Review article

Percutaneous forefoot surgery

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ABSTRACT

Percutaneous methods can be used to perform many surgical procedures on the soft tissues and bones of the forefoot, thereby providing treatment options for all the disorders and deformities seen at this site. Theoretical advantages of percutaneous surgery include lower morbidity rates and faster recovery with immediate weight bearing. Disadvantages are the requirement for specific equipment, specific requirements for post-operative management, and lengthy learning curve. At present, percutaneous hallux valgus correction is mainly achieved with chevron osteotomy of the first metatarsal, for which internal fixation and a minimally invasive approach (2 cm incision) seem reliable and reproducible. This procedure is currently the focus of research and evaluation. Percutaneous surgery for hallux rigidus is simple and provides similar outcomes to those of open surgery. Lateral metatarsal malalignment and toe deformities are good indications for percutaneous treatment, which produces results similar to those of conventional surgery with lower morbidity rates. Finally, fifth ray abnormalities are currently the ideal indication for percutaneous surgery, given the simplicity of the procedure and post-operative course, high reliability, and very low rate of iatrogenic complications. The most commonly performed percutaneous techniques are described herein, with their current indications, main outcomes, and recent developments.

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1. Introduction: development of percutaneous surgery

Percutaneous forefoot surgery has gained ground in France over the last decade, changing a number of concepts and practices in the field of forefoot surgery. Although first developed by podiatrists in the US over 50 years ago, percutaneous forefoot surgery was rapidly abandoned, as no theoretical or practical learning bases were available and no studies of objective outcomes had been published. Nevertheless, work started by Stephen Isham in the US, then extended in Spain by Mariano de Prado and Pau Golano, produced valuable knowledge and built an anatomic and technical foundation for percutaneous forefoot surgery [1,2]. These advances prompted the introduction in France of percutaneous forefoot surgery by the GRECMIP (Groupe de recherche et d’enseignement en chirurgie mini-invasive du pied), which has evolved over the last 10 years into a hub of teaching, dissemination, and research [3,4].

2. Prerequisites

2.1. Experience with foot disorders and foot surgery

An important point is that, although percutaneous surgery changes a number of concepts, in no case does it decrease the need for in-depth theoretical and practical familiarity with medical and surgical foot disorders. Thus, percutaneous techniques should be used only by experienced surgeons, who regularly perform procedures on the foot and who are therefore able to select the best treatment option on a case-by-case basis, according to the disorder, the patient, and their usual practice. Percutaneous surgery is not intended to supersede conventional surgery but should instead be integrated within the full array of treatment options.

2.2. Material

The first major challenge that cannot be avoided is the need for specific equipment if percutaneous forefoot surgery is to be performed under optimal conditions.

2.2.1. Knives and blades

The blades used (attached to Beaver-type handles) allow incisions measuring 2 to 3 mm in length (Fig. 1). They are sufficiently thin to ensure a high level of precision when releasing capsules and ligaments or performing tenotomies, thereby avoiding injury to neighboring structures; in contrast, the inadequate length and thickness of conventional blades unavoidably results in injury to the vessels, nerves, and skin.
2.2.2. Elevator
The elevator serves to detach the soft tissues from the bone in order to create a working space (Fig. 2). This space is crucial to ensure accuracy of the bone procedures (osteotomy and bone resection) with no risk of injury to the vessels, nerves and tendons.

2.2.3. Burrs
Burrs are essential (Fig. 3). They fall into two main groups:

- wedge burrs of variable width for bone resection;
- and straight Shannon burrs of variable width and length for performing osteotomies.

2.2.4. Motor
The motor is the crucial piece of equipment for percutaneous surgery. If the motor is not appropriate, the procedures on the bone lack precision and complications may appear. The handheld device should exhibit several characteristics:

- the motor and burr should have the same axis of rotation, to facilitate manipulation of the handheld device during bony procedures (Fig. 4A);
- the on-off switch and speed adjustor should be controlled by a foot pedal to leave the hand free for manipulating the handheld device (Fig. 4B);
- the motor must have a strong couple to allow initial burr rotation during bony procedures at a very low speed, of about 5000 to 7000 rpm or 10,000 to 15,000 rpm, depending on the motor (Fig. 4C); if the couple is insufficient and the rotation speed excessive, the motor may cause severe injuries such as burns of the skin, soft tissues, or bone.

