RESEARCH

Surgical Treatment of Non-septic Non-unions of the Humeral Shaft. A Biomechanical Study

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Objetivos. Comparar la rigidez y la distribución de tensiones en los implantes de dos modelos experimentales: un húmero con pseudoartrosis diafisaria estabilizado con placa y un húmero con pseudoartrosis diafisaria estabilizado con clavo encerrojado.
Material y método. Con un húmero de cadáver y los dos dispositivos de fijación se crearon las geometrías con el programa de diseño CATIA v4.2® (IBM, Armonk, USA). Posteriormente estas geometrías se modelaron con el preprocesador informático MSC-PATRAN® (IBM, Armonk, USA). Finalmente se establecieron las propiedades mecánicas de los materiales, las condiciones de contorno y las cargas a las que fueron sometidos los modelos.
Resultados. El modelo con clavo fue más rígido que el modelo con placa a compresión, tracción y torsión, sin embargo, el modelo con placa fue más rígido que el modelo con clavo en flexión anteroposterior, lateromedial y cizallamiento lateromedial. La distribución de tensiones ha sido más heterogénea en el clavo que en la placa, siendo esta última el implante que soporta los mayores valores tensionales en todos los estados de carga estudiados.
Conclusiones. La rigidez del modelo experimental depende no solo del implante sino del estado de carga aplicado, siendo superior el clavo en unas condiciones de carga y la placa en otras. El clavo sin embargo, absorbe menos tensión que la placa en todos los estados de carga estudiados.

Palabras clave: *pseudoartrosis, biomecánico, húmero, método de elementos finitos.*

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Purpose. To compare the firmess and stress distribution patterns in the implants of two experimental models: a humerus with shaft pseudoarthrosis stabilized with a plate, and a humerus with shaft nonunions stabilized with a locking nail.
Materials and methods. The two fixation devices are attached to cadaver humerus bones; geometries are created with the CATIA 4.2 design software (IBM, Armonk, USA). Subsequently, these geometries were modelled with the MSC PATRAN® computer processor (IBM, Armonk, USA). Finally, the mechanical properties of the materials were established as well as the contour properties and the loads the models were subjected to.
Results. The nailed model was firmer that the plated model as regards compression, traction and torsion. Nonetheless, as far as A/P and lateral-medial flexion and lateral-medial shear stresses were concerned, the plated model was firmer than the nailed model. Stress distribution was more heterogeneous in the nail than in the plate, the latter being the implant type supporting the highest stress levels in all the loading phases studied.
Conclusions. For some stress levels, the nail proved to be more stable than the plate, although for other stress levels the opposite was the case. In any case, the nail provides a better stress distribution than the plate.

Key words: *pseudoarthrosis, biomechanical, humerus, finite-element analysis.*

In trauma and orthopedic surgery one of the main advantages of using simulation with finite elements[1] is that it is possible to determine the biomechanical behavior of implanted material without having to resort to synthetic experimental models or cadavers. Humeral shaft non-union is a condition with high morbidity and there is no universally accepted protocol for its treatment. The most commonly

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used synthesis methods are locking nails and compression plates, both of which are widely accepted and each of which has advantages and disadvantages. We propose a comparative finite-element analysis of two models of humeral diaphysis non-union, one treated with a locking UHN® nail (Synthes, Paoli, USA) and another treated with a compression DCP® plate (Synthes, Paoli, USA). The aim of this study is to compare biomechanical properties of the compression plate and locking nail in the treatment of humeral shaft non-union and determine which of the two implants responds best to the mechanical demands of a healing humerus.

MATERIALS AND METHODS

The biomechanical study was carried out using a calculation program and simulation with finite elements. Using a humerus from a cadaver and the two fixation devices, the geometric parameters and grids were generated, as is explained below.

Creation of Geometric Parameters

Humerus

The geometric parameters of the tri-dimensional humerus were obtained by means of projections taken from X-rays and CAT scans of a humerus from a cadaver. Series of 3 mm sections of a longitudinal (OZ axis) CAT scan of the humerus made it possible to view cortical and cancellous bone in each section. Subsequently all the CT were scanned to digitalize the hard copy of the humerus. A digital format made it possible to work with a CAD program Corel Trace-Corel Draw v10® (Microsoft, Washington, USA) that extracted the curves of the cortical and cancellous parts of the humerus. Finally the design program CATIA v4.2® (IBM, Armonk, USA) imported these curves to the corresponding planes, closing the resultant solid volume, that is to say a tri-dimensional humerus (Figure. 1). From that moment on a grid could be made.

