Lengthening of the Humerus Using a Motorized Lengthening Nail: A Retrospective Comparative Series

Stewart G. Morrison, MBBS,† Andrew G. Georgiadis, MD,*† and Mark T. Dahl, MD*†*

Background: Lengthening of the humerus has traditionally been accomplished by the use of external fixation. Intramedullary motorized lengthening nails are now frequently used for lower limb lengthening, and this technology is slowly being adopted for use in the humerus.

Methods: A retrospective, single-surgeon experience of pediatric humeral lengthenings was performed. The time period surveyed included use of external fixation (EF) for lengthening, and the use of a motorized nail (MN) for lengthening. The primary outcome measures were lengthening magnitude achieved, duration of lengthening, frequency and type of complications encountered, or further procedures required, during each lengthening.

Results: From 1999 to 2018, 13 humeral lengthenings were performed in 9 patients. Six lengthenings were performed using the MN technique and 7 using the EF technique. The average absolute lengthening achieved was 8.5 ± 1.3 cm in the EF group and 6.6 ± 2.3 cm in the MN group. The duration of lengthening averaged 114 days in the MN group and 103 days in the EF group. The average duration of EF time was 215 days. Two patients underwent an initial EF lengthening of a humerus and then underwent a second lengthening using the MN technique. Two of 6 (33%) MN lengthenings and 3 of 7 (43%) EF lengthenings experienced complications during treatment. Two patients in the MN group underwent planned reversal and redeployment of their motorized nails to attain the planned lengthening magnitude.

Conclusions: Humeral lengthening using motorized intramedullary nails is a safe technique that mitigates some of the complications of EF including pin site infection. It is well tolerated by patients. For lengthenings of a large magnitude, reversal and reuse of MN can be considered.

Key Words: limb lengthening, distraction osteogenesis, physeal arrest, achondroplasia, humerus

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From the *Department of Orthopaedic Surgery, University of Minnesota, Minneapolis; and †Department of Orthopaedic Surgery, Gillette Children's Specialty Healthcare, St Paul, MN.

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Reprints: Stewart G. Morrison, MBBS, Department of Orthopaedics, Gillette Children's Specialty Healthcare, 200 University Avenue East, St Paul, MN 55101. E-mail: stewartgmorrison@gillettechildrens.com.

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Humeral lengthening by distraction osteogenesis is well described in the orthopaedic literature. Upper limb length discrepancy from humeral shortening maybe because of congenital conditions including achondroplasia, Ollier's disease, and brachial plexus palsy, or acquired conditions secondary to physeal arrest, postinfectious or post-traumatic deformity, or tumor.[1] Historically, relative shortening of 5 cm was considered the lower limit of the indicated range for humeral lengthening. Recent evidence suggests that even smaller discrepancies may interfere with high demand activities, for example, musical instrument use and sport.[2]

Similar to the lower limb, proposed methods of achieving humeral length have included acute or gradual lengthening with external fixators. The first recorded case of gradual humeral lengthening was reported in 1978 using a Wagner-type external fixator.[3] Since then, a number of authors have reported a series of patients undergoing humeral lengthening using circular[4–8] or monolateral "rail" type fixators.[2,9–15]

The introduction of fully motorized intramedullary lengthening nails has prompted a paradigm shift in lower limb lengthening. This technology initially included ratchet-based devices such as the Intramedullary Skeletal Kinetic Distractor (Orthofix, Valley, Germany), which use skeletal rotation for lengthening. Rate control of these devices proved unpredictable in the lower limb because of inconsistent lengthening by patient motion, mechanical impingement, and physical pain. More recently, the FITBONE (Wittenstein Intens GmBH, Igersheim, Germany) and the PRECICE (Nuvasive, San Diego, CA) intramedullary MNs have been used extensively for lower limb lengthening and now hold promise for use in the upper limb. Both implants are activated by an external signal (radiofrequency and magnetic, respectively).