2.2.5. Fluoroscope
A fluoroscope is used to guide the various steps of percutaneous procedures (Fig. 5). Mini-image intensifiers are very well suited to this type of surgery, as they are compact and easy to handle, produce highly accurate images, and deliver radiation doses that are 10 to 100 times lower than those delivered by conventional image
amplifiers. A fluoroscope must be used at the beginning of the learning curve to guide all the steps of the procedure. The resulting radiation exposure is a disadvantage but decreases very markedly with increasing experience.

2.2.6. Rasps
Specific rasps are used to remove the bony debris that accumulate in the working space during bone resection (Fig. 6). This step prevents the risk of persistent inflammation or stiffness.

2.2.7. Internal fixation systems
Many internal fixation systems designed for forefoot surgery can be used percutaneously. Various types of cannulated screws and pins are available, as well as endobutton devices.

2.3. Post-operative management
All the corrective percutaneous techniques were initially used without internal fixation. The correction was maintained by specifically designed dressings, which were changed after 8–10 days then at regular intervals during the first month (Fig. 7). Specific training is required to learn how to manage with these dressings, and close monitoring is crucial to ensure maintenance of deformity correction while allowing early resumption of ambulation. These techniques involving specific dressings raise logistical challenges. Expertise in this area is crucial.

2.4. Learning curve
The learning curve is lengthy, for several reasons:

- the surgeon must learn to use the specific tools, particularly the motor, which differ from those used in conventional surgery;
- familiarity with the specific tactile sensations associated with the approach, various steps of the procedure, force applied to the bone with the burr, and release of the soft tissues is crucial.
to ensure reliability and reproducibility and can be gained only through experience;
• the use and interpretation of intra-operative fluoroscopy require a certain amount of experience;
• in the post-operative period, time is needed to gain expertise with the specific dressings and with the radiological and clinical evolution.

Before starting to perform percutaneous surgery, the surgeon must follow one or more theoretical and practical cadaver courses in order to gain hands-on familiarity with the specific tools [5].

3. Percutaneous treatment of hallux valgus

The percutaneous management of hallux valgus (HV) involves several procedures, depending on the degree and reducibility of the deformity, relative length of the rays, and presence or absence of symptoms related to the lateral rays.

Some procedures such as exostectomy, lateral metatarso-phalangeal (MTP) arthrolysis, and osteotomy of the first phalanx (P1) are used in all techniques and can be performed to various extents in all cases of HV. Other procedures such as metatarsal osteotomies and the (not indispensable…) intermetatarsal suture procedure are selected on a case-by-case basis.

In every case, a specific dressing is fashioned at the end of the procedure to maintain the correction, particularly when no internal fixation is performed. Proper fashioning and monitoring of these specific dressings during the first month is crucial to maintain correct first-ray alignment and osteotomy position.

Finally, immediate full weight bearing in a flat stiff shoe is allowed in nearly every case. The osteotomies must therefore be sufficiently stable (or stabilized) to prevent secondary displacements (Fig. 8).

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3.1. Exostectomy

3.1.1. Technique [6]

A medial approach is used. The Beaver blade is introduced at the proximal part of the medial prominence of the head of the first metatarsal (M1). Once contact with the M1 head is obtained, a working space is created using first the Beaver blade and then the elevator to fully release the dorsal and medial aspects of the M1 head. A wedge burr is applied to the medial aspect of the M1 head and moved in a windshield-wiper pattern to achieve bone resection. Close monitoring by palpation and fluoroscopy ensures that the resection is sufficient (Fig. 9). The bony debris are then extruded manually. Rasps and lavage with saline are used to clear the working space of the bony debris, which otherwise can cause persistent stiffness and inflammation.

3.1.2. Indications

Exostectomy is basically indicated to remove the dorsal and medial prominence of the M1 head and to create a flat surface before performing a metatarsal osteotomy if needed. The exostectomy should not be excessive, to avoid compromising primary stability or lateral translation potential of a chevron osteotomy.

