review the galley proofs and to introduce this book to my colleagues is an opportunity which I deeply appreciate.

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Preface

This volume is a compendium of the recent techniques developed for the management of high velocity accidents of which the motorcyclist remains the hallmark and a suitable counterpart for a wartime casualty.

On two previous occasions external fixation was temporarily accepted as a suitable method of stabilization for complex fractures with soft tissue loss and marked comminution or loss of bone. On both of the previous occasions external fixation fell into ill repute for several reasons. While the frames then available possessed inadequate rigidity and other weaknesses in design, the salient problem was the dearth of widespread knowledge of a satisfactory method for the application and maintenance of an appropriate external frame. Another serious flaw was the limited general knowledge possessed by many fracture surgeons on the crucial reconstructive procedures that generally are required to salvage the severely traumatized limbs managed by resort to external fixation. In many instances external fixation appeared to be deceptively simple and, perhaps, less technically demanding than the principal alternative methods of stabilization, the use of a cast or of internal fixation. Undoubtedly external fixation is the most complex method of stabilization for its use implies and necessitates a knowledge of a wide array of soft tissue and bony reconstructive procedures including myoplasties, free flaps with microvascular anastomoses and numerous bone grafting techniques. Even if the trauma surgeon does not personally undertake all of these diverse procedures he requires a knowledge of their indications, contraindications and access to a plastic surgeon, who can assist in the management.

In virtually every case where external fixation is applied, ultimately the device is replaced by a cast or a cast brace or by internal fixation. The surgeon, therefore, requires an intimate knowledge of the available techniques of immobilization. Unless future trauma surgeons who employ external fixation possess a knowledge of the diverse array of reconstructive procedures, undoubtedly, once again this method will recede to the periphery of orthopaedics. Given the extraordinary results that presently can be attained, such a retrograde step would be most unfortunate.

In this volume I have attempted to document the basic tenants and the principles of surgical practice of external fixation including the allied techniques of reconstruction and stabilization of the limbs and pelvis. Also, several special applications of external fixation for immobilization of the spine and for the implementation of limb lengthening are reviewed.

In many instances external fixation provides an alternative salvage solution where otherwise, a suitable amputation would be performed. In the latter instance soon after the patient sustains the traumatic insult the patient would undergo prosthetic fitting, gait training and rehabilitation towards an appropriate vocation. Lamentably, in many instances external fixation has encouraged an inordinant prolongation of treatment whereby the patient endures numerous painful hospitalizations, with operative procedures and dressing changes. Unfortunately, after 1 or more years, many of the patients still progress to amputation although the late oblative procedures are accompanied by more deleterious psychological upset as well as the inordinate expense with large medical bills and the prolonged delay from gainful employment. About 5 years ago when we initiated the extensive reconstructions on what is now more than 500 cases, at first we were guilty of the same error. Subsequently my plastic surgeon colleague, Dr. William Swartz, and I decided that we would outline a suitable treatment protocol for each patient from the time of their presentation. This protocol included sequential debridements, stabilization with external fixation, soft tissue restoration and appropriate alterations in stability. The time of one or more bone grafting procedures was included. If a stable united fracture with adequate soft tissue coverage could not be realistically predicted by the end of 1 year from the time of the injury, even in the presence of a sensate functional foot or hand, we recommended an appropriate amputation. Admittedly, especially during our earlier years of experience, some of the treatment periods dragged into the second year, although that is now a rarity. We now believe strongly that a predictable time course according to a rigorously defined treatment protocol is a crucial part of the management of patients who sustain these catastrophic injuries.

In addition to the invaluable assistance of my collaborative authors, I am most grateful for the cooperation of my professional colleagues and members of the orthopaedic staff, not least of all for the referral of many challenging traumatic problems. Several of my orthopaedic residents provided considerable assistance both in the research laboratory, the operating room and on the wards, especially, Drs. Freddie Fu, Patrick Stone, Dirk Nelson and Harry Rubash. Drew Steis served as my personal editor to direct the organization of the entire manuscript and periodically of its author. Sally Greenwood spent many long evenings with a critical eye directed towards proof reading. Dr. Albert B. Ferguson has provided recurrent support, advice and encouragement in a pleasant environment without which this work would have been impossible.