There are 3 reports on the use of motorized intramedullary nails for humeral lengthening. Kurtz et al[16] and Hoel et al[17] presented separate case reports, and Fürmetz et al[18] have reported on a series of 4 patients. None of these studies compared motorized internal humeral lengthening to external fixator humeral lengthening. The objectives of our study were to compare humeral lengthening through the 2 separate techniques: external fixation (EF), and intramedullary motorized nails (MN). The senior author utilized EF from 1985 to 2014 and thereafter used MN for humeral lengthening. Using EF as a historical comparison, lengthening parameters, radiographic

results, technical considerations, and complications will be compared between techniques.

METHODS

This was an IRB-approved retrospective comparative series of all consecutive patients who underwent humeral lengthening between 1999 and 2018 by the senior author at a single institution. Baseline demographic data collected included patient age, sex, and etiology of shortening. Data included method of lengthening (EF vs. MN), number of previous surgeries, latency period, initial humeral length, lengthening achieved, number of days of lengthening, additional procedures performed, hospital length of stay, and complications encountered. Patients with <6 months follow-up from index lengthening were excluded from the analysis. Data pertaining to range of motion (apart from those patients with reported contractures) and data pertaining to pain and narcotic usage were not consistently recorded and hence not included in the study.

The senior author's preference is to adjust lengthening rate and rhythm at weekly outpatient visits on the basis of clinical (eg, joint motion, pain, and pin site inflammation) and radiographic (quality of regenerate formation) parameters. The lengthening rate was averaged over the entire distraction period for the purposes of study data. Complications were recorded and graded using the Clavien-Dindo classification.[19]

Surgical Technique

Preoperative templating identified the location and magnitude of any angular deformity. EF was performed using 1 of 3 devices on the basis of industry advancements and surgeon experience: a circular external fixator (CEF-Ilizarov, or Taylor Spatial Frame, Smith and Nephew, Memphis, TN), monolateral rail fixator (MRF-Orthofix, Lewisville, TX), or monolateral multiplanar (MM EBI – MAC, Zimmer Biomet, Warsaw, IN). All external fixators were removed under general anesthetic in the operating room at the conclusion of treatment.

Motorized intramedullary lengthening was performed using the PRECICE nail (NuVasive Specialized Orthopedics, San Diego, CA). Informed consent was obtained for "off-label" use of the device. Preoperative computer tomography scans were obtained to allow for planning of any concurrent complex deformity correction, and to appreciate better the anatomy of the distal humerus to accurately plan nail implantation. It is of critical importance for the surgeon considering this technique to appreciate the decreased sagittal plane diameter of the distal humeral canal. Failure to do so may result in fracture or inability to implant the planned device. Particular attention during templating was paid to the insertion site to determine whether a straight nail, or one with a Herzog bend (ie, a femoral or tibial nail), would best be accommodated by the patient's anatomy.

Retrograde nail insertion was performed with prone positioning and a triceps splitting approach, after identification of the radial nerve by palpation and nerve stimulation (Fig. 1). No prophylactic radial nerve decompressions were performed. Corticotomy was performed using a new 4.0-mm drill bit. The humerus was vented with multiple drill holes at the corticotomy site to diminish canal pressure while reaming. Canal entry was performed with a burr under irrigation through an elliptical window 15 mm proximal to the olecranon fossa. The canal was reamed in half-millimeter increments to 10.5 mm (an 8.5-mm diameter nail was used in all cases). Four nails were shortened at either or both ends, as the patient's humeral length was too short for the available nail inventory at that time. Nail modification was performed by the use of a Midas Rex radial wheel, with attention to thermal and swarf management.

FIGURE 1. Clinical photograph of a patient after undergoing right humeral lengthening through retrograde motorized nail technique (patient 4).

Soft tissues were protected with 2 narrow pointed Homan retractors, and an osteotome was introduced to cut the bone after advancing the nail to the corticotomy site. Gentle rotation of the osteotome within the humerus completed the corticotomy. The nail was then advanced beyond the corticotomy, and gentle stress fluoroscopy confirmed corticotomy completion. Locking screws are inserted by a "perfect circles" technique. A postlengthening clinical photograph demonstrating the midline posterior scar for retrograde nail insertion is depicted in Figure 2.