Fixations

The geometric parameters were obtained with the program CATIA v4.2® (IBM, Armonk, USA) in the same way as with the humerus from real physical models of fixation. The plate model used is a LC-DCP® (Synthes, Paoli, USA) of 4.5 mm in thickness and with 7 holes. The endomedullary nail used as a model was a UHN® (Synthes, Paoli, SA) of 6.7 mm in diameter an 240 mm in length, with proximal and distal locking. Both fixation devices were made of titanium and were contributed by Synthes® (Paoli, USA). The screws were computer designed during pre-processing with finite elements.

Figure 1. *Final tri-dimensional view of the humerus and thickness of the cortical bone of the diaphysis. Performed with CATIA v4.2® (IBM, Armonk, USA).*

Figure 2. *Tri-dimensional view of nailing performed with CATIA v4.2® (IBM, Armonk, USA).*

Humerus-Fixations Unit

Using the CATIA v4.2® (IBM, Armonk, USA) program the humerus was joined to the fixation devices. A simulation was performed of a laterally fixated plate with 6 cortical anchorages on each side of the focus of the non-union. The nailing was modeled with anterograde introduction and locking with one proximal and two distal screws (Figure 2).

Creation of models based on finite elements and grids

In this phase the geometric model was adapted to the calculations to perform. To do this a grid was made with the geometric parameters and the mechanical properties of

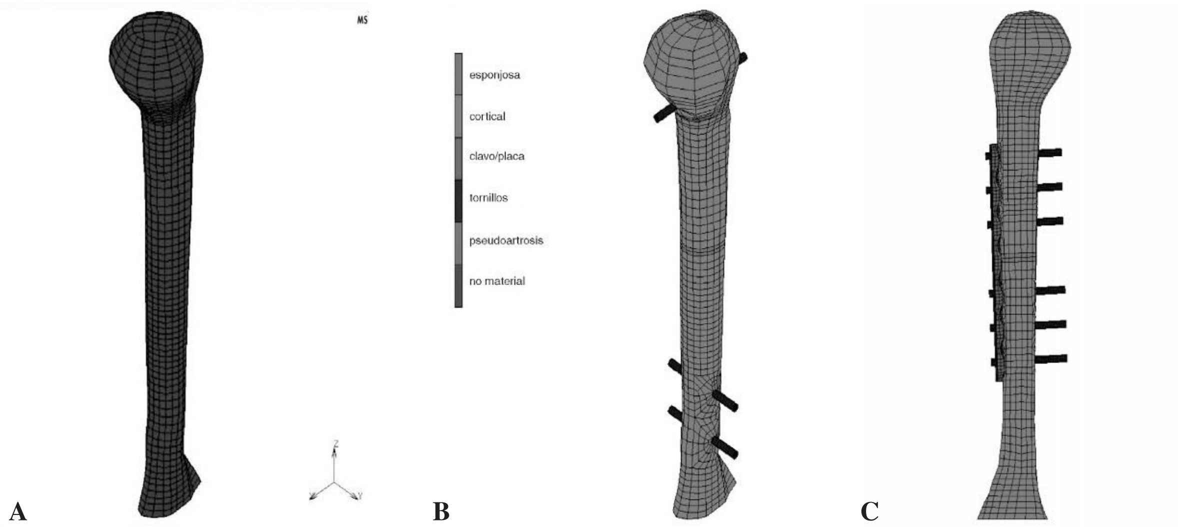

Figure 3. *Grid models of a healthy humerus (A), humerus with nailing (B) and humerus with plate (C). Performed using MSC-PATRAN® (IBM, Armonk, USA).*