My father, Dr. Robert B. Mears, reviewed all of the earlier stages of the manuscript as well as the proofs and continued his life-long support which transforms tedious labor into a pleasure. Janice Westwood has typed the several revisions of the entire manuscript, amidst numerous other chores, with her meticulous attention to detail and high standard.

If the reader gleans as much from this book as I have observed primarily from my motorcyclist patients and from preparing this manuscript the effort will be handsomely repaid.

DANA C. MEARS, M.D.

PROFESSIONAL MOTORCYCLIST REPAIRS, INC.

(Legs a Speciality)

We also repair motorists who speed,
beat the lights, weave, tailgate,
Cyclists and pedestrians who think that
motorists will avoid them.
Victims of all of the above, and
Drunks of every description.
Every care is taken, but due to the nature
of the material presented,
the results cannot be guaranteed.

(Gratefully presented to me by a sympathetic orthopaedic colleague)

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Contents

CHAPTER 1

Introduction

JACQUES VIDAL

External fixation refers to a technique for the immobilization of osseous fragments by their impalement with metallic transfixing pins that are stabilized in a rigid external frame of metallic or other elements. The first attempt to employ the concept of external fixation for the stabilization of an osseous segment was made in the middle of the 19th century. The need for the technique arose from staunch limitations of the then available techniques of nonoperative immobilization of fractures and by the anticipated poor results of the techniques of internal fixation and allied operative procedures. The history of external fixation is logically divided into three periods which are described in turn. The first pertains to the second half of the 19th century, the second applies to the first half of the 20th century while the third refers to the most recent period.

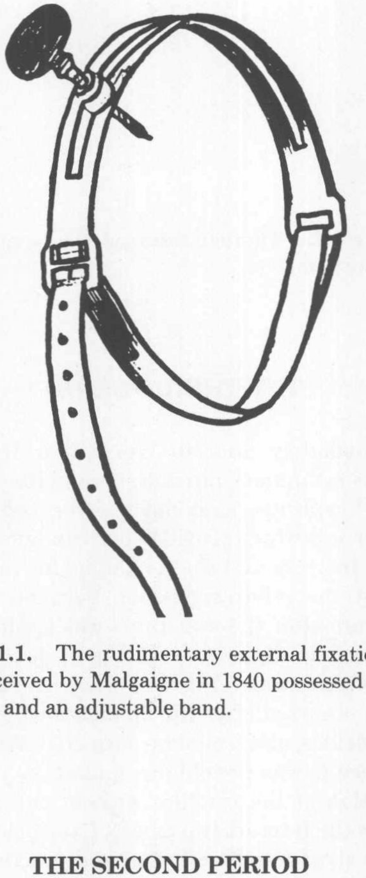

Figure 1.1. The rudimentary external fixation device conceived by Malgaigne in 1840 possessed a metallic pin and an adjustable band.

THE FIRST PERIOD

In 1840, Jean Francois Malgaigne[1] provided the first initiative for the development of external fixation. He prepared a rudimentary device for the immobilization of a fracture of the lower extremity. The apparatus consisted of a simple metallic pin that was inserted into the displaced osseous fragment and attached to a metallic band. The latter was adjusted by the use of a belt (Fig. 1.1). From this initial concept numerous modifications have been introduced primarily in an effort to improve both the clamps, which secure the skeletal fixation pins, and the longitudinal elements of the frame. While the equipment was too rudimentary to be efficient, nevertheless, the concept of external fixation had arisen.

THE SECOND PERIOD

In 1902, Albin Lambotte,[2] in Belgium, first employed percutaneous half pins attached to a rigid bar (Fig. 1.2). His advice provided the first successful external fixation device from which numerous subsequent models have evolved. It provided satisfactory immobilization of a fracture although it could be applied only after the fracture had been reduced. It did not permit alteration of the reduction unless the device was removed.