Antegrade insertion was performed by first identifying the corticotomy location unique to each individual, which was then accessed using an anterolateral, muscle splitting, subperiosteal exposure (Fig. 3). The humerus was entered proximally through a traditional antegrade humeral entry point through a supraspinatus split. When proximal humeral angular deformity required acute

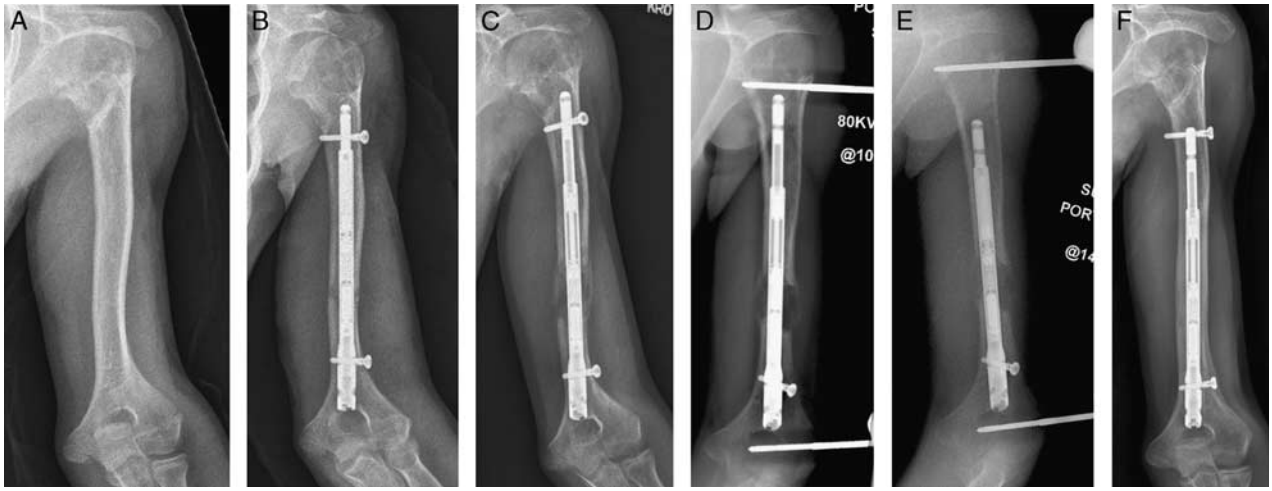

FIGURE 2. Radiographs of the patient after undergoing humeral retrograde lengthening, including use of temporary external fixator to allow for retraction and redeployment of the nail: preoperative (A); following corticotomy and nail implantation (B); after 3 cm of distraction, before redeployment surgery (C); following application of external fixator and removal of proximal interlocking screws (D); same day, following nail retraction by patients family using ERC with external fixator in situ (E); following 3 cm redeployment of nail, hence affording 6 cm total lengthening, during consolidation phase (F) (patient 2). ERC indicates external remote controller.