3.1.3. Risks and complications

The main risk is excessive medial bony resection (especially in patients with osteoporosis), which can cause stiffness and joint or sesamoid-bone pain and, in very rare cases, hallux varus deformity. This last complication is extremely rare if the resection is performed cautiously and checked as it proceeds. The resection may be insufficient at the beginning of the learning curve, mainly because of a too small working space that does not allow proper use of the burr. Insufficient resection results in the creation of a cavity at the medial aspect of the M1 head with persistence of a peripheral bony prominence that can cause recurrent pain and impingement in shoes.

3.2. Lateral metatarso-phalangeal arthrolysis

3.2.1. Technique [7]

Lateral MTP release is achieved by introducing a Beaver blade through a dorso-lateral incision over the MTP joint space, lateral to the extensor hallucis longus tendon. The blade is introduced through the skin down to the joint, parallel to the tendon, then rotated outwards 90° so that it is parallel to the joint space (Fig. 10A). The blade remains within the joint space and directed towards the infero-lateral corner of the base of the phalanx. The great toe is placed in forced varus to put the lateral capsule and ligaments under tension, allowing them to be cut gradually. The blade should be kept at the plantar part of the joint to avoid cutting the lateral collateral ligament of the first MTP joint. By applying pressure in varus to the great toe, the surgeon can feel the joint being gradually released and can stop the process as soon as sufficient release is obtained. Fluoroscopy (which is needed only at the beginning of the learning curve) with dynamic views in forced varus confirms the release by showing opening of the lateral MTP joint space with no displacement of the lateral sesamoid bone (confirming complete section of the lateral sesamoido-phalangeal ligament) (Fig. 10B). In case of metatarsal chevron, the osteotomy is performed before the release of the joint, to improve control of the lateral translation of the M1 head.
3.3. Risks and complications

The main risk associated with P1 osteotomy is loss of correction with recurrence of the valgus deformity. If the osteotomy is excessively distal, at the level of the diaphysis, correction is more difficult to achieve because the cortical bone is fragile and breaks easily; at the metaphysis, in contrast, plastic deformation ensures maintenance of the correction. Rupture of the lateral cortex also carries a risk of secondary displacement in dorsal flexion.

3.4. Osteotomies of the first metatarsal

Several types of percutaneous metatarsal osteotomies have been described.

3.4.1. Reverdin-Isham osteotomy

A distal metatarsal osteotomy is performed, at the junction of the metaphysis and epiphysis, then closed medially to correct the orientation of the joint surface of the M1 head (thereby decreasing the distal metatarsal articular angle [DMAA]) [1,2,9].

3.4.1.1. Technique. A Shannon bone burr inclined at a 45° angle relative to the axis of M1 is used to cut the bone from distal and dorsal to proximal and plantar. The approach is the same as for exostectomy. The osteotomy is performed after exostectomy and before lateral arthrolysis. The lateral cortex is left intact. Correction of the DMAA is achieved by medial closure during forced varus of the great toe. Fluoroscopy is used to check the orientation of the metatarsal joint surface and the stability of the osteotomy (Fig. 12A–C).

3.4.1.2. Indications. The Reverdin-Isham osteotomy is reserved for isolated congenital HV (with no repercussion on the lateral rays) with mild deformity, increased DMAA and a congruent joint.

3.4.1.3. Risks and complications. The main complication is DMAA overcorrection, which can lead to rapid recurrence of the deformity and MTP joint incongruence. The risk of joint incongruence is greater when osteotomies of the lateral rays are performed also [10,11]. Rupture of the lateral cortex carries a risk of secondary displacement and inadequate correction.

3.4.2. Percutaneous distal chevron osteotomy

A complete osteotomy is performed through the distal metaphysis of the metatarsal to allow displacement of the distal fragment and correction of the metatarsus varus, MTP valgus, DMAA, M1 length, and joint incongruence [12] (Fig. 13A).

3.4.2.1. Technique. The osteotomy is performed using a Shannon bone burr (that must be long enough to allow a sufficient plantar cut). The approach may be the same as for exostectomy (if the incision is not too plantar) or may consist in a dorso-medial incision. Chevron osteotomy is performed after exostectomy and before lateral arthrolysis. The burr is introduced into the dorsal half of the metatarsal head, in a direction perpendicular to the axis of the second metatarsal and from dorsal and medial to plantar and lateral, so that translation of the chevron osteotomy exerts a lowering effect (Fig. 13B). The first cut is dorsal, short, and nearly vertical (or angled slightly in the proximal direction). The second cut is plantar, longer, and nearly horizontal. The two cuts form an angle of about 60° (Fig. 13A). Several modifications in the length and orientation of the cuts have been described, but a short dorsal cut with a long plantar cut confers the best primary stability to the osteotomy. Translation is obtained by pushing the metatarsal head laterally using an instrument introduced into the diaphysis of M1 (forceps, etc.).

