Radiolucent Lines and Aseptic Loosening in Primary Total Knee Arthroplasty

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Existe -il pour l'homme un bien plus précieux que la santé ?

Socrate

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List of abbreviations

AA	Anatomical Alignment
ACL	Anterior Cruciate Ligament
AL	Aseptic Loosening
aMA	adjusted Mechanical Alignment
BMD	Bone Mineral Density
BMI	Body Mass Index
CCK	Condylar Constraint Knee
CT	Computed Tomography
CR	Cruciate Retaining
DEXA	Dual Energy X-ray Absorptiometry
DCT	Dual Energy Computed Tomography
DPD	Deoxypyridinoline
FMA	Femoral Mechanical Axis
HVC	High Viscosity Cement
HKA angle	Hip Knee Ankle angle
KA	Kinematic Alignment
iKA	inverse Kinematic Alignment
MA	Mechanical Alignment
MC	Medial Constraint
mm	Millimeter
OA	Osteo-Arthritis
PS	Postero-Stabilized
PE	Poly-Ethylene
PCL	Posterior Cruciate Ligament
PMMA	Polymethyl Methacrylate
PSI	Patient-Specific Instrument
rKA	restricted Kinematic Alignment
SPECT	Single Photon Emission Computed Tomography
RLL	RadioLucent Line
ROM	Range Of Motion
RSA	Radio Stereometric Analysis
G	Gentamicin
THA	Total Hip Arthroplasty
TMA	Tibial Mechanical Axis
TKA	Total Knee Arthroplasty

Radiolucent lines and aseptic loosening in primary total knee arthroplasty

Chapter 1: Total knee arthroplasty, limb alignment and survival of the implant

1. Osteoarthritis and total knee arthroplasty

Total knee arthroplasty (TKA) is a complete resurfacing of the knee joint.
The replacement is performed in patients complaining about pain and decreased function in case of severe osteoarthritis of the knee.

TKA is a device that consists of a metal alloy femoral and tibial component, that can be cemented or not, with a piece of compression molded polyethylene (PE) between the femoral and tibial implant. The patella is most of the time resurfaced, with a piece of PE fixed to the bone with surgical cement. Stability of the implant is achieved by the design of the PE and the degree of constraint used.

Tibial fixation in primary TKA is obtained in two contact areas of the bone: the epiphyseal and metaphyseal zone of the proximal tibia.
Looking at the geometry of the implant, the epiphyseal zone corresponds to the tibial base plate and the metaphyseal zone to the keel (Fig. 1).

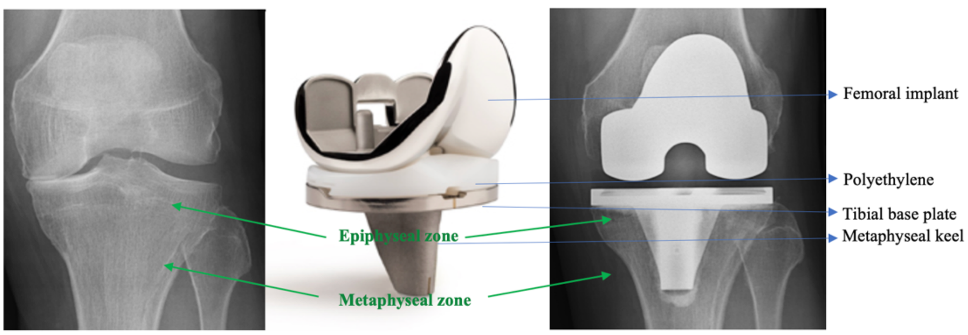

Fig. 1 *Tibial fixation in primary total knee arthroplasty: on the left a frontal X-ray of knee osteoarthritis, in the middle an image of a total knee arthroplasty and on the right a post operative frontal X-ray of the same type of total knee arthroplasty*

2. Implant design and level of constraint

The implant and the type of constraint used, depend of the type of surgery chosen for the patient and the alignment philosophy [1, 2]. The level of constraint is defined by the design of the implant. The necessary level of constraint depends of the bone cuts, gap balancing and soft tissue quality, but also the amount of correction wanted or needed in the frontal and coronal plane [1, 2] .
The more the constraint is increased, the more the stress on the implant and the bone -implant interface will increase, needing optimal fixation with a sufficient implant-bone contact surface. Currently, the non-constrained implants seems to be more and more used, due to the improvements in the design and congruency of the PE [3].

A cruciate retaining (CR) implant, is used, in case of preservation of the posterior cruciate ligament (PCL). It is a non-constrained implant. The bone quality needs to be optimal, with a well-balanced implant in the frontal plane.

The medial constraint (MC), is a newer implant, with a PE design as for the CR, but with a highly congruent medial compartment and a nearly flat lateral compartment, offering a better physiological rolling movement of the medial condyle and rolling-sliding of the lateral condyle during flexion. This implant offers higher patient' satisfaction, specially due to greater stability in mid flexion [4, 5].

The postero-stabilised (PS) implant is a partially constrained implant, in this implant the PCL is replaced by a post and cam mechanism. The design offers a better range of motion (ROM) with a deeper flexion because of the roll-back of the PS system.

A more constrained PS design is the Condylar Constraint Knee (CCK) that increases the medio-lateral constraint of the implant design in the frontal plane.

The hinge, is the most important constrained implant, rarely used in primary TKA. It can be indicated in cases with important ligament instability, trauma cases or in revision for implants with ligament insufficiency.

More than the design of the implant, the type of insert, mobile and fixed, influences the amount of stress on the joint and the bone-implant interface.

3. Limb alignment and mechanical load constraints

The goal of surgery is to relieve pain, obtain stability and mobility of the knee with a well-aligned limb [6, 7].

Physiological alignment of the lower limb, evolves during the growth phase, with typically varus alignment until 2-3 years old. This changes into valgus until 7-years-old. After that it can become either neutral, as in 32% of males, and 17% of women [8, 9], or still remain in varus or valgus alignment [10]. The final alignment of the lower limb is influenced by both geno- and phenotype. Factors such as the alignment of the parents, but also the type of sports realized during the growth phase will determine final coronal alignment [11, 12].

Prevalence of valgus and varus knee in the global population is variable, depending on gender and origin [13]. Varus knees are more represented in Caucasians, sport players [11] and males and valgus knees are more predominant in women [14] .
In the varus knee, the majority of the weight passes through the medial side of the knee and in the valgus knee on the lateral side of the knee, resulting in osteoarthritis of that compartment with time (Fig. 2). Literature reports that 60 to 70% of weight passes through the medial side of the native neutrally aligned knee during gait, going up to 90% in case of varus osteoarthritis [4].

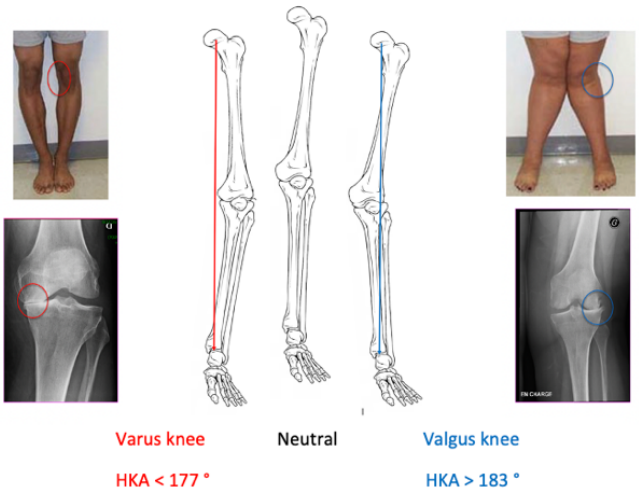

Fig. 2 *Lower limb alignment: on the left side, the picture shows the clinical and radiological aspect of a varus knee and on the right side of a valgus knee*

There are two classic representations of lower limb alignment (Fig.3).