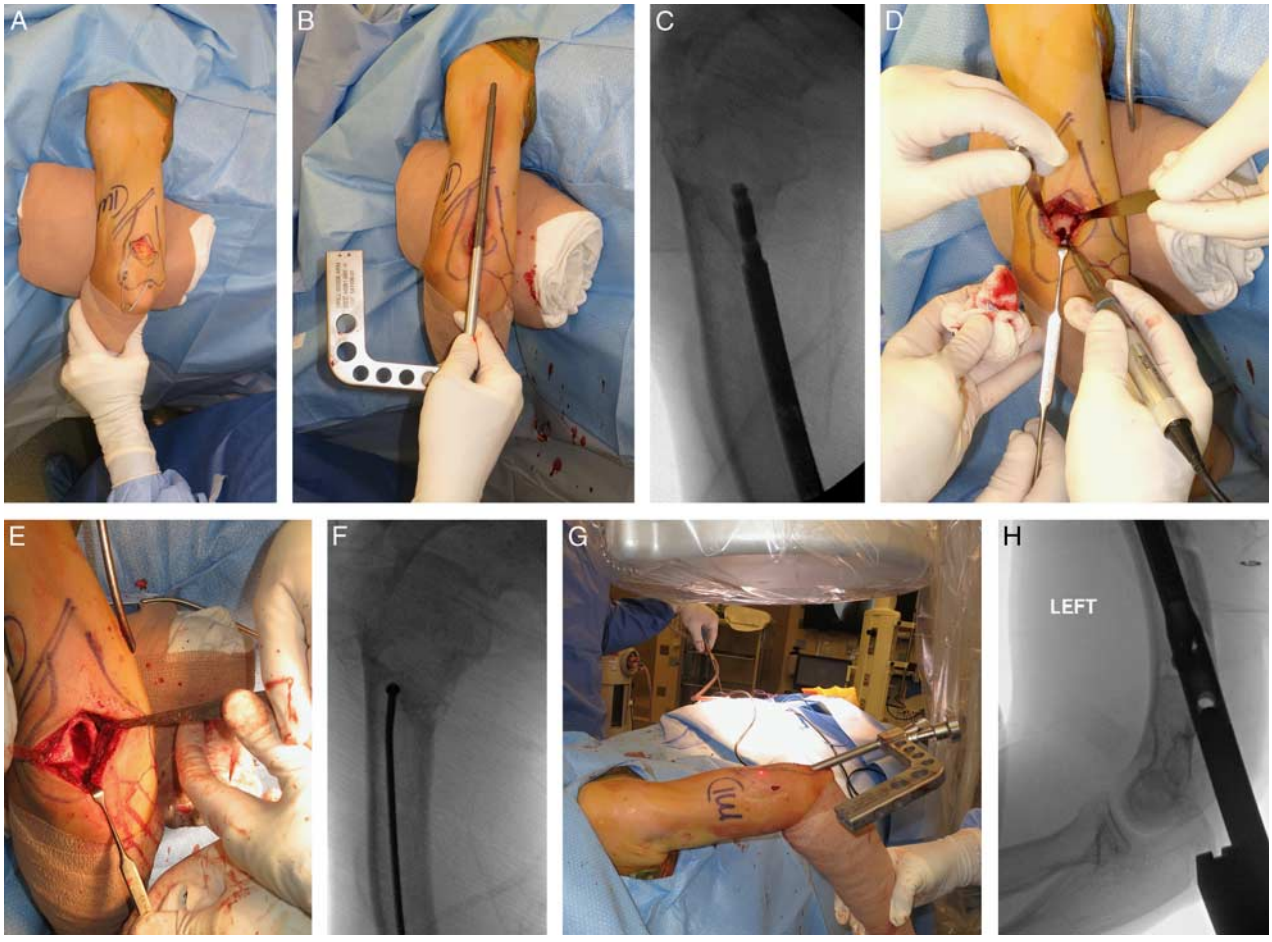

FIGURE 3. Intraoperative steps of retrograde humeral lengthening: position, marking of landmarks, initial entry incision (A); confirming nail length and fit (B and C); fashioning of entry hole (D and E); guide wire insertion (F); nail insertion (G and H) (patient 2).