3.4.2.2. Indications. A chevron osteotomy is performed in patients with a large deformity, either asymptomatic or with plantar compression. It is contraindicated in patients with a subluxed joint or with a large articular space.

3.4.2.3. Risks and complications. The complications of chevron osteotomy are similar to those of Reverdin-Isham osteotomy and include excessive correction, plantar pinch, and soft-tissue complications. The complications of chevron osteotomy are similar to those of Reverdin-Isham osteotomy and include excessive correction, plantar pinch, and soft-tissue complications.
Fig. 12. A. Reverdin-Isham osteotomy: principle of the procedure. B. Reverdin-Isham osteotomy: pre-operative appearance. C. Reverdin-Isham osteotomy: appearance 2 years post-operatively.

3.4.2.2. Indications. Percutaneous chevron osteotomy of M1 can be used to treat most cases of HV, as it corrects the metatarsus varus, MTP valgus, DMAA, and joint incongruence.

3.4.2.3. Risks and complications. The main risk associated with percutaneous chevron osteotomy is excessive shortening of M1, due to the thickness of the burr and absence of intrinsic stability of the osteotomy when the cuts are short [5,13]. Even when internal fixation is performed, there is a risk of secondary displacement with elevatus, loss of correction, and medial rotation if the plantar cut is too short [14].

3.4.3. Percutaneous osteotomy of the base of the metatarsal

Osteotomy of the base of M1 corrects certain deformities characterized by marked metatarsus varus. This osteotomy has little intrinsic stability and must therefore be followed by internal fixation.

3.4.3.1. Technique [15]. A Shannon bone burr is introduced through a dorsal approach and positioned on the lateral edge of M1, lateral to the extensor hallucis longus tendon. The osteotomy is performed after exostectomy and lateral arthrolysis. The cut is through the proximal metaphysis, oblique, from distal and lateral to proximal and medial. The lateral and planar cortices are cut, whereas the dorsal and medial cortices are left intact. Correction is achieved by lateral closure during lateral displacement of the metatarsal head. The orientation of the osteotomy and preservation of the dorso-medial cortex allow lowering of the metatarsal head. Internal fixation is achieved using a cannulated screw inserted perpendicularly to the osteotomy. Temporary intermetatarsal pinning can be added in the event of instability to prevent secondary displacement.

3.4.3.2. Indications. Percutaneous osteotomy of the base of M1 is reserved for deformities characterized by marked metatarsus varus. When the deformity is severe, this procedure can be combined with percutaneous distal metatarsal chevron osteotomy [16,17].
Fig. 14. A. Percutaneous chevron osteotomy: pre-operative appearance. B. Percutaneous chevron osteotomy (combined with DMMOs and P1 osteotomy of the second toe): appearance 2 years post-operatively.

Fig. 15. A. Percutaneous chevron osteotomy with fixation: intra-operative antero-posterior view (courtesy of Dr Olivier Laffenêtre). B. Percutaneous chevron osteotomy with fixation: intra-operative oblique view (courtesy of Dr Olivier Laffenêtre).

Fig. 16. A. Percutaneous intermetatarsal suture technique: the suture is threaded through the tunnel in M1. B. Percutaneous intermetatarsal suture technique: appearance after reduction.
3.4.3.3. Risks and complications. The main risks associated with this type of osteotomy are secondary displacement in elevatus, related either to rupture of the dorso-medial cortex or to persistent instability despite the internal fixation.

3.5. Other procedures on the first metatarsal

Percutaneous methods for lacing M1 and M2 have been suggested to decrease the intermetatarsal angle without performing a metatarsal osteotomy.