Anatomical alignment that follows the native coronal anatomy of the two bones of the knee (femur and tibia) and their respective “anatomical axes” with the alignment line passing through the center of the femoral and tibial bones (diaphysis).

The other option is mechanical alignment, represented as the global lower limb alignment, where the axis passes through the center of the femoral head, the middle of the knee to the center of the ankle (Maquet line).

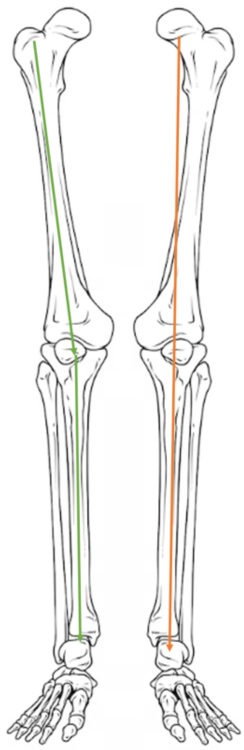

Fig. 3 *Mechanical axis and anatomical axis of the knee: the orange line represent the mechanical axis (Maquet line), and the green line represent the anatomical axis of the lower limb*

4. Surgical alignment philosophies

When TKA is performed, surgeons aim for some type of alignment correction depending on their own alignment philosophy. Often the concept of the safety zone is discussed. It means that the limb can accept 3° of deviation in varus or valgus, without increasing the risk of too much constraint on the implant and the bone and potentially leading to less failures [15-19].
During the last years, the philosophy of surgical techniques has evolved, with the aim of achieving a more "physiological" alignment while maintaining a very good survival rate. Indeed , 50% of the population having a neutral mechanical alignment [8], in case of osteoarthritis a more individualized surgery reproducing this preoperative condition can be proposed [20].

In the 80's, Hungerford and Krackow introduced the concept of "Anatomical Alignment" (AA), that consists of achieving a systematic oblique coronal joint line with a fixed 3 degrees (3° femoral valgus and 3° tibial varus in the coronal plane) relative to the mechanical axis of the limb [21]. This technique has been limited in its success by the poor options for instrumentation and the risk for outliers.

As a result, John Insall introduced the future gold standard of the last forty years, "Mechanical Alignment" (MA) [22]. This philosophy was a systematic alignment technique with a femoral cut perpendicular to the mechanical axis of the femur and a tibial cut, also perpendicular to the tibial axis [23, 24]. This technique was easier to perform and more reproducible. Unfortunately, both of these systematic alignment philosophies, don't offer sufficient patient satisfaction, and were considered as potential causes for residual knee pain after surgery [21, 25-27].

The improvement in technologies during the last decade, permits to avoid surgical outliers from the neutral mechanical axis, as proposed by Howell with three-dimensional and patient-specific instruments (PSI). This precision-enabling technology, would help surgeon to implant the same prostheses in different outlier position, depending on the surgeon's preferred alignment philosophy [23, 28]. The technique planned by computer technology, permits to correct deformities when conventional instrumentation can be used.

A consensus in 2021 [28, 29], defined and resumed the most recent alignment philosophies, as follows:

Kinematic Alignment (KA) is an alternative surgical technique aiming to resurface articular surfaces in order to preserve as good as possible the native joint line of the knee taking into account the ligament status. The goal is to restore the knee to its pre-disease position [21, 30] (Fig.4).

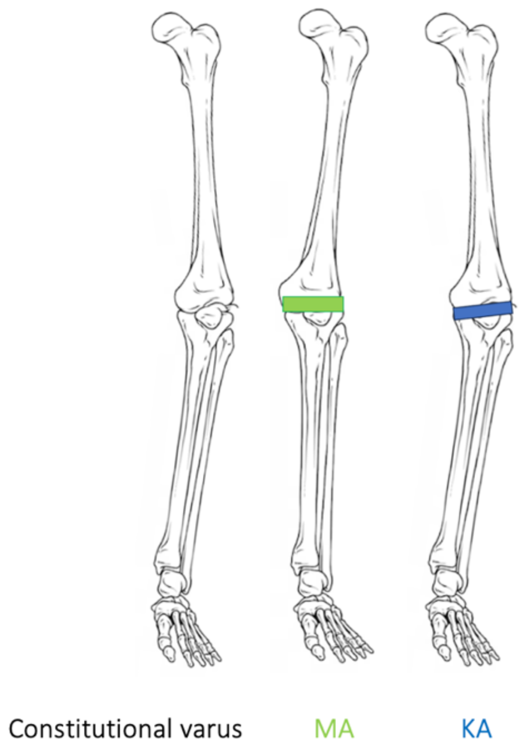

Fig 4 *The surgical alignment philosophies: on the left, the picture represents a constitutional varus deformity. In the middle, the green line represents mechanical alignment after surgery, on the right the blue line represents kinematic alignment after surgery*

In 2017, Venditolli, introduced the concept of "Restricted Kinematic Alignment" (rKA), as a hybrid option between MA and true KA introducing a "safe alignment zone" of 5° [31]. This technique wants to reproduce the patient's constitutional knee anatomy with KA, but within a safe range avoiding extreme pathological anatomies. In this technique the femoral anatomy is preserved and the gaps are adapted with the varus/valgus position of the tibia within the given safe range of +/- 5°.

Inverse Kinematic Alignment (iKA) is an evolution of KA with a tibia resurfaced equally maintaining the native tibial joint line obliquity and adjusting the tibio-femoral gap in extension parallel to the tibial cut.

Adjusted Mechanical Alignment (aMA) is an adaptation of the neutral mechanical alignment (180°) to obtain slight under-correction in the coronal plane, by adapting the femoral cut to retain a minor deformity of 3° and keep the tibial implant mechanically aligned.

5. Evolution with time and survivorship of the implant

The consequences of an excessive alignment outlier of the lower limb can be too much constraint on the implant or on the bone and bone-implant interface. Increasing constraint can progressively lead to loss of fixation of the implant [19]. This is called aseptic loosening (AL), because the loosening of the component is not due to a bacterial infection [32, 33].

It results from a reduction in fixation of the contact surfaces between the implant and the bone, leading to micro-mobility of the implant initially, followed by macro-mobility of the implant afterwards. Signs of macro-mobility of the implant are often accompanied by changes in lower limb alignment and can lead to clinical symptoms. These symptoms are usually pain, pain on weight-bearing or mobilization, instability because of deformity and swelling because of the production of joint fluid in between the loose components and bony surfaces.
This failure mode often needs a revision of all loose components, where attention is needed to understand the underlying mode of failure and to address this with the revision surgery.

Literature reports more and more cases of revision due to AL, becoming today, the main cause of revision of TKA, before infection [34-40].

6. Radiological follow-up and detection of radiolucent lines and aseptic loosening

a. Conventional radiography

After surgery, standard radiographies are performed to follow the patient and detect some local reaction, such as bone modification or apposition, changes in implant position or migration, etc… This type of imaging is not considered in the literature as sufficient to detect early loosening [41] , but still used in daily practice.
When patients are still painful after surgery, complementary examens can be performed in order to understand the physiopathological process.

b. Nuclear imaging

Bone scintigraphy was the first nuclear medicine used for investigating pain after TKA. Three phase bone scans use a gamma camera to create planar images after Technetium-99m diphosphonate is injected IV into the patient. This tracer accumulates on the surface of bone remodeling, with a physiological appearance around the TKA, up to one year after the surgery. The low specificity of radionucleotide bone imaging in knees with pain after TKA makes this modality useful as a screening test, more than as a diagnostic test. Currently, the tendency is to associate it to tomographic imaging, such as SPECT-CT [41, 42].