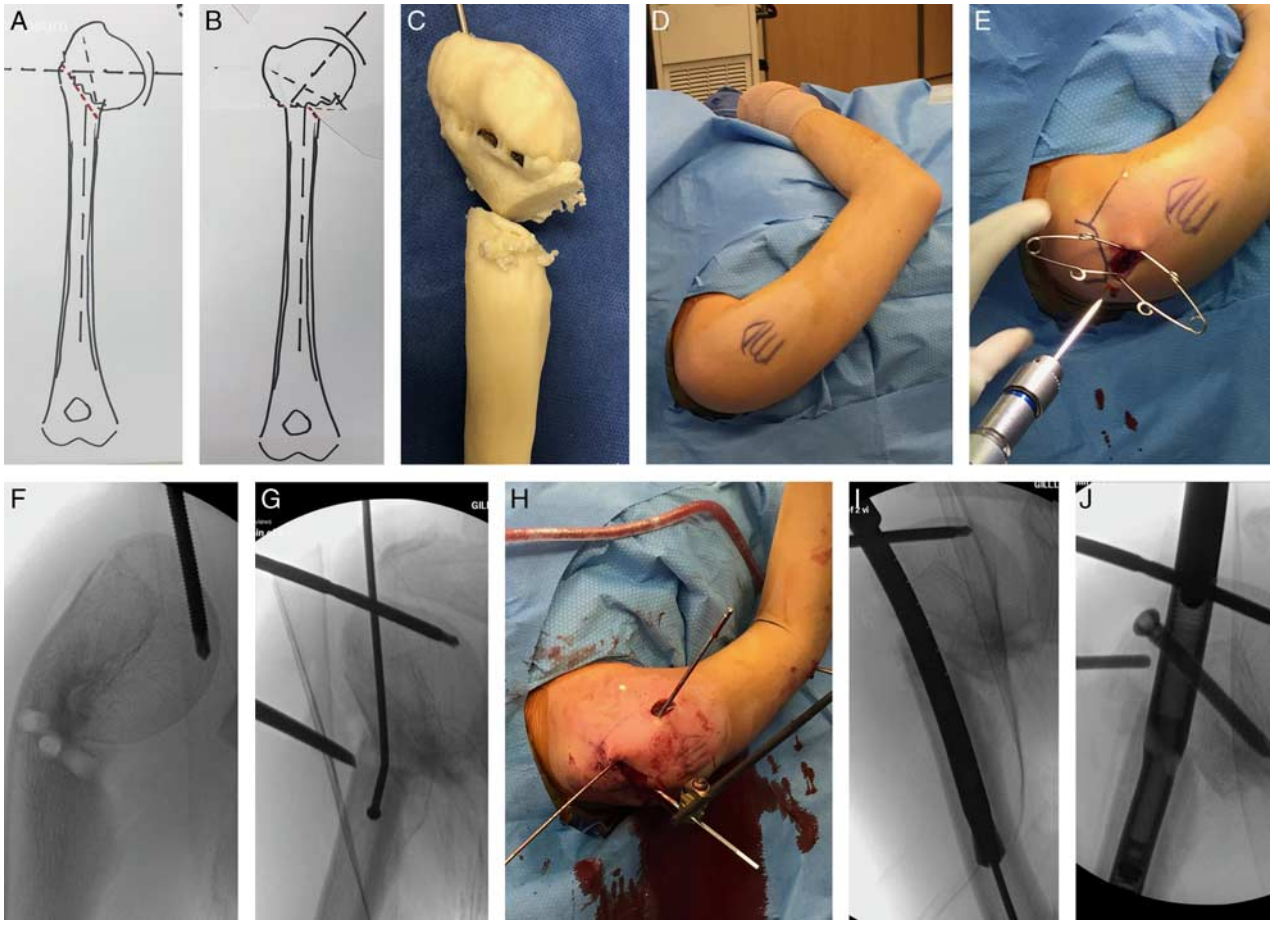

FIGURE 4. Intraoperative steps of antegrade humeral lengthening: tracing of planned correction (A and B); 3D printed bone model demonstrating planned correction (C); supine operative set up (D); superior approach, supraspinatus split, and placement of first Schanz pin (E); corticotomy (incomplete) and head before correction (F); postcorrection demonstrating position of Schanz pin (G); use of temporary monolateral fixator (H); reaming (I); nail insertion (J) (patient 3).

correction, Schanz pins were inserted in the proximal segment posterior to the midsagittal line and in the distal fragment at the epicondylar ridge, thereby marking rotation and angular correction. These could be connected with a temporary monolateral fixator if required. Indications for antegrade lengthening include proximal deformity requiring simultaneous correction. Antegrade lengthening is more likely to cause issues about the shoulder joint, whereas retrograde lengthening has a tendency to affect the elbow range of motion. There may also be other anatomic considerations, in determining which method to use, careful planning is required. Use of the antegrade method predicates careful longitudinal splitting and retraction of the supraspinatus tendon.