3.5.1. Technique

Implantation of a suture connecting M1 and M2 is performed after exostectomy and lateral arthrolysis. Either a simple suture or a suture connected to two endobuttons can be used [18]. When endobuttons are used, two bone tunnels must be created (one in M1 and the other in M2). One of the endobuttons and the suture are then threaded through the tunnels. Tension placed on the suture between the two endobuttons gradually corrects the metatarsus varus deformity. With a simple suture, a single tunnel through M1 is needed (Fig. 16A). A suture passer is used to wind the suture around M2 then to the dorsal aspect of M1. Putting pressure on M1 corrects the deformity, and the knot is tightened in the reduced position (Fig. 16B).

3.5.2. Indications

The suture method is reserved for moderate reducible deformities with a congruent MTP joint in patients with hyperlaxity or hypermobility of the first ray.

3.5.3. Risks and complications

Creating a tunnel in M2 increases the risk of M2 fracture [19]. The peak stress created by the suture or buttons in contact with M2 can result in persistent pain in the second ray. Overcorrection with hallux varus is rare. The main risk is recurrence of the deformity in patients with first ray hypermobility and hyperlaxity.

3.6. Main outcomes of percutaneous treatments for hallux valgus

The percutaneous management of HV relies on a large number of procedures (on the bone, capsule, and ligaments) that can be combined according to the needs of each patient. All these procedures are performed according to the rules of percutaneous surgery, which involves specific manual skills, instruments, and post-operative care techniques. The various percutaneous procedures should be selected on a case-by-case basis, depending on the symptoms, physical findings (severity and reducibility of the deformity, range of joint motion, and symptoms arising in the lateral rays), radiological features (metatarsus varus, MTP valgus, DMAA, joint congruence, metatarsal length, and presence of osteoarthritis), and experience of the surgeon. With this customized treatment approach (“à la carte”), the various percutaneous procedures produce significant functional improvements (post-operative AOFAS score > 85/100) with over 85% of patients being satisfied or very satisfied with the result [1,10,11,20–26].

The treatment of HV by isolated exostectomy combined with lateral arthrolysis and P1 osteotomy should be reserved for mild deformities with medial metatarsal prominence and a congruent joint. The HV angle is corrected by about 10°, mainly by the phalangeal osteotomy. The post-operative course is usually uneventful, with immediate weight bearing and resumption of walking in normal shoes within 1 month.

Connecting M1 and M2 with a suture but no endobuttons is usually also followed by an uneventful post-operative course, with rapid resumption of walking in normal shoes. The MTP valgus is corrected by about 15° and the metatarsus varus by about 6° [18,19].

The Reverdin-Isham osteotomy is reserved for HV with very increased DMAA. The MTP valgus correction is about 15°, the metatarsus varus is decreased by about 3°, and the DMAA is decreased by about 8° [10,11]. Thus, the Reverdin-Isham osteotomy is reserved for the rare cases of congenital HV with a congruent joint and no repercussion on the lateral rays.

Percutaneous chevron osteotomy corrects the MTP valgus by more than 15°, decreases the metatarsus varus by 7°, and corrects the DMAA [21–24]. In addition, this procedure preserves the congruence of the MTP joint in over 90% of cases. Thus, percutaneous chevron osteotomy is appropriate for most cases of HV.

Osteotomy of the base of M1 is reserved for HV cases characterized by marked metatarsus varus. This procedure decreases the MTP valgus by more than 20° and the metatarsus varus by 10°. It can be combined with percutaneous chevron osteotomy [17].

4. Percutaneous treatment of hallux rigidus

Percutaneous surgical techniques seem very well suited to the management of hallux rigidus (HR) at all stages. They allow procedures on the bone through tiny incisions, thus limiting the risk of stiffness and osteoarthritis flares. In all patients, full weight bearing is allowed immediately after surgery, in a stiff-soled shoe.

4.1. Techniques

4.1.1. Cheilectomy [2,27]

Painful osteophytes about the metatarsal head can be resected using a wedge burr. The approach depends on the location and size of the osteophyte: the conventional medial approach allows the resection of medial and dorsomedial osteophytes, whereas the dorso-lateral approach (lateral to the extensor hallucis longus tendon, over the base of P1) can be used to remove a dorso-lateral metatarsal or phalangeal osteophyte. A working space is created around the osteophytes. The burr should be kept in contact with the osteophytes to allow complete resection with no risk of soft tissue injury. All the bony debris should be removed (by pressure and using rasps) and the working space should be abundantly irrigated with saline to avoid persistent inflammation and stiffness. Fluoroscopy is used to check that the resection is sufficient and that the edges are smooth, with no residual bony spur.