the study material were established, as also the forces that would be applied to the models. This was all done with a MSC-PATRAN® (IBM, Armonk, USA). During the first step all the geometric parameters were imported from the program CATIA v4.2® (IBM, Armonk, USA) except those of the screws and the area surrounding the non-union, that were generated by the computer itself. A tri-dimensional grid was made in which the elements (minimum grid unit) were 8 node hexahedrons and the size varied according to the geometric parameters. A minimum of 2 elements were established in the thickness of the cortex and also in the fixations (Figure 3). The mechanical properties of the materials that interacted in the simulation and also those of the non-unions can be seen in Tables 1 and 2. The simulated material in the fixations and the screws were made of a titanium alloy Ti-6Al-4Va. The non-union was simulated as a mid-diaphysis area of 4.5 mm in length with mechanical properties similar to those of fibrous tissue. As far as contact conditions, three contact points were established: humerus, fixations and screws that were joined by a *blue* type of contact. Finally, the calculation parameters used to solve different problems in different cases varied according to contact conditions. In the humerus without fixation, and therefore, with no type of contact, calculations were static. However, in the humerus with non-union and fixations, where there were contact points, the calculations were non-linear static. The integration method used was Newton-Rapson and the condition of large deformities, elastic rebound and deformation forces was activated.

For the biomechanical behavior study of the healthy humerus fixated with a plate or nail over a non-union most of the weight-bearing states were simulated that a real humeral shaft with a non-union would have to undergo under real conditions. Six weight-bearing situations were simulated: compression, traction, anteroposterior flexion, lateromedial flexion, torsion and lateromedial shearing. Two parameters were studied: the rigidity of the whole

Table 1. Mechanical properties of the humerus and the implants

	Cortical bone	Cancellous bone	Pseudoarthrosis	Implants	Screws
E (MPa)	7,500	1,000	1	110,000	120,000
V	0.3	0.3	0.45	0.33	0.33

E: Young's module. v: Poisson's ratio.

Table 2: Rigidity of the 3 models undergoing 6 different weight-bearing situations

	Healthy humerus	Pseudoarthrosis with a plate	Pseudoarthrosis with a nail
Compression (N/mm)	5.115.3	789.7	3,002,8
Traction (N/mm)	5.462.5	1,559.9	6,576.7
Anteroposterior flexion (N/mm)	29.1	11.6	4.9
Lateromedial flexion (N/mm)	20.8	5.8	5.0
Torsion (N/mm)	16.9	2.7	4.7
Lateromedial shearing (N/mm)	7.621,4	1.117,3	173.5

Weight-bearing and surrounding conditions

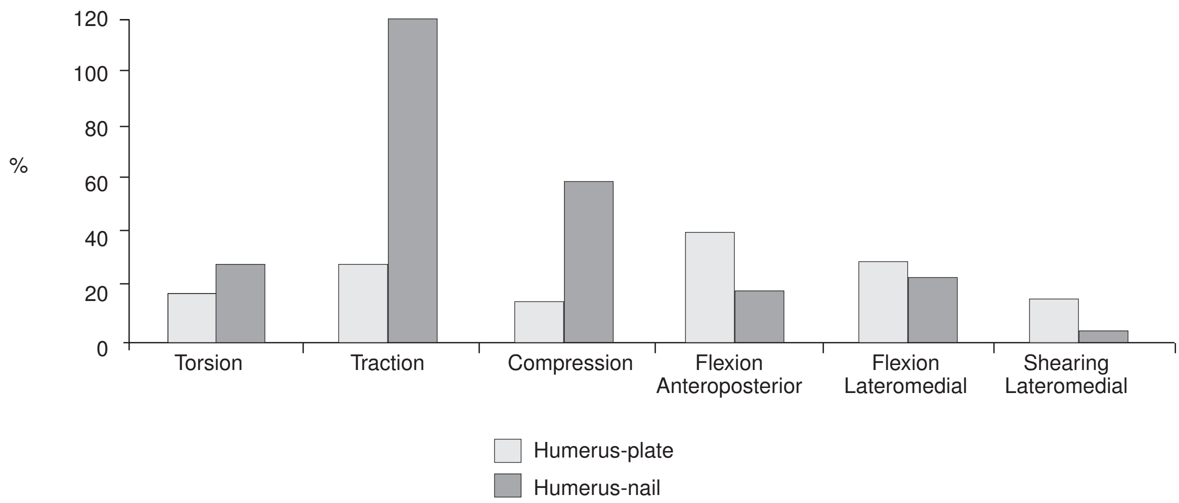

Figure 4. *Percentage, compared to the healthy humerus, of rigidity of the models with an implant.*

unit and implant tension distribution during weight-bearing.