Two patients underwent lengthenings that exceeded the maximal deployment of the device. In these cases, the surgeon returned the patient to the operating room once the nail had reached maximal deployment, placed a 2-pin temporary spanning external fixator to preserve the length achieved, removed the distal (telescopic portion) interlocking screws from the nail, to allow redeployment. The patient was then awakened from anesthesia. The patient's family then "retracted" the nail at a rate of 7 minutes per mm, after which the patient returned to the operating room, 3 to 4 hours later the same day. New interlocking screws were placed, the frame was removed, and lengthening resumed through the existing lengthening site (Fig. 4). This technique required meticulous preoperative measurement to ensure that the newly placed interlocking screws were not in the lengthening site. A hand-held "quick lengthening/reversing" device is now available, so that the nail may be reversed intraoperatively at 7 mm per minute, with no second anesthesia required.

RESULTS

During the study period, 13 humeral lengthenings were performed in 9 patients. One patient underwent bilateral simultaneous lengthenings. One patient underwent an EF lengthening, followed by 2 MN lengthenings, and 1 patient underwent 1 EF followed by 1 MN lengthening. Seven lengthenings were performed using an external fixator, and 6 lengthenings were performed using a motorized intramedullary nail. Underlying etiologies included

achondroplasia (2), physeal arrest because of sepsis or trauma (9), brachial plexus palsy (1), and unicameral bone cyst (1).

Five angular deformity corrections were performed at corticotomy sites (2 in the MN group and 3 in the EF group). These ranged up to 50 degrees in magnitude. Two patients underwent removal of previously placed humeral plates. One patient underwent concurrent femoral lengthening with a MN while using an external fixator for the humeral lengthening.

The mean age at humeral lengthening in the EF group was 13.4 (range, 6.9 to 18.1) and in the MN group was 15.4 (range, 13 to 17.7). The mean absolute lengthening achieved was 8.5 cm in the EF group, and 6.6 cm in the MN group, and a mean percentage lengthening of 52% and 29%, respectively. The duration of lengthening averaged 106 days in the MN group and 98 days in the EF group. Noncompliance in 1 MN patient resulted in an overall lengthening period of 190 days, excluding this number reduces the average to 84 days. The average duration of EF time was 215 days. Data pertaining to each patient are available in Tables 1 and 2. The clinical and radiographic results of a patient lengthened through retrograde technique is demonstrated in Figures 1, 2, and 4.

Complications

Overall, 2 of 6 (33%) MN lengthenings and 3 of 7 (43%) EF lengthenings experienced complications (Clavien Dindo grade ≥ 2) during treatment. In the EF group, 3 pin site infections occurred. Two patients were managed with oral antibiotics, and 1 required reoperation for pin removal and new pin insertion. One fixator required revision of components in the clinic because of malalignment. One patient's fixator required realignment in the operating room under anesthesia. One patient underwent release of multiple tethered pin site scars, 2 years postremoval of fixator. All patients underwent frame removal in the operating room.

Two MN patients underwent a planned return to the operating room for nail a redeployment procedure. One MN patient, undergoing retrograde lengthening, lost fixation and developed an apex-posterior deformity at the corticotomy toward the end of the lengthening treatment, requiring application of external fixator for deformity correction and stability. One patient developed a 40-degree flexion contracture of the elbow, requiring application of a dynamic splint for treatment, with contracture resolution. One patient experienced a radial nerve palsy postoperatively, which resolved after 14 days. One patient had an extended lengthening period secondary to improper use of the external remote-control device, with eventual successful lengthening. There were no infections in the MN group.