4.1.2. Metatarsal and phalangeal osteotomies [2]

The medial approach can be used for distal metatarsal osteotomies such as the M1 Weil osteotomy (with or without fixation) or the Waterman osteotomy (taking care to preserve the plantar cortex). The Moberg osteotomy can also be performed through the conventional dorso-medial approach used for percutaneous phalangeal osteotomy, taking care to leave the plantar cortex intact.

4.1.3. Resection arthroplasty

Valenti- or Keller-type resection arthroplasty of the MTP joint can be performed percutaneously. A wedge burr is introduced into the joint space and used to resect the joint surfaces.

4.1.4. First ray metatarso-phalangeal arthrodesis [28]

A wedge burr is introduced into the MTP joint via the medial approach at the level of the joint space. The metatarsal and phalangeal surfaces are resected to create two flat surfaces that are parallel to each other in the coronal and sagittal planes (Fig. 17A). The burr is held against the base of the phalanx, where the bone is more sclerotic and harder that at the metatarsal head, to accurately control the resection and to keep an orientation that is perpendicular to the phalanx. Percutaneous arthrolysis may be performed when there is a marked valgus deformity. After removal of the bony
debris and lavage of the joint, fluoroscopy is used to check that the resection is sufficient, the bone surfaces flat, and contact (during MTP joint compression) adequate (Fig. 17B). The position of the great toe is checked in two different ways:

- by direct vision, the position of the toe is assessed in the coronal plane, sagittal plane (P1 should be parallel to the ground), and axial plane (position of the toe pad);
- and fluoroscopy is used to analyze toe position in the coronal and sagittal planes, bone-to-bone contact, and absence of subluxation.

Once proper toe position and bone-to-bone contact have been confirmed, internal fixation with two cannulated screws is performed and then checked fluoroscopically (Fig. 17C).

4.2. Indications

The indications of cheilectomy, osteotomy, resection arthroplasty, and joint fusion performed percutaneously are identical to those of the same procedures performed by conventional methods.

4.3. Results

Relief of the pain due to osteophyte impingements is excellent and is obtained very rapidly. Healing seems to proceed far more smoothly than with open techniques. After conservative treatments and resection arthroplasty, patients should be encouraged to mobilize the great toe as soon as possible and to resume the use of soft shoes, in order to promptly increase the MTP joint range of motion. However, as with open surgery, percutaneous surgery of osteoarthritic joints may be followed by prolonged post-operative inflammation that adversely affects the post-operative course and delays the resumption of walking and the use of normal footwear.

Percutaneous MTP arthrodesis rapidly produces very good results, with immediate full weight bearing, minimal post-operative pain, significant functional improvements after 1 month, use of normal footwear after 2 months in 2/3 of cases, and fusion in over 90% of cases [28].

5. Percutaneous treatment of lateral metatarsal pathologies

Disorders affecting the lateral metatarsal pathologies are very good indications for percutaneous surgery, which allows correction of malalignment and procedures on the soft tissues if needed, while minimizing the morbidity related to the approach.

5.1. Techniques

The approach is dorsal, at the metatarso-phalangeal joint space in the intermetatarsal space. The blade is held parallel to the extensor tendon, on the medial or lateral edge of the metatarsal head, which must be palpated before the incision is performed (the side of the incision depends on the side that is operated on, the procedures to be performed, and the dominant hand of the surgeon). Several procedures can be performed through this single approach:

- MTP artholysis: the Beaver blade is introduced into the joint then rotated 90° so that it is parallel to the joint space. The toe is then manipulated to put tension on the capsule and ligaments that are to be released. This method allows selective dorsal capsulotomy and lateral or medial artholysis.
- section of the transverse metatarsal ligament: the Beaver blade can be introduced via the same dorsal approach or through a
web-space incision along the metatarsal neck, in the intermetatarsal space. The blade is kept in contact with the metatarsal and is advanced distally along the axis of the bone until it is nearly parallel to the metatarsal axis. In this position, the section of the transverse metatarsal ligament is easily felt. Repeated movements are performed to ensure that no residual fibres are left intact. Scrupulous adherence to the technique avoids both the occurrence of complications and incomplete section of the ligament [29].