SPECT-CT, is an association of Technetium-99m diphosphonate injected IV into the patient coupled to a CT scan of the bone, 4 hours after the injection, creating a 3D image. This exam permits to detect radiolucent lines (RLLs) of 2 mm with better anatomic localization, but the difficulty of this exam is the non-uniform fixation of the tracer depending of the cement and the type of implant used [41, 42].

c. Radiostereometric analysis

RSA, is a geometrical projection by analyzing the localization and position of an implant. Two pictures of the implant are taken in two different positions permitting to detect the mobility of the implant to the bone. This technique has permitted to understand implant loosening patterns, depending of migration profiles according to implant constraint used, mode of fixation (cemented or not), gender and inflammatory diseases [18].

RSA is highly accurate analysis, but is rarely used, because of the need to implant tantalum markers into the bone during the surgical procedure, as a landmark defining the bone and TKA in 3D [18, 43-45].
More recently, a computed tomography-based RSA (CT-RSA) method showed a realizable and accessible option for researchers, with minimal specialized equipment and training [46].

7. The bone status of the knee

The increased use of cementless implants, leads to more attention to the bone status of the knee. The initial stability of the implant and the adequate ingrowth can depend of the bone mineral density of the knee [47].

Screening the bone status before the surgery and treatment before surgery, will reduce complications and migration of implants and the risk for periprosthetic fractures [48].
In elderly patients, the bone mineral density (BMD) around the implant, will not be better after surgery. The literature reports the interest to screen for osteopenia or osteoporosis before the surgery in women aged > 65 years and 70 years for men [49], as well as in patients with medication altering their bone status , low BMI and high Kellgren-Lawrence scores [49].

Recently, the use of the Dual energy CT (DCT) has shown interesting results in the preoperative screening of BMD before surgery [47].
The use of antiresorptive drugs, has shown improvement of BMD after TKA, as bisphosphonate still is the gold standard medication, follow by denosumab. Those treatments can be taken during a long time, with always the risk to develop complications, with as the most common necrosis of the jaw for the bisphosphonate. Denosumab can be taken during 36 months with a decreased rate of fracture.

Teriparatide, a recombinant human parathyroid hormone is the first anabolic treatment approved for osteoporosis [50]. It is recommended to stop the treatment after 2 years, due to the risk to develop osteosarcoma as shown in rats.

8. From the ancient mode to the modern definition of radiolucent lines and aseptic loosening

    a. Radiolucent lines

Radiolucent lines, have been described first in the 70s by Salvati with RLLs in cemented total hip arthroplasty (THA) [51] and studied around the tibial implant at the end of the 70s by J.A Lacey [52].

A RLL was defined in the literature as a line of 1-2 mm between the implant/cement and the bone (Fig. 5). These lines are observed on postoperative X-ray's quickly after surgery or later on during the implant life-time [53].

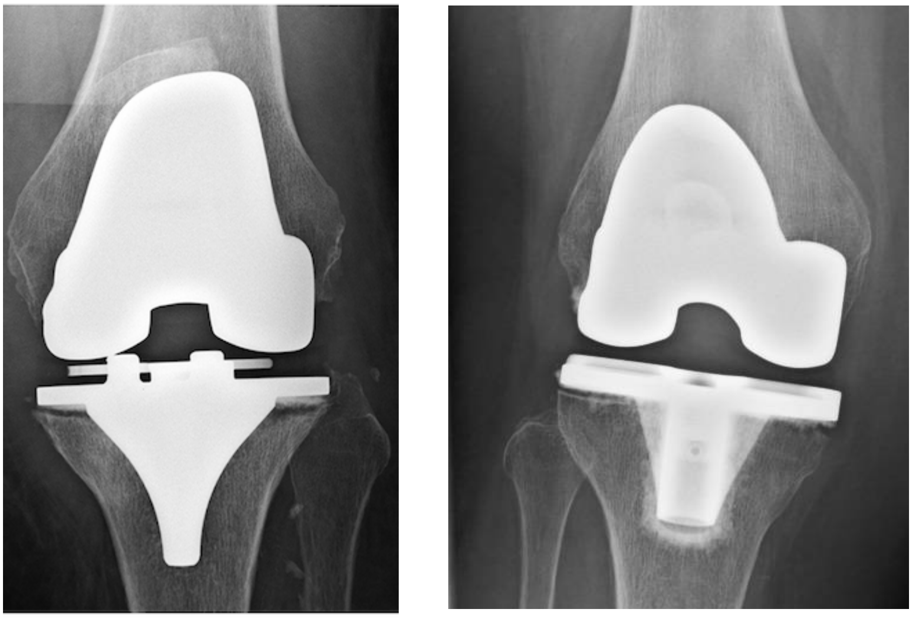

Fig. 5 *Radiolucent lines on postoperative X-ray's below both sides of the tibial base plate*

The first classification and mapping and sizing of the RLLs, was described by Ewald in 1989 [54]. The authors classified RLLs, by localization under the tibial, femoral and patellar implant on RSA on the AP and lateral view. More than the number of RLLs observed, the major factor for loosening was a RLL of more than 2 mm in more than one zone under the implant.

Ewald [54] has described and classified first the localization around the implants (Fig. 6) called the Knee Society Roentgenographic Evaluation System (KSRES) and after him others have modified the Ewald's classification and described the evolution (decreased or increased) and the potential link to AL [55].

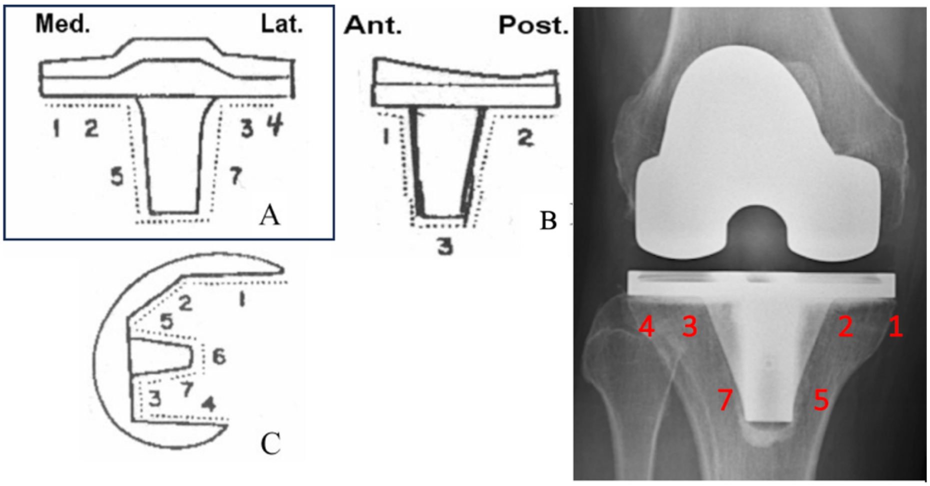

Fig. 6 *Ewald's classification*
On the left: The Knee Society Roentgenographic Evaluation System.
a. *Anteroposterior view of representative tibial component,*
b. *Lateral view of representative tibial component,*
c. *Lateral view of representative femoral component*
On the right: an X-ray representing the Ewald classification at the tibial side on an AP view

b. Aseptic Loosening

Aseptic loosening is defined as a complete loss of fixation between the implant and the bone/cement without notion of infection (Fig. 7).