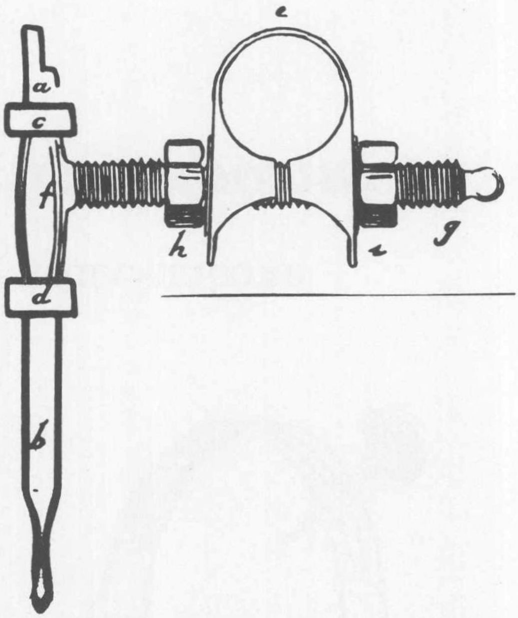

Figure 1.2. The initial external fixation concept devised by Lambotte.

THE THIRD PERIOD

Immediately prior to World War II, Roger Anderson,[3] in the United States and Raoul Hoffmann,[4] in Switzerland, developed external fixation devices which provided both immobilization of the fracture and the technique for modification of the relative position between various segments after the apparatus was applied. Adjustments in alignment could be made to correct a malreduction. Alternatively, displacement which occurred after the application of the fixation device, also, could be corrected. With such a device it was possible to undertake a closed reduction of the fracture without the need to expose the fracture fragments. External fixation had evolved into an efficient and practical clinical technique.

Subsequent improvements in external fixation have focused upon attempts to improve the tolerance of the body to the prolonged presence of the apparatus, the stability of the external frame to the degree that previously was realized by techniques of internal fixation, and the ease of application of the equipment and of the subsequent precise manipulation of the osseous fragments. The improvements are discussed in terms of the transfixing pins or bolts and the external frame that connects the several pins.

OSSEOUS TRANSFIXING PINS AND BOLTS

In 1840, Malgaigne[1] perceived of a "nail" that would bear upon the cortical surface of an osseous fragment with minimal impalement of the fragment. Secondary displacement of the fragment was inhibited by the attachment of the nails within a rigid external frame. In 1843, Malgaigne[1] applied an external fixation device to a patella with a transverse fracture (Fig. 1.3). A double system of clamps provided a way to undertake a suitable closed reduction and effective immobilization of the fracture.

In an effort to improve the fixation within the osseous fragment, Ragiud of Strasbourg,[5] first employed wood screws that impaled the cortical surface. In 1898, Clayton Parkhill[6] in Denver, CO., used threaded bolts in a similar way. In 1907, Lambotte[2] proposed the use of threaded rods from which all of the subsequent types of fixation pins or osseous transfixing pins are derived. While the first pins were made of iron, subsequently, they were manufactured of plain carbon steel. In his second model that employed transfixing pins, Lambotte[2] modified the insertional end of the pin to provide the first self-tapping configuration. In 1916 Juvara[7] of Bucarest, described the use of several different types of pins each of which was intended for use in a particular bone. He devised a guide which facilitated the orientation of a pin during its insertion. In 1931, Boever[8] used a rod which ascertained the appropriate depth of insertion of a pin within a bone. This worker was the first to employ pins manufactured of stainless steel which greatly improved their corrosion resistance and tissue tolerance. Henri Judet[9] further modified the external fixation device devised by Boever.[8] Judet[9] was the first surgeon to employ transfixing pins that penetrated both osseous cortices. The design by Henri Judet[9] was further improved by Robert and Jean Judet.[10] With the more recent embodiments, the need for a separate insertional guide to ensure the orientation of the fixation pins is obviated by the use of the external fixation device itself as a guide during the insertion of the pins. Henri Judet[9] was probably the first worker to insist upon the need for a wide releasing incision at each pin site as a method to limit the liability to pin track infection. The modifications provided by Boever[8] and the Judets[9, 10] greatly improved the tolerance of the body to the presence of an external fixation device and decreased the numbers of clinical failures associated with the method.