- resection of an MTP osteophyte: after arthrolysis of the MTP joint, the wedge burr is introduced through the same approach and used to gradually remove any osteophytes located on the head of the metatarsal or base of the phalanx.

- distal metatarsal mini-invasive osteotomy (DMMO [30]: this osteotomy significantly displaces the metatarsal head upwards and backwards, thus eliminating pain due to excessive weight bearing on the central metatarsal heads (Fig. 18A). A skin incision is made and an elevator is introduced into the intermetatarsal space at an angle of 45° with the axis of the metatarsal, along the neck. A Shannon bone burr is then introduced in the same direction (Fig. 18B and C). The osteotomy is performed from plantar and proximal to dorsal and distal, at an angle of 45° with the axis of the metatarsal, using the cutaneous portal as a reference point so that the lateral and plantar cortex is cut first, in the same sagittal plane as the metatarsal, and that the osteotomy ends with the dorsal cortex, perpendicularly to the initial plane. The osteotomy is extra-articular, through the distal metaphysis. It is important to check that the osteotomy is complete by applying traction and compression forces along the axis of the toe in order to mobilize the distal fragment and to disrupt any periosteal

Fig. 18. A. Diagram of DMMO. B. Positioning of the osteotomy burr for performing DMMO. C. DMMO: intra-operative view of burr position before the osteotomy. D. DMMO: pre-operative appearance. E. DMMO: appearance 2 years post-operatively.
attachments. Immediate full weight bearing is crucial to correct the malalignment.

5.2. Indications

MTP arthrolysis is indicated if the joint is stiff or the phalanx is deviated laterally or medially. Section of the transverse metatarsal ligament is performed only to release the interdigital nerve in patients with Morton’s neuroma.

Osteophyte resection is considered in patients with MTP osteoarthritis and advanced Freiberg’s disease.

The main indication of DMMO is static metatarsalgia resistant to conservative treatment (with plantar orthoses). Osteotomies of the second, third, and fourth metatarsals must be performed to confer an adequate shape to the distal metatarsal arch.

5.3. Results

Arthrolysis is highly effective in correcting MTP joint deviations, provided the toes are kept aligned in a specific dressing for about 1 month. DMMO should be performed also when joint subluxation is noted pre-operatively. In Morton’s neuroma, percutaneous treatment combining section of the transverse metatarsal ligament and DMMOs seems as effective as open neuroectomy and provides faster improvements with stable mid-term results [31]. DMMOs are extremely effective in static metatarsalgia, which usually resolves after 2 months [32,33]. This osteotomy produces only minimal stiffness and is easily reproducible, with a short learning curve. Healing is achieved in over 99% of cases, after a highly variable period (from 6 weeks to more than 18 months) (Fig. 18D and E). The main complication is prolonged forefoot oedema, which lasts at least 3 months.

6. Percutaneous treatment of toe deformities

The percutaneous treatment of toe deformities is determined on a case-by-case basis. Variable combinations of procedures on the soft tissues and bones are used depending on the nature of the lesions; whether the deformity can be reduced completely, partially, or not at all; and the symptoms.

6.1. Techniques [34]

Section of the extensor tendon can be easily added to MTP release via the same approach. Plantar release (arthrolysis?) of the proximal interphalangeal joint is performed via a lateral approach at the head of P1, with the toe maintained in plantar flexion. Isolated section of the flexor digitorum brevis tendon is performed through the same approach. For isolated flexor digitorum longus tenotomy, a distal plantar approach over the distal interphalangeal joint is used.

P1 osteotomy can be achieved via a plantar or dorso-lateral approach. Complete osteotomy of the proximal metaphysis is frequently used and produces not only shortening, but also plantar flexion. P2 osteotomy can be done via the dorso-lateral approach.

Resection arthroplasty of the proximal interphalangeal joint is performed using a wedge burr introduced through a dorso-lateral approach (Fig. 19A and B).

6.2. Indications

The percutaneous treatment of toe deformities starts with soft-tissue procedures. Procedures on the bone may then be performed depending on the residual deformities, reducibility and length of the toe.