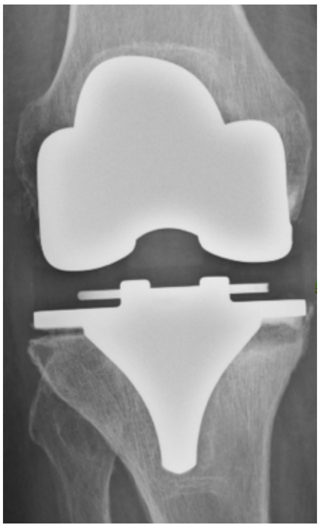

Fig. 7 *Aseptic loosening of tibial base plate: tilt of the implant in varus with mobility chamber around the keel, metaphyseal densification and periosteal apposition on the medial side and loss of implant-bone contact on the lateral side*

The tibial implant is the most common localization for loosening and may be due to inadequate initial fixation or mechanical loss of fixation as described before [56]. This last condition is attributed to changes of implant position or development of progressive RLLs.

The first descriptions of AL were attributed to PE wear, particulate disease and a biological reaction in response to third bodies [57]. Gallo described, the evolution on the time line as a close relation between mechanical and biological factors, contributing to loosening of the implant.

Constraint on the implant, leads to micro movement, bone or cement fracture and production of wear debris. These third bodies will create and maintain a biological inflammatory reaction, which leads to osteolytic lesions (osteolysis) and finally loosening of the implant [53].

c. Osteolysis around the implant

Functional forces on the implant may induce, directly after the surgery, generation of inert particles from the main component of the implants, PMMA, metal and PE.

Those particles, different in size and volume, called third bodies, will be present in the joint fluid inducing at their time, wear of the implant, as a vicious circle. Moreover, the inflammatory cells activated by presence of those particles in the joint fluid, would try to eliminate them.

This inflammatory reaction will present itself in two simultaneous ways. First, the cellular inflammatory response will induce a direct bone resorption around the implant, and a positive retroactive stimulation of inflammatory cells themselves with on effect on the synovial tissues and production of joint fluid, maintaining secondly the local osteolysis reaction and expansion of osteolytic cavities around the TKA.

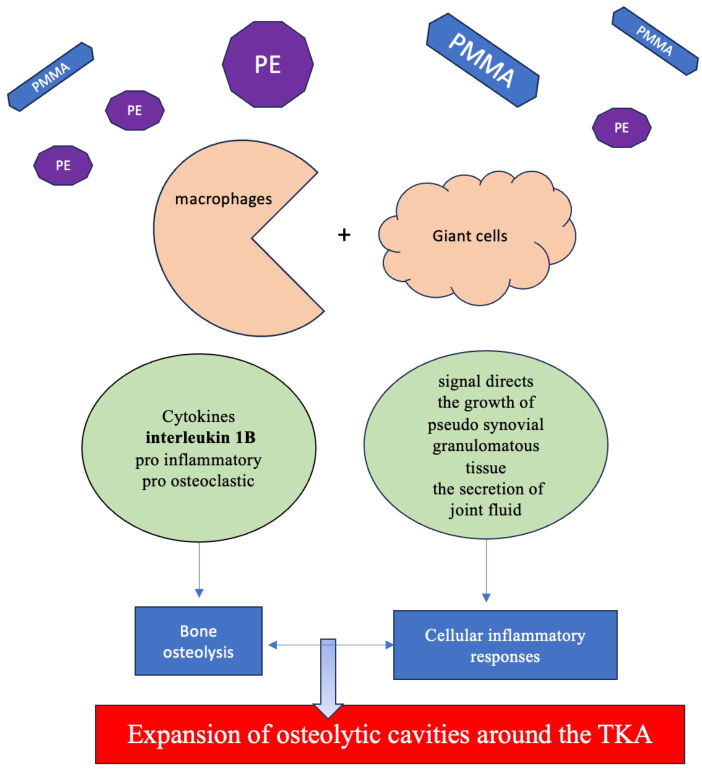

Fig. 8 *Third bodies inflammatory response and peri-prosthetic osteolysis reaction around the TKA*

9. Aseptic loosening of the implant

Depending of the time of apparition of loosening, early or late, the physiopathological process will be different. From a bone reaction due to the surgical procedure to an inflammatory response induced by wear of the implant, the literature report decreased frequency of those process notably by the positive evolution of research and surgical technic.

With progression of cementation technique, and cement properties, the mode of early failure have changed. It could be attributed to multiple and entangled factors:

- Fixation mode: cemented and uncemented
- Mechanical factors
- Surgical factors
- Biological factors
- Patient factors

a. Fixation of the implant to bone: cemented and uncemented implants

First generation of cementless implants have a high incidence of loosening due to an insufficient implant fixation to the bone. With the improvement of technologies, and particularly, the coating of the implant, the use of cementless implants has considerably increased [58].

Trabecular metal, which allows better osteointegration with morphological and biomechanical properties approximating that of trabecular bone, probably leads to better fixation due to a more normal peri-prosthetic bone mineral density (BMD) induced by stress loading.

Cemented implants show excellent results with the evolution of the technique of cementation, cement viscosity, etc... [53]. First generations of cement, created third bodies responsible for osteolysis around the implant, but with the improvement of the quality and viscosity of the cement, in case of poor bone quality or bone defects, cemented implants still remain the gold standard. Moreover, in case of constrained implants or in case of the use of a stem, cemented implants seem to be indicated.

However, the protocol of quality cementation needs to be respected as follows: After cleaning and well preparing the host bone (pulse lavage, drilling holes for sclerotic bone) a sufficient mantle 3-4 mm of cement is applied 2 minutes after mixing. This can be done by finger packing and hand applied on the femur and the tibia in one stage or with a pressurized application device. After cement application the knee should be positioned in full extension in order to have adequate pressure on the implant during the curing and hardening phase [59].

b. Mechanical factors

Mechanical factors may be resumed as an excess of resultant forces on the implant and the bone, due to the global limb alignment.
Excessive varus alignment of more than 3°, or tibial component positioning and excessive tibial resection are mechanical factor contributing to early loosening of the implant [53].

c. Surgical factors

The surgery, and especially the implant itself may be a risk factor for poor results. The design of the total knee arthroplasty, the size of the implant used (small), but also the length and the shape of the keel (small, thin, blade) are three majors factors influencing the fixation of the implant to the epiphyseal and metaphyseal bone (Fig.9).

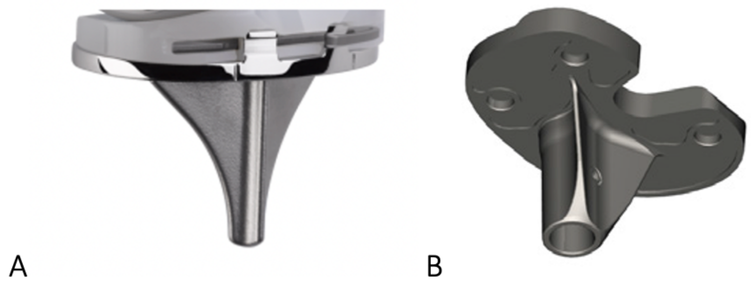

Fig.9 *Tibial implant design in total knee arthroplasty:*
a. *Vanguard knee design with a sharp finned tray*
b. *Persona knee design with a larger and more squared keel with robust fins*

d. Biological factors

The bone quality around the implant is also a patient factor contributing to the survival of the implant. This lack of sufficient bone quality can be present preoperatively because of osteoporosis or osteoarthritis or it can appear postoperatively due to the surgery with bone necrosis or resorption because of inflammatory changes to the bone. Indeed, BMD around the implant will change in the first years after surgery and decrease from baseline (5 % to 44% reduction after surgery) to the 12-month follow-up, but often reaches baseline levels again after 24 months.

Bone osteolysis around the implant [57] may be due to a bone reaction to the implant and the surgery, inducing tissue remodeling around the implant (Fig.10).
Micromotion of the implant will also induce bone remodeling and cement loosening.