RESULTS

Rigidity

The relationship between the weight-bearing applied and the displacement of the focus was studied in three models: healthy humerus, established non-union with a nail, established non-union with a plate. As can be seen in Table 2, the model with a plate was more rigid than the model with a nail under flexion and shearing forces, whereas the model with a nail was more rigid than the model with a plate under traction, compression and torsion forces. Figure 4 shows a comparison of the rigidity between both implant models in all the weight-bearing situations studied.

Distribution of forces on implants

The Von Mises distribution of forces on implants varied according to the type of implant used and prevailing weight-bearing conditions. In the case of the plate, forces were distributed in a concentrated fashion around the holes of the screws near the area of the non-union. However, the nail distributed the forces in a heterogeneous manner all along the implant. Under the same conditions, plate weight-bearing has always given the highest values for forces, as can be seen in Table 3. In Figure 5 it is possible to see the distribution of forces in the implants when they undergo torsion.

Table 3. Maximum stress (MPa) on the implants during different weight-bearing situations

	Plate	Nail
Compression	182	54
Traction	250	23
Anteroposterior flexion	86	86
Lateral flexion	132	75
Torsion	106	75
Lateromedial shearing	808	185

MPa: Megapascals

DISCUSSION

In the orthopedic literature there are no previous studies comparing compression plates and locking nails in humeral non-union using the finite elements method. However, there are biomechanical studies with experimental models in which different implants used to stabilize osteotomized humerus are compared[3-8]. Amongst the studies that do not include plates, but only compare different types of nails, the studies of Dalton et al[4], Schopfer et al[6] and Blum et al[7,8] can be highlighted. Reviewing these studies chronologically it is possible to see the technical improvements of endomedullary devices over time and how these have progressively increased the rigidity of the implants.

The flexible nail, frequently used in the 1980s, provided poor stabilization on all planes, and they tended to be accompanied by external stabilization for some weeks. In 1989 Seidel[9] presented his endomedullary nail for anterograde insertion. It had an umbrella shaped distal locking device that was very criticized for its doubtful efficacy in pro-