Fig. 19. A. Long second toe: pre-operative appearance. B. Long second toe: appearance 2 years after percutaneous resection arthroplasty.

6.3. Results

The results seem similar to those obtained using the various open techniques, although the vast array of different clinical situations makes comparisons difficult. Adequate alignment of the toes is often obtained, sometimes with stiffness, but with fewer cutaneous and vascular complications than with open techniques. The main constraint is the need to fashion and monitor the post-operative dressings that maintain toe alignment.

Section of both flexor tendons is advisable, as the resulting loss of strength on grasping of the toes is often poorly tolerated. This procedure should be reserved for severe dynamic deformities due to neurological disorders [35].

7. Percutaneous treatment of pathologies of the fifth ray

Tailor’s bunion (‘bunionette’) and quintus varus are ideal indications for percutaneous surgery involving both the bone and the soft tissues.

Fig. 20. A. Tailor’s bunion and quintus varus: pre-operative appearance. B. Tailor’s bunion and quintus varus: post-operative appearance.

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Lateral condylotomY of the fifth metatarsal performed with a wedge burr introduced through a dorsal or plantar approach is never sufficient to eliminate symptoms due to tailor's bunion. Metatarsal osteotomy must be added to decrease the divergence between the fourth and fifth metatarsals. Quintus varus is an extremely common concomitant abnormality and should be corrected percutaneously, according to the same modalities used for all toe deformities (Fig. 20A and B).

The results are similar to those obtained with conventional techniques. However, the time to improvement is substantially shorter, with immediate full weight bearing and, above all, a considerably decreased risk of scarring-related complications [36,37]. Thus, pathologies of the fifth ray seem to constitute ideal indications for percutaneous surgery.

8. Conclusion: current role for percutaneous forefoot surgery

The development of percutaneous techniques has radically changed the treatment strategies used in forefoot surgery. The current concept is dynamic, with immediate full weight bearing, in marked contradiction to the classical view involving fixation and initial avoidance of weight bearing. Within this strategy of early rehabilitation and prompt resumption of former activities, percutaneous surgery has taken on a major role, thereby improving overall patient management [38].

However, despite the ‘minimization’ of the surgical procedures, information of the patient and quality of the procedures remain key priorities. The goal is to achieve a prompt improvement that is stable over time, with the lowest possible morbidity rate [39].

Despite the lack of prospective randomized trials comparing the outcomes of percutaneous surgery to those of conventional surgery, experience teaches that some indications are ‘ideal’ and that others should be viewed with some degree of circumspection [40,41].

Abnormalities of the fifth ray and lateral metatarsals are very good indications for percutaneous surgery. Very good results are obtained rapidly, with few iatrogenic complications and a fairly short learning curve.

Hallux rigidus also seems to be a very good indication for percutaneous surgery, given the simplicity of the procedure and post-operative course, particularly for joint fusion. However, conservative treatment, even when performed percutaneously, does not eliminate the risk of joint stiffness and osteoarthritis progression.

The percutaneous treatment of toe deformities produces similar outcomes to those obtained with conventional techniques, within the same time frame. However, percutaneous surgery is associated with fewer iatrogenic complications, most notably involving the skin and vessels.

Thus, older patients who are fragile or who have a history of prior forefoot surgery are very good candidates for percutaneous surgery. The correction of deformities, even when complex, can be achieved with a lower risk of iatrogenic complications.

In the treatment of HV, the use of percutaneous techniques to perform exostectomy, arthrolysis, and P1 osteotomy has modified and simplified certain procedures performed to correct mild deformities. In most cases of HV that require metatarsal osteotomy, percutaneous surgery provides similar results to those obtained with open surgery, within the same time frame. However, disadvantages of percutaneous surgery in this situation are the lengthy learning curve and poor reproducibility. The current trend for procedures on the first ray consists in a mixed strategy combining a minimally invasive approach (2–3 cm incision) for chevron osteotomy of M1, internal fixation, and percutaneous techniques for arthrolysis and P1. This mixed strategy for first ray surgery seems more rapidly reproducible than a fully percutaneous strategy yet maintains the advantages of percutaneous surgery.

Disclosure of interest

The author declares that he has no conflicts of interest concerning this article.

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