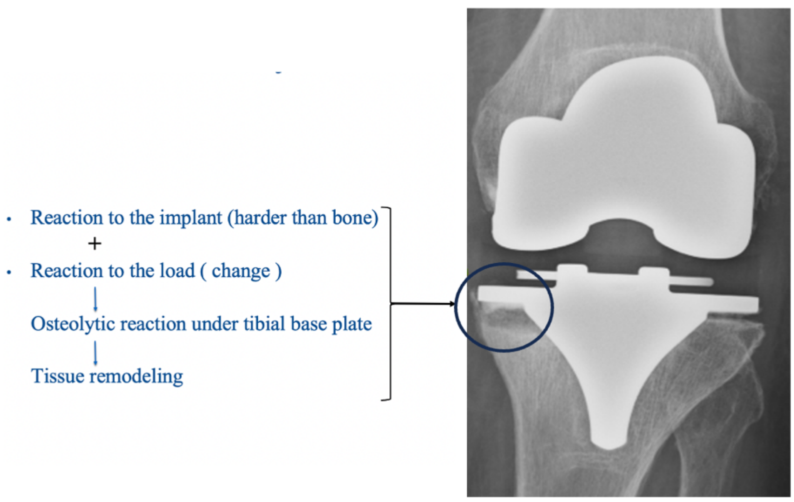

Fig.10 *Osteolytic cavities under the tibial base plate*

e. Patient factors

Loosening may be attributed to demographic factors such as age, gender or BMI of the patient. In the literature, some reported loosening due to younger age with high demand on their implant and more particularly on their PE and bone cement interface.
Men are also known to be more at risk than women for loosening, for the same reason than young patients. High BMIs of more than 35 have also a higher correlation with loosening.

Patient and biological factors are the 2 main causes over which we have the least control. Young men, with high BMI and tibial varus alignment are reported in the literature as a major cause of overload and loss of cohesion with the cement [60].

The diagnosis of AL can be subjective, with different definitions and management depending on literature reports and surgeon's experience.
Some defined AL as a peri-implant lucency greater than 2 mm in absence of local infection [33]. Others defined RLLs and considered them as a sign of loosening in case of progression and created a mismatch in definition and pattern process comprehension [61].
The consequence is an increased rate of AL report in the register data. This uptake in revision rates for AL has beaten revision for infection in the majority of reports [62].

10. Management of radiolucent lines and aseptic loosening according to the literature

The management of RLLs reported in the literature is completely binary.
Indeed, the evolution of RLLs could be asymptomatic and stable, and authors consider only radiological observation with time. Or, RLLs can be progressive (Radio lucent zones progress from 3 months to 2 years) or with signs of mobility and in this case the implant needs to be revised. The mean time to failure for progressive radiolucent lines is around 3 to 4 years in the literature [63-65] .

The grey zone between both mechanisms led us to investigate about these subjects. Based on our clinical and radiological observations, we were not convinced about RLL, the process, the evolution, and the relation to AL.

The aim of this scientific work was first of all, to obtain a clear definition of RLL and AL, while understanding the physiopathological process of each of them, in order to prevent and decrease the rate of RLL and as a result the inappropriate revisions that come with it.

Therefore, a radiologically study about the radiological appearance and follow-up of successive X-rays, of the same patient, was undertaken. Furthermore, the potential influence of different types of implants (with the same constraint) were studied for the same surgeon, in the same indication (OA) and for the same surgical technique (alignment philosophy, level of tibial cut, cementation technique, etc..).

With the radiological definition in place, we will be in order to compare our results with clinical information about the main reason for loosening observed in the literature: firstly, with clinical data: demographic data (age, gender, BMI), but also clinical risk factors for poor bone quality (tobacco, endocrinological diseases, rheumatoid pathologies, etc..). Secondly, with mechanical data: pre and post operative HKA angle, degree of correction (delta of correction) and final alignment in the “non safety zone”.

With all this information, it will be possible to define and understand the physio-pathological and mechanical processes at the origin of RLL and AL.

We have found two different patterns more or less related, with a clear definition and observation to predict whether RLLs will be dangerous and found some “predictive signs of loosening”.

With this observation and definition, we decided to act on modifiable parameters like the design of the implant and the quality of fixation of the implant to the bone, firstly at the epiphyseal level and then at the metaphyseal level, in order to observe the impact of these changes on survival of the implant.

Radiolucent lines and aseptic loosening in primary total knee arthroplasty

Chapter II: Radiolucent lines around knee arthroplasty components: a narrative review

What did we learn from this scientific work?

As the rate of AL has dramatically increased, as reported in the orthopedic literature in the last 10 years, the literature was reviewed about these two concepts: RLLs and AL. The aim of the review was to obtain scientific information about the development process and to conclude to a definition for these two issues.

All medical publications treating RLLs and AL were searched on PubMed and Google Scholar.

A huge amount of publications was found about both these subjects. Of 1121 publications found during the initial search, 296 were retained after first screening and only 71 publications (6%) were considered pertinent enough for literature review.

It was hypothesized that a clear and practical definition would help surgeons in their daily practice about observations and decisions to be taken in the presence of RLLs and AL.

This narrative review had the ambition to answer the following research questions:

What does AL of knee components exactly mean?
How should we define RLL according to literature?
How can we recognize and classify them?
How can we distinguish RLLs from osteolysis?
Are all RLL identical?
Are all RLL diagnostic for loosening of knee components?

Radiolucent lines around knee arthroplasty components: a narrative review

Adapted from: Wautier D, Ftaïta S, Thienpont E. Radiolucent lines around knee arthroplasty components: a narrative review. Acta Orthop Belg. 2020 Mar;86(1):8294. PMID: 32490778.

Abstract

Aseptic loosening of TKA components is one of the frequent reasons for early revision together with infection and instability. Aseptic loosening is usually preceded by the observation of RLL on radiographs. Radiolucent lines have conventionally been considered a sign of osteolysis due to particles disease of either PE or cement wear.

However, RLL can be observed quite early after TKA, way before wear and osteolysis can even occur. Immediate postoperative RLL are secondary to surgical technique with either inadequate cement penetration in sclerotic bone, insufficient preparation of the bone or mal-positioning of the component relative to the bone cuts.

This type of RLL can be observed radiologically but remains often without clinical symptoms. Early development of RLL, on an initially satisfying radiograph, is secondary to changes to the cement-bone interface. These are most often related to micromotion because of constraint, malalignment, remaining mechanical deformity, erroneous bone cuts or osteoporosis.

This type of RLL is observed progressively on follow up radiographs and can be accompanied by pain complaints despite of initial good outcome. Young age, male sex or osteoporotic bones often found in elderly females, are all risk factors. A special form of AL is tibial debonding that has been observed for different types of implants and different types of cement. It occurs at the cement implant interface with cement remaining well attached to the trabecular bone. Probably it is a lack of cement adhesion between the high viscosity cement and the component. Revision is proposed upon diagnosis to avoid component's displacement with secondary destruction of the proximal tibial bone.

Finally, RLL can develop over time secondary to PE wear. These lines appear because of osteolysis and bone loss and will lead at the end to AL of the components. Symptoms are related to failure of the implant-bone construct. Radiolucent lines without clinical symptoms should be analyzed according to their potential reason of development and followed up closely with adequate radiological techniques. If symptoms develop or radiological imaging objectivizes failure and component mobility, revision knee arthroplasty might be necessary.

Keywords : Aseptic loosening · Radiolucent lines · Knee arthroplasty · Cement · Revision.