One patient undergoing MN lengthening failed to attend initial follow-up, did not commence lengthening, and progressed to premature consolidation. This patient had previously undergone humeral lengthening through the EF technique, and subsequent to the failed MN

TABLE 1. Motorized Nail Group

Patient No.	M/F	Diagnosis	Age	Side	ULLD (cm)	Length Achieved (cm)	Preoperative Humeral Length (cm)	%	Latency (d)	Duration of Lengthening (d)	Avg mm/day	Complications (CD Grade)
1*	M	Physeal arrest (septic)	17.3	R	*5*	*1*	*23.3*	*4*	*NA*	*30*	*0.33*	*Transient radial nerve palsy (1)* *Premature consolidation (II) (removed from analysis)*
			17.7	R	4	3	24	13	7	55	0.55	Flexion contracture of elbow (II) (patient 1) Loss of fixation of nail (III)
2*	M	Physeal arrest (traumatic)	15.8	L	7	6	25.2	24	14	72	0.83	*Nail redeployment (planned)*
3	M	Brachial plexus palsy	14	L	9	8	31	26	14	190	0.42	Initial noncompliance resulting in slow distraction (I)
4	M	Physeal arrest (traumatic)	13	R	9	9	15.9	57	14	132	0.68	*Nail redeployment (planned)*
5	F	Unicameral bone cyst	14.4	R	8.1	7	28.2	25	4	80	0.88	

Italic indicates data was removed from analysis.
*Note that patients (1) and (2) are present in both groups.
CD indicates Clavien Dindo; F, female; L, left; M, male; NA, not applicable; R, right; ULLD, upper limb length discrepancy.

TABLE 2. External Fixator Group

Patient No.	M/F	Diagnosis	Age	Side	ULLD (cm)	Length Achieved	Preoperative Humeral Length (cm)	%	Latency (d)	Duration of Lengthening (d)	Avg mm/day	Complications (CD Grade)
1*	M	Physeal arrest (septic)	9.1	R	13	8	12	67	7	86	0.93	
2*	M	Physeal arrest (traumatic)	6.9	L	7.5	7.5	14.9	50	14	105	0.71	
6	F	Physeal arrest (septic)	12.5	R	8.5	9.5	18.4	52	7	70	1.36	Pin site infection Gd 1 (I)
7	M	Physeal arrest (septic)	18.1	L	10	10	25.6	39	3	188	0.53	Pin site infection Gd 2 (II) Loss of frame position (II) (adjustment in clinic)
8	F	Post-traumatic growth arrest	12.4	L	7	7	23.4	30	4	58	1.21	Pin site infection Gd 3 (III) Scar revision of pin sites (III)
9	F	Achondroplasia	17.3	R	BL	7.6	16.7	46	3	81	0.94	Automator malfunction (I) Loss of frame position (III) Poor regenerate formation (II)
		Achondroplasia	17.3	L	BL	10	16.7	59	3	81	1.23	

*Note that patients (1) and (2) are present in both groups.
BL indicates Bilateral; CD, Clavien Dindo; F, female; L, left; M, male; NA, not applicable; R, right; UULD, upper limb length discrepancy.

lengthening underwent repeat MN lengthening several months later. This failed lengthening has been excluded from the numerical analysis.

DISCUSSION

This study describes the experience of MN humeral lengthening in 6 patients and compares it to humeral lengthening using an EF technique. Presented are the attendant advantages, disadvantages, and technical considerations of the application of this newer technology.

All patients in our series undergoing unilateral lengthening achieved length within 1 cm of the target. One patient undergoing bilateral lengthening for achondroplasia ceased lengthening at 7.6 cm on one side, compared with 10 cm on her other side, because of poor regenerate formation. In 3 patients, achieving the target length involved a planned staged approach in which 2 lengthenings were performed. Two cases used EF for the first lengthening and MN for the second lengthening. Both patients and parents expressed a strong preference for the MN treatment, describing less pain, less scarring, less school time lost, and easier social interactions with a more normal life during treatment.

The overall rate of distraction was slower in the MN group, resulting in longer lengthening durations. Given that rate of distraction was adjusted on the basis of radiographic parameters, it could be inferred that regenerate formation was better in the EF group. Another reason for this difference may also be the need to proceed "with caution," that is, by distracting more slowly, in this newer technique.