In 1905, Codivilla,[11] and subsequently in 1912, Steinmann,[12] described the use of transcalcaneal pins for the application of skeletal traction to displaced fractures in the lower extremity. In 1910, Lambret[13] inserted transfixing pins into each of the fracture fragments so that traction could be applied on either side of the fracture. In 1921, Putti,[14] and subsequently in 1939, Abbott and Saunders[15] modified this principle to produce the elongation of a limb after undertaking an osteotomy. The distraction was realized by traction applied to a transfixing pin inserted into each fracture fragment. In 1974, Bonnel[16] developed threaded transfixing pins in which the thread was limited to a central region of the pin which came in contact with cortical bone.

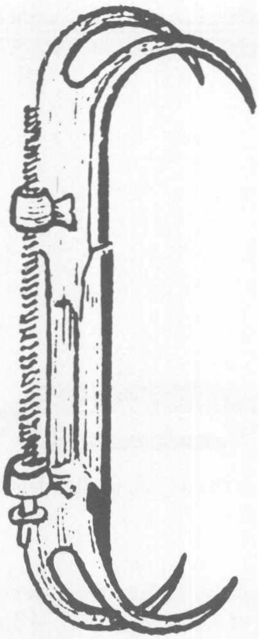

Figure 1.3. The patellar clamp of Malgaigne is shown.

EVOLUTION OF THE EXTERNAL FRAME

The initial types of external fixation devices connected the transfixing pins in various osseous fragments but provided a precarious stability. This is clearly evident in the metallic band developed by Malgaigne[1] (Fig. 1.1). Admittedly, the band also facilitated the orientation of the transfixing nail. Subsequently Roux, and Ollier,[17] improved the anchorage of the transfixing nail to the external frame. The former employed an external wooden splint while the latter used a somewhat more sophisticated type of splint. In 1870, Rigaud[5] connected the adjacent transfixing bolts inserted into olecranon fracture fragments by the use of a simple wire. Subsequently, Rigaud[5] used colodion polymeric ribbons or plaster casts to anchor the transfixing bolts, in what might be described as an early example of the use of "pins and plaster." This concept was the precursor of the connection of transfixing pins by the use of a polymeric material. Some Japanese workers have reported the use of polymethylmethacrylate cement. Alternatively, Murray[19] of Harrisburg, PA, has devised cylindrical reservoirs filled with acrylic cement.

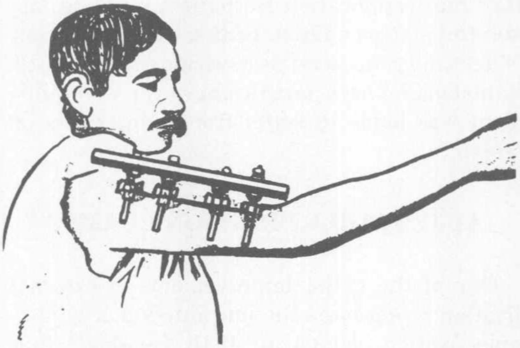

Figure 1.4. An early adjustable frame, designed by Lambotte permits postoperative adjustment in distraction and compression.

ADJUSTABLE EXTERNAL FRAMES

From 1853, with the patellar fixation concept of Malgaigne[1] (Fig. 1.3), attempts have been made to provide an adjustable linkage between various fixation pins. Lambotte,[2] in his device of 1907, employed a metallic tube (Fig. 1.4). Numerous subsequent workers modified and lengthened the tubular elements. All of these designs, derived from the Lambotte[2] model, required an initial reduction of the fracture prior to the application of the external frame. Nevertheless, Lambotte had recognized a possible method by which compression or distraction could be imposed upon a fracture site after the application of the device. Numerous other workers have implemented such improvements. The device by Parkhill[6] permitted some mobility during its assembly, at least within the plane of the fixation. In 1917, Chalier devised an adjustable clamp comprised of two sliding plates. Each plate possessed numerous drill holes so that the