Introduction

Osteoarthritis of the knee is one of the future medical challenges for the next decades. An increase in TKA demand of 673% is forecasted for 2030 with a cumulative rate of 306% increase between 2012 and 2030 for revision surgery [66]. Patients undergoing this type of surgery remain more active than ever before and have TKA performed much earlier in their lifetime than previous generations [63, 67-73]. Knee OA is becoming more frequent because of an increase in BMI with a growing burden of obesity, due to the consequences of previous knee surgery (meniscectomy, anterior cruciate ligament (ACL) reconstruction) and because of lower limb malalignment. Bellemans et al have shown that especially athletes during their adolescence develop varus alignment, with potentially later in their life time the development of OA.

Patients undergoing TKA expect longevity of the implant and wish to avoid revision of their arthroplasty. Failure in TKA can be either early or late. Instability, infection and AL are the three most frequent causes of early revision [60]. Radiolucent lines are often the reason to suspect AL and to revise one or more components for loosening. Radiolucent lines come however in different shapes and forms. The radiolucency can be early or late onset.

The most frequent causes for early RLL are bone osteolysis because of thermal necrosis during cementing, debonding at the cement-implant interface, mechanical bone resorption because of poor bone quality, micromotion of the implant at the cement-bone interface or cement allergy [74-77]. Sometimes it is a late-stage development because of PE wear and debris resorption.

Radiologic imaging can assess RLLs if the imaging is performed according to standard guidelines and fluoroscopic positioning of the beam parallel to the components [34]. If the RLLs are asymptomatic and stable over time, observation is sufficient. If, however, the radiolucency is progressive and signs of component mobility are observed, surgery might be required. In those cases, a diagnostic algorithm should help the surgeon identify and differentiate component loosening for aseptic or septic reasons.

This narrative review on RLLs around knee arthroplasty components has the ambition to answer the following research questions. What does AL of components exactly mean? How should we define RLL according to literature? How can we recognize and classify them? How can we distinguish RLLs from osteolysis? Are all RLL identical? Are all RLL diagnostic for loosening of the components?

Materials and methods

A systematic literature search was conducted by the authors (DW and SF). The senior author (ET) advised about inclusion of a paper in case of doubt between the other two authors. The electronic databases searched were: MEDLINE and Google Scholar. Search was based on "arthroplasty, replacement, knee"[MeSH Terms] OR ("arthroplasty"[All Fields] AND "replacement"[All Fields] AND "knee"[All Fields]) OR "knee replacement arthroplasty"[All Fields] OR ("total"[All Fields] AND "knee"[All Fields] AND "arthroplasty"[All Fields]) OR "total knee arthroplasty"[All Fields] AND ((radiolucent lines [Title/Abstract]) OR (radiolucency [Title/ Abstract]) OR (osteolysis [Title/Abstract]) or (aseptic loosening [Title/Abstract])) .

Initially, 1121 articles were found. Based on the title and abstract read and after removal of duplicates, 286 articles remained. The full text of each of these articles was read and another 91 articles were considered nonrelevant and removed from the database. The final number of articles included in this review was 71. Their data and content were used to define and answer the following questions covered in the discussion.

Discussion

1. What does aseptic loosening of components exactly mean?

Aseptic loosening is a frequent mechanism of implant failure [78] because of the loss of fixation between the implant/cement and the bone because of inadequate initial fixation, mechanical loss of fixation over time or periprosthetic tissues remodeling associated or not with osteolysis due to an intraarticular inflammatory response. Polyethylene wear, osteolysis and instability can all lead to AL [7, 63] The tibial component is the most common site of loosening in TKA [64, 79, 80].

Aseptic loosening is the most common late mechanism of failure [7, 63, 65, 77, 81, 82] over a period of 10 to 20 years [83] leading to progressive arising of pain, functional limitation, difficult weightbearing and gait alterations, leading finally to component mobility, implant migration [16, 78] and revision surgery [56].

2. What is the frequency of aseptic loosening according to both literature and registries?

A recent review [60] based on arthroplasty register data showed that the risk of revision after TKA in UK was <5%, 4% in Sweden, 5% in New Zeeland and 6.8% in Australia at ten years post operatively.
According to the registries, AL is still the main cause of revision with 29.8% [36] and this can reach up to 40% according to previous studies [38] , followed by 14.8 % for infection and 9.5% for pain. This finding is in contrast with retrospective studies based on US registries, which showed that infection was the first cause of revision followed by loosening, PE wear and instability [76, 85]. In Asia [86] infection is still the most common cause of failure (38%) in the 5 first years followed by loosening 33%, wear 13% and instability 7%. But AL was the most common cause of failure after 2 years [64, 76, 77, 87] , as shown in a recent multicenter study.

3. How can we define radiolucent lines according to the literature?

Radiolucent lines are defined as a radiolucent interval (measured in mm) between implant and cement or between cement and bone [65, 79, 82]. Radiolucent zones are quite often observed in the immediate postoperative phase [79], and are frequently localized under the most medial or lateral zones of the tibial plateau (zone 1 and zone 4 according to KSRES) [82, 88].

Radiolucent lines may be attributed to poor cement penetration into cancellous bone or micromotion between the implant-cement or bone cement interface, leading to bone resorption and cement loosening [64, 65, 79].

Several studies have shown that the width and extent of RLL zones of the tibia tend to progress from 3 months to 2 years post operatively [64, 65, 79] with a mean time to failure of progressive RLL within 3,7 years as observed by Berend et al [16, 89, 90].

4. How can we recognize and classify radiolucent lines?

The KSRES of Ewald and the Modified Radiographic Evaluation System of Bach et al are the most reproducible and reliable protocols to study RLLs on radiography [90, 91]. This method consists of adding in each of the specific component zones, the measured width of the RLLs present on the two radiographic views (frontal and lateral view) to classify it as narrow or wide. If the sum of the widths of the RLL is 4 mm or less, the category "narrow" is used, if the total is greater than 4 mm the category "wide" is used.

Widths numerical additional score of each zone for each component is calculated. For the tibial component a numerical score of 0-4 suggests a stable or nonprogressive RLL, followed by progressive RLLs (score 5-9) and finally failure implant status when the total score reaches 10 or more [54].

A RSA study by Ryd et al, showed that the tibial component is at higher risk for AL than the femoral component [80]. Moreover, RSA permits to define and predict implant loosening, by observing early migration [64, 80] . They define migration of more than 2 mm between 12-24 months to be considered as "continuous migration" with increased risk of AL [80]. A recent Cochrane review showed that cemented implants migrate less than uncemented components, but showed a higher risk for AL due to a continuous migration pattern [80].

More recently, a modern KSRES and methodology for TKA, has been developed, describing the general location/ regions of RLL, and osteolytic lesions in primary and revision knee [55]. The lucent lines are graded as partial or complete and osteolytic regions should be documented in mm in the zone location [55]. This evaluation system is descriptive, not predictive or prognostic.

5. What is the difference between radiolucent lines and osteolysis? Which pathophysiological mechanisms and radiological observations can we make?

Constraint on the implant, leads to micro movement, bone or cement fracture and production of wear debris. These third bodies will create and maintain a biological inflammatory reaction, which leads to osteolytic lesions (osteolysis) and finally loosening of the implant [57].

Osteolysis occurs as the result of a foreign body response to particulate wear debris from the prosthetic joint with a frequency between 0 and 16% for cemented TKA [92]. These particles of PE, PMMA cement or metal, will induce a distinct inflammatory response [57, 93, 94]. The macrophages and giant cells in the synovial and periprosthetic tissue will phagocyte these wear particles. These cells will induce osteolysis by direct bone resorption or indirectly by stimulating cellular inflammatory responses. The activated macrophage begins the production of cytokines, especially interleukin 1B, a pro inflammatory and pro-osteoclastic cytokine. This interleukin 1B has also a minor effect on decreasing bone formation by its action on osteoblast activity [94]. Simultaneous, the inflammatory signal directs the growth of pseudo synovial granulomatous tissue and the secretion of joint fluid, all contributing to the expansion of osteolytic cavities around the TKA [57].