The humerus is reported to tolerate proportionally greater lengthening than the femur.[20] In addition, the humerus is proportionally more affected in achondroplasia than the femur, hence requiring a greater lengthening for proportional restoration.[5] A limitation of the MN technique is that the maximal deployment capacity (all known as "stroke") of the available nail inventory relative to available humeral starting length is often insufficient to achieve the goal length. The PRECICE nail implants available at the time of implantation had available strokes of 30 mm for a 150-mm nail, whereas a 175-mm nail had a 50-mm stroke and a 245-mm nail had an 80-mm stroke. At the time of this writing, the available stroke range of nails has increased. These available implant lengthening capacities will still be insufficient in some cases, as humeral lengthenings will often increase the humeral length by 34% to 60%.[2,5,9] This problem does not exist with EF because of the wider range of modularity available.

The 2 "workarounds" utilized in our patient cohort included: (1) cutting a longer nail to a shorter starting length, and (2) redeploying the nail so that a greater lengthening may be achieved with the same implant. Both of these techniques are "off-label," and are unsupported by the manufacturer, requiring informed consent and careful surgical planning. In our view, large lengthenings should also not deter the surgeon from an MN technique; indeed, improvements in nail design allowing redeployment or greater amounts of proportional deployment may not be far away.

In addition, several authors have advocated a staged approach of multiple, gentler lengthenings.[12]

Complications

Many of the complications of EF lengthening relate to the nature of the external fixator and the obligate pin and wire sites as they traverse the limb and potentially impinge on soft tissue. This can lead to pin site inflammation and infection, with subsequent scarring with functional and cosmetic implications. The prevalence of pin site infection in our EF cohort was 3 of 11 (27.3%), aligning with that quoted in the literature.[21] Although only 1 severe flexion contracture occurred in this cohort, avoiding such a complication requires careful regular clinical assessment. The development of a contracture should prompt temporary cessation of lengthening and appropriate physical therapy and dynamic splinting until resolved.

To avoid fracture, a frame must not be removed too early. In the lower limb, techniques such as plate-assisted lengthening, and lengthening over nail, and lengthening and then nailing are described.[22,23] In the upper limb, options include augmentation with an small fragment plate[3] or flexible intramedullary nails.[7] Fractures through regenerate did not occur in either cohort, with published reports indicating a prevalence of this complication between 4% and 13%. The risk of regenerate fracture in MN lengthening is low given that nails are, in practice, not removed until full corticalization of the regenerate has occurred. Despite our results, the risk of fracture is not zero. Fracture of the MN itself is described[24] and Fürmetz et al[18] report the risk of peri-implant fracture for retrograde humeral nailing in a trauma setting to be 2% to 10%.

Limitations

This investigation has several limitations. There are a small number of cases to report, which precludes a statistical analysis of complication rates. A historical rather than contemporaneous control group also allows for the introduction of unforeseen surgeon bias.

Another significant limitation surrounds the selection of appropriate outcome measures for patient cohorts and interventions of this type. Beyond measurements of length achieved and range of motion, clinician-derived outcome measures used in limb lengthening often pertain to the use of EF of the lower limb. This is exemplified by the commonly described External Fixation Index (EFI) and Consolidation Index (CI). The use of patient-reported outcome measures is of particular importance once one considers the purported advantages of MN over EF lengthening, being considerations of patient satisfaction, body image, perception of scars, and functional abilities both during and after lengthening. Alas because of the retrospective nature of this study, there was no ability to collect such data.

Strengths

Our study's strength lies in its ability to compare lengthening through EF and MN techniques in single center and a single surgeon, with comparable patient populations. Complications were recorded and reported stringently in both groups.

CONCLUSIONS

Lengthening of the humerus can be reliably achieved by both traditional EF or use of newer intramedullary motorized lengthening nails. The complication and reoperation profiles seem comparable, although the use of intramedullary devices mitigates the difficulties of EF, and as such our study solidifies the MN technique's role in the limb reconstruction surgeon's armamentarium. The use of motorized intramedullary nails when compared with EF has been established to provide higher patient satisfaction for lengthening in the lower limb.[25] We believe a similar finding of increased satisfaction will be demonstrated in the humerus. Further research and refinement of the MN technique, with a strong focus on patient experience, will provide the evidence to enhance the care of this unique patient cohort.

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