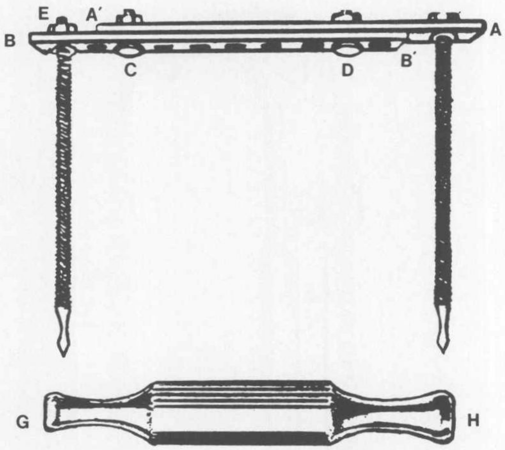

Figure 1.5. The adjustable fixation device of Chalier is seen.

two plates could be secured in several positions by the use of bolts (Fig. 1.5). Adjustment was possible in one plane. In 1929, Ombredane[20] modified the design by Chalier so that it could be used in children. The last design was fabricated of mild steel which could be deformed at the time of application. Both the transfixing pins and the plates could be bent so that correction of deformity was possible in various planes. With its malleable characteristics, however, the equipment was liable to suffer from a later loss of stability.

ADJUSTABLE FIXATION CLAMPS

One of the major improvements in external fixation represented the introduction of adjustable fixation clamps. In 1931, Goosens[21] first reported such an adjustable clamp to connect the transfixing pins to a longitudinal external frame (Fig. 1.6). After the application of the device, and prior to the tightening of the mobile elements, the reduction of the osseous fragments could be altered. In 1933, Joly[22] described another type of adjustable clamp (Fig. 1.7). A solid bar was attached to each osseous fragment and an adjustable clamp could be used to secure the two bars. Each of the previous types of adjustable clamps facilitated the initial application of the external fixation device after the fracture had been reduced. The systems were not really designed for careful adjustments in reduction after their applications. Another major improvement represented the introduction of adjustable clamps that permitted precise alteration of the

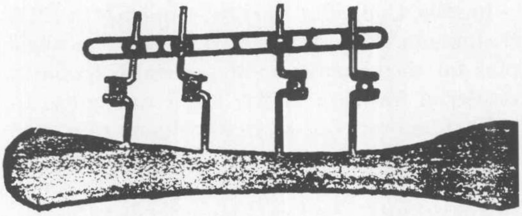

Figure 1.6. The external fixation device of Goosens possessed adjustable fixation clamps.

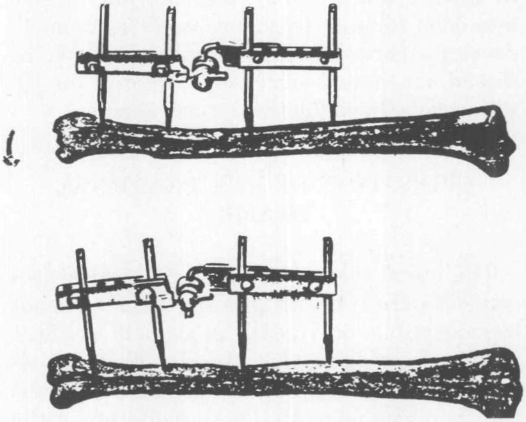

Figure 1.7. An adjustable fixation clamp devised by Joly is revealed.

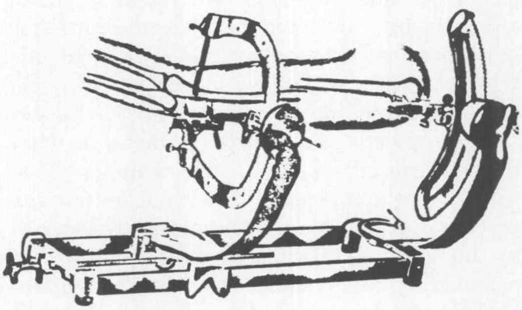

Figure 1.8. The adjustable clamp improvised by Anderson permitted precise alteration of the alignment of the fracture.

alignment of the fracture after the frame had been applied. In 1934, Anderson[3] provided the first suitable example (Fig. 1.8). In his embodiment, the external frame possessed two adjustable elements that could be oriented in several planes. Each adjustable element was attached to a principal fracture fragment by the use of transfixing pins. In his earliest designs, a plaster cast was used to augment the stability of the