Polyethylene wear is a chemically inert material comparable to metal particles; in consequence macrophages are unable to degrade them once they have been phagocyted [95]. Polyethylene wear particles in joint arthroplasty may differ in type and size according to the wear mechanism. The generation of particles starts immediately after surgery, due to functional forces [57], but the osteolytic potential of wear particles is dependent on particle size and volume [95]. Polyethylene wear in TKA occurs from a combination of rolling and sliding and rotational motion creating smaller bioactive particles. Other sources of wear such as third body wear, fatigue fracture or delamination of the PE surface or stress fracture of the post will create large flakes or pitting particles [57, 93, 94]. Osteolysis around the tibia tends to occur along the periphery of the component or along the access channels of the cancellous bone [83, 94].

6. What are the major causes of radiolucent lines? Why do they appear? What is their natural evolution?

Radiolucent lines, which often precede loosening, can be a direct witness of mechanical or biological processes firmly entangled that lead to weakening of the bone and loss of cohesion with the cement [57]. During the first year after TKA, the loss of bone density is almost 23% and generally normalizes in the majority of patients after 3 years [57]. However, mechanical factors such as daily life or physical activities in young patients, obesity, malalignment, are all influencing the bone cement interface [57, 93].

Loosening of an implant, in the early phase, may be due to a cementation complication such as thermal or chemical necrosis or a technical error. In younger and more active patients micromotion may induce loosening of the implant by loss of interlock between bone cement and trabecular bone [80, 96, 97]. Over time, loosening may occur due to an osteolysis phenomenon, by wear debris or loss of periprosthetic bone stock in older patients, influencing the longevity of the implant [72, 80, 96, 98].

It’s important to distinguish failure due to mechanical, or cumulative stress on an initial well-fixed implant, and an early loosening due to technical error [57]. In the past, many authors tried to explain the histology of RLL. Some theories proposed RLL as macrophage induced osteoclasis by Freeman in the 70s and 80s, another theory saw RLL as thermal necrosis and micromotion by Charnley in 1970 and a third potential explanation was seen in trabecular bone quality at the level of the bone cuts by O’Connor and Goodfellow in 1982 [99]. Since these times no new theories have been proposed.

The preparation of the tibial surface with cleaning and pulse lavage, the cementation technique and the technical side of the surgery are well known factors to have a significant effect on reducing the occurrence of RLLs [79, 82]. As well as imperfect cuts (stress shielding) and micromotion that both increase the risk of loosening [82]. Smith et al [65] described on RSA, two types of RLLs.

The first type is a nonprogressive RLL that results from poor cement penetration into sclerotic bone. This occurs in about 15% of tibial implants on early-onset, they are nonprogressive and typically in relation with preoperative sclerosis, but no tibial osteolysis and no tibial component revision for AL are observed.

Non progressive RLL are <2mm thick, have shown no correlation with a poor clinical outcome and thus confirm other studies, which have suggested that tibial implants presenting these RLL were not automatically subject to revision [64, 99]. Such RLL do not affect fixation, but they could facilitate the entry of debris into the interface, they can progress and become the second type, which is progressive, and can quickly expand to become obvious areas of osteolysis [64, 65, 79].

Radiolucent lines can also be a sign of interface membrane growth with the mechanical and fluid pressures in association with the biological cascade of osteolysis and the AL process [57]. When a gap at the cement-bone interface occurs, it's always present immediately after TKA surgery [57, 100]. This empty space at the bone-cement interface will be filled by fibrous tissues containing few cells and blood vessels. The mechanical stress and fluid movement induced by walking, leads to proliferation of fibroblast synthesizing extracellular matrix in order to adapt the stress and strain around the implant. The macrophages specially activated by PE wear and pressure increases their expression of cytokines [57]. In this environment, a combination of mechanical stress and hypoxic condition will lead to proliferation of fibrous tissues containing macrophages, fibroblast, and multinucleate giant cells [57].

Aseptic loosening has a multifactorial etiology [64, 85, 100, 101] with as main factors; the patient (age and BMI), the implant (type of PE, type of constraint, design) and the interface (type of cement and cementation technique). Some surgical or technical errors such as inadequate fixation [83], excessive tibial cut or varus alignment [36, 85, 101] but also bone quality, genetics, and endotoxin factors may be responsible [36, 64, 83, 102].

a. Patient Host Factors

A recent study on host factors affecting survival of the implant found a significant correlation between the age and sex of the patient, with especially young men at risk for AL [36, 57, 60, 86].

All studies agree that the revision rate increases with decreasing age [36, 60]. According to the Swedish register, patients younger than 65 years have twice the risk of revision than those with an age of more than 75 years.

In Australia, at 4 y follow-up, patients younger than 55 years have a more than 4.5 times increased risk for revision compared to those aged more than 75 years [60]. In Asia, a multicenter study [87] confirmed that loosening was the first cause of failure (33%) for people younger than 65 years.

They also found that for each 10 years of increment of age, there is a decreasing risk of AL of 70% [87]. Others found an increased risk of 5% per decreasing year of age [100]. Some report that men have a higher rate of revision than women, with a cumulative risk of revision (CRR) of 1.6.

In the English registries, the CRR for men aged more than 75 years is 2% at ten years and the CRR for men younger than 55 y is 12%. The main reason is that young people are more demanding and have higher expectations of their TKA combined with higher activity levels [60, 68, 87]. The consequence is that either PE wear or too much constraint on the bone-cement interface leads to loosening of the implant.

A recent study, based on the risk of AL in obese patients [100, 103] found a significant correlation between a higher BMI of 35 $kg/m^{2,}$ despite a well aligned TKA, and the risk of AL. In their series, 1% of the TKA were revised for AL, closely matching the 1.3% rate previously cited by Breed et al with a mean time to revision of 5.6±0.4 years. They calculated a cumulative probability of revision of 0.8% and 2.7% at 5 years and 15 years respectively [103].

They also found that obesity with a BMI > 35-40 kg/m^2 has a cumulative risk of revision for aseptic tibial loosening at 5 years and 15 years of 1.2% and 4.3% versus 0.5% and 2.2% respectively for normal weight, so 2 times more at 15 years.

Another potential factor adding to RLL, is excessive tibiofemoral varus alignment, varus tibial component positioning and excessive tibial resection [57]. Although studies have shown that residual varus alignment in patients with preoperative varus leads to better clinical outcome [67, 70, 87]. Several biomechanical studies have demonstrated that postoperative tibial varus alignment of more than 3° increased medial tibial surface strain [57, 76, 80, 85, 89, 92, 101, 104, 105] with a load distribution over the medial plateau between 70 and 77% [92].

This overload on the medial side leads to asymmetrical PE wear but also medial cancellous bone strain and finally implant failure by medial collapse, especially in younger active patients [92, 105].

Toksvig Larsen and Ryd [82, 88], reported that a gap of 1mm to 2mm between the lower and the uppermost point of the tibial plateau after cutting, will induce more tibial stress shielding. Berend et al showed that the cumulative risk of high BMI > 33.7kg/m^2 associated with varus tibial component alignment, increases the risk of failure by 168-fold [101, 103, 104, 106].

b. Bone Quality

Successful TKA depends also on the quality and the mechanical properties of the periprosthetic bone [105, 106]. This quality may be altered by preoperative conditions such as osteoporosis and osteoarthritis or because of the surgery leading to a higher risk of loosening and revision.