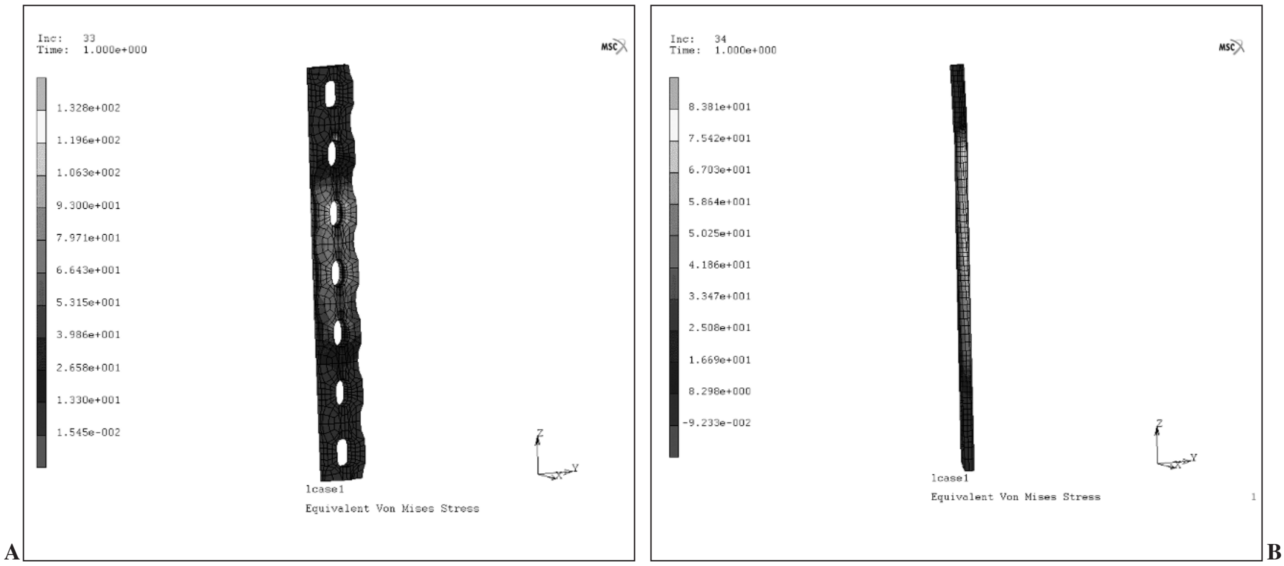

Figure 5. *View of weight-bearing distribution during torsion. Tension is indicated in megapascals.*

viding rotational stability. The Russell-Taylor® (Smith & Nephew, Memphis, TN, USA) nail, initially introduced in the lower extremity, was an improvement on its predecessor since a screw was used as a distal locking device on a different plane from the proximal one, increasing stability to torsion. Subsequently double locking nails, with proximal and distal locks, appeared (ACE®, DePuy, Johnson & Johnson, New Jersey, USA), (Uniflex®, Biomet Orthopedics, Indiana, USA), etc., that increased resistance to torsion even more and finally the UHN® nail (Synthes, Paoli, USA) that as well as offering many blocking possibilities on different planes, incorporated a compression of the focus device that improves rotational stability in comparison with previous nailing devices. The studies comparing plates and nails are scarce and contradictory. Henley et al[5] studied the rigidity of 5 types of synthesis with an osteotomized humerus from a cadaver that underwent 2 different weight-bearing situations: torsion, anteroposterior flexion and lateromedial flexion. The implants compared were: Seidel® nail, Russell® nail, Hackethal nailing, Ender nailing and an AO® plate. The rigidity of healthy non-osteotomized bone was also studied. The results of these studies showed that greater rigidity was seen with the Russell® nail compared to a plate during anteroposterior and lateromedial flexion, whereas the rigidity of the plate model was greater than that of the nail model during torsion. Exactly the opposite of what was seen in this study. Zimmerman et al[3] compared 4 synthesis for humerus stabilization: AO® plate with triple screws on either side of the focus, a Seidel® nail, a solid nail with proximal and distal double locking on the same plane, and double Ender locking. These were compared with lateromedial flexion, anteroposterior flexion and torsion weight-bearing forces. During lateromedial and anteroposterior flexion the plate was significantly more rigid than any other type of nail model, whereas with torsion the double locking nail was the most rigid structure. These results do coincide with the ones seen by our group. The finite elements method has not been used previously, therefore, we cannot compare this study with others, however, conceptual coincidences (Zimmerman et al[3]) and numeric ones (Blum et al[7,8]) with previous studies performed with mechanical assays make this method a valid tool for future use. Modeling with finite elements allows the distribution of forces on the implant, which is impossible in mechanical assays. This possibility allows how intense forces are and on what areas of the implant they are applied under different weight-bearing conditions, this makes it possible to predict implant failure under excessive weight-bearing.

This study allows us to conclude that UHN® nails are superior to AO® plates for stabilizing humeral diaphysis non-unions when undergoing compression, traction and torsion and that AO® plates are superior to UHN® nails for stabilizing humeral diaphysis non-unions when undergoing anteroposterior and lateromedial flexion and lateromedial shearing. On the other hand, from the point of view of the distribution of forces on the implant, distributions were more heterogeneous with nails than plates under any weight-weight-bearing conditions, and the value of forces is lower. The biomechanical behavior of implants is one of the many variables that form part of the healing process after treatment of a non-union. It is necessary to study all the involved variables that affect treated non-union healing (type of non-union, type of implant, graft contribution, rasping of focus, etc.) to conclude precisely which is the best treatment for non-septic humeral diaphysis non-union.

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Conflict of interests: We, the authors, have not received any economic support to carry out this study. Nor have we signed any agreement with any commercial firm to receive benefits or fees. On the other hand, no commercial firm has provided nor will provide economic support to non-profit foundations, educational institutions or any of the other non-profit organizations that we are members of..