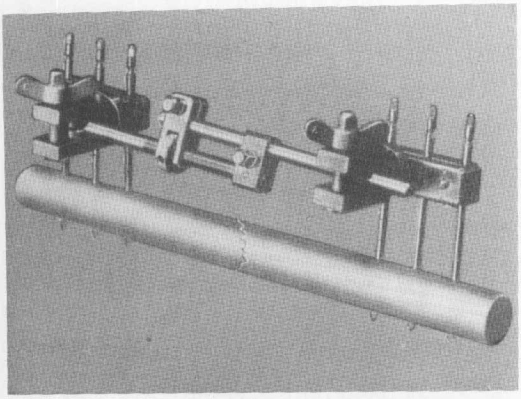

Figure 1.9. The original unilateral type of fixation device devised by Hoffmann is seen.

frame. In 1937, Otter Stader[23] modified the Anderson[3] device and applied it to experimental dogs and to humans. A longitudinal member possessed a worm screw for alteration of the interfragmentary spacing. In his design an ancillary plaster cast was unnecessary.

CLAMPS FOR MULTIPLE PINS

Another major improvement was the development of clamps which could secure several transfixing pins inserted into a single osseous fragment. With this feature, considerable control over the manipulation of a fracture fragment could be realized. In 1938, Hoffmann,[4] surgeon, Doctor of Theology and master carpenter, designed the equipment which bears his name. It provided a suitable clamp now known as a ball joint rod, to hold multiple pins (Fig. 1.9). The clamp permits the displacement of a fracture fragment in three spacial planes. With his apparatus a closed reduction, or osteotaxis, could be undertaken after the external fixation device had been applied to a displaced fracture. Subsequent corrections in angular or rotational alignment, interfragmentary compression and distraction of the fragments all were possible. Hoffmann inserted two insulating plates into each of the pin holders which prevents the creation of an electrical couple between the various pins or between the frame and the pins.

ATTEMPTS TO IMPROVE THE STABILITY OF THE EXTERNAL FIXATION DEVICE

Since the work of Anderson[3] and Hoffmann,[4] many surgeons have attempted to improve the stability of the external fixation device so that it would rival that degree of rigid fixation achieved by the use of internal fixation. Their interest in rigid fixation arose from the biological experiments performed by Schenk and Willenegger,[24] and Rittmann and Perren[25] who investigated the pathophysiology of fracture repair. Previous workers had documented the conventional mechanism of fracture healing that occurs in the presence of skeletal traction or cast immobilization. In these instances, under the auspices of the small amount of motion at the fracture site, an external ring of callus provided an early biological splint. Subsequently, a prolonged period of remodeling occurred which culminated in the dismantling of the peripheral callus and the restoration of a tubular bone of anatomical configuration. In 1949, Danis[26] of Belgium and subsequently Schenk and Willenegger[24] in Switzerland documented another type of fracture repair that accompanies rigid internal fixation such as is seen with the use of a lag screw or of a tension band (*e.g.* a so-called compression) plate. At the sites of close apposition of adjacent fracture fragments, osteoclasts penetrate directly across the fracture site. Capillaries invade these cylindrical channels which are subsequently invaded by osteoblasts. Cylinders of new bone are deposited across the fracture site to provide a biological type of weld. The latter mechanism of so-called primary bone healing must accompany the use of lag screws and onlay plates or the degree of cyclic deformation of the fracture site that otherwise occurs almost inevitably leads to a fatigue failure of the fixation device prior to the time when union of the fracture ensues. In the presence of an infected fracture or osteotomy, primary bone healing provides the optimal condition where the minimal amount of sequestered and infected bone is formed. From these and other observations, undertaken on healing soft tissues, it is evident that rigid fixation provides the optimal mechanical environment for the healing of infected fractures and those injuries accompanied by extensive soft tissue disruption. These observations stimulated interest in the development of techniques that would optimize the immobilization of the fracture surfaces and the rigidity of the external frame itself. The rigidity of the fracture is greatly increased by the application of interfragmentary compression. From 1956, Robert and Jean Judet[10] employed elastic elements around the transfixing pins (Fig. 1.10), that provided compression across the fracture site. Many other workers evolved various techniques to improve the rigid-