The measurement of BMD, is based on the amount of mineral calcium of the bone by Dual-Energy X-ray Absorptiometry (DEXA), a validated and suitable method for monitoring bone remodeling close to the implant during the postoperative period [57, 80, 105]. However, measurements might be wrongly influenced by knee positions such as flexion or rotation [80, 105]. Studies based on this method have shown that BMD in a well aligned TKA decreases from baseline to the 12 month follow up but reaches baseline levels after 24 months suggesting that implant migration is related more to interface issues such as the general condition of trabecular bone than a change in BMD below the implant [80].

Preoperative osteoporosis seems to be a risk factor for TKA surgery, exposing patients to a higher risk of AL and revision by a reduction of the BMD [57, 80]. However, any significant correlation based on actual DEXA measurement and urinary DPD/creatinine ratio studies have been found [72]. Although, the use of bisphosphonates in postmenopausal women, has shown an increased BMD in spine and hip densitometry after 1 year of treatment [107]. Any significant results in terms of fracture prevention after TKA have been shown [107].

The use of bisphosphonates 10 mg in association with calcium 500 mg per day during 6 months post operatively [108] prove to maintain bone microarchitecture and greater implant stability at 12-24 months postoperatively by a reduction of periprosthetic BMD loss reducing the rate of revision surgery [72].

The tibial metaphyseal bone, can adapt to mechanical alterations such as malalignment caused by osteoarthritis [57]. For example, preoperative varus knees have a higher BMD under the medial plateau due to mechanical stress caused by the mechanical deformity.

The change in BMD post TKA has been widely studied, from the early postoperative period to the long term, with a range of reducing BMD from 5.1% up to 44% [80, 107]. This change may be due to stress shielding or changes in load after correction of any preoperative malalignment [109].

Patients with low postoperative BMD have demonstrated to be at higher risk of failure by prosthetic loosening and migration [57, 106] but also those with a high BMD in the medial tibial region. This finding suggests that proper alignment might be important in maintaining optimal conditions for bone density [80, 81, 106].

This change comes from the stress inducing strains on supporting bone, stimulating remodeling and resorption, leading to a postoperative decreasing bone density [81].

In case of sclerotic medial bone, failure of implant may occur by poor penetration of cement into the trabecular bone. But when the BMD is lower, the process of failure comes from the possible fragility of the trabecular bone supporting the tibial component, leading to fracture or collapse under the tibial tray, suggesting that proper balancing of forces, to a more physiological status, and proper alignment, is more important to maintain good conditions for bone density [106].

In 2014, Ritter proposed to use a routine x-ray protocol to predict failure on pre and postoperative radiographs [80]. He observed in the general TKA population, a significant reduction of density in all regions over time, from 2 month to 10 years postoperatively, with a greatest decline in density in the medial regions, followed by the lateral and distal regions to the keel [80].

In the progressive RLL and medial collapse knee group, he observed early on significantly higher medial bone densities beyond one year in all medial regions before failure [80, 106]. He attributed this earlier (2 months) high medial density to an excess altered mechanical load (varus and BMI) increasing stress and bone remodeling leading to medial collapse or failure. This was confirmed by biomechanical studies showing a significant correlation between tibial strains and component malalignment [80, 106].

Another factor that may influence bone quality is bone resorption, induced by micro motion between cement and trabecular bone, leading to increased circulation of interstitial fluid, which causes fluid induced resorption of trabeculae. This strain shielding could also cause bone resorption [70] in younger and more active patients.

c. The Implant

The properties of the implant may lead to failure either by a mechanical or a biological loosening process. Due to excess wear, PE particles produce a pro inflammatory state, which leads to increased osteoclast differentiation and macrophage production. This ultimately leads to local osteolysis and AL around the prosthesis [36, 60, 83, 101].

Some studies have pretended that the relative frequency at which RLLs appear on postoperative radiographs and their location depends on the design of the TKA [79]. Subsequent changes in design and surgical technique have decreased the risk of early aseptic failure of the tibial or femoral implant [70]. Historically, aseptic tibial implant loosening at the bone–cement interface was an observed cause of failure with semi-constrained TKA implant designs [76]. Cheng et al described early AL of the tibial component after TKA with debonding between the tibial component and cement mantle and an intact cement–bone interface [56, 76].

It's well known that smaller tibial size and higher BMI have an increased cumulative risk of mechanical loosening and migration [101]. Kajetanek et al observed more AL with smaller tibial keels in the same knee design [110].

7. Cemented versus cementless implant, do new technologies permit to forget the past?

New cementless implants have evolved considerably thanks to new surface coatings. Some are 3D printed and others are in trabecular metal, which allow better osteointegration with morphological and biomechanical properties approximating that of trabecular bone. This has potential benefits, but still these techniques remain more expensive [38, 111-113]. Advantages of a cementless implantation are shorter surgical time, preservation of bone stock, revision without cement removal and elimination of complications associated with cemented fixation like third body wear and retained loose fragments [38, 114].

Compared to cemented implants which provide immediate stability, cementless implants have a higher risk of early postoperative loosening with nevertheless long-term results comparable to cemented implant [38, 111].

Previous studies reported that both clinical outcome and long-term survival were inferior for cementless components, specifically on the tibial side [38, 111, 114, 115]. This was observed for the first generation of cementless designs, metal backed patellae and the use of conventional PE. With time, cemented implants became the gold standard but better surgical techniques and comprehension, improvement of biomaterials, and higher rates of osteolysis in the young patient led surgeon to search for a new solution for fixation [38, 115]. Specifically for patients younger than 65 years where the bone stock is good enough to allow osteointegration.

To ensure good primary stability of the implants bone resections must be performed accurately while avoiding gaps between the host bone and the components. In cemented TKAs, the cement mantle can easily fill small defects in resections without affecting the stability [115] . Rotating platform designs reduce the stresses at the tibial plateau interface and reduce shearing forces, often at the origin of early loosening [115] .
Literature reports similar long term results for modern hybrid fixation systems, combining a cemented tibial and patellar implant with a cementless femoral implant [115] .

8. Which indication is reserved for a cementless implant?

The number of patients younger than 65 years suffering from OA have considerably increased. These patients have high expectations and more demanding level of activities, despite the advances in surgical technique this remains a challenge. There is still concern that these implants will not last for the entire lifetime of many patients, with consequently a high revision rate due to more loosening phenomenon by greater stress on the implants [115]. In THA, cementless implant have improved by decreasing the cause of failure, particular osteolysis around the implant and cementless TKAs in young patients (<65 years) with adequate bone stock is the concept that osteoconductive component surfaces, in the presence of a very active bone metabolism, show high biological properties [115].

9. Which pattern of loosening can be observed with a cementless implant?

Fricka et al described that osteolysis patterns also differ depending on the mode of fixation. Among cemented components, loosening is characteristically preceded by the development of a linear radiolucency at the cement bone interface. In contrast, osteolysis associated with cementless implants typically demonstrates an expansive pattern in the metaphyseal bone that rarely interferes with component fixation [38, 114, 115].

Radiostereometric analyses allow to understand the different migration patterns shown by TKA components with the two different fixation methods. Cementless tibial baseplates may migrate early, i.e., in the first three months postoperatively, usually reaching stability after this interval; but cemented tibial components, on the other hand, do not migrate in the immediate postoperative period, while they may show micromotion over 60 months [115]. Cement is known to have poor resistance to shear and tensile forces, which can result in disruption of the bone cement or cement implant over time, creating third bodies leading to osteolysis and migration patterns [38]. Recent RSA studies have shown better osteointegration, mineral density and retention of bone stock and remodeling capacity, and so better long-term survival [111, 115]. Cementless implants have shown in the morbidly obese better fixation and lower loosening rates, probably due to the osteo-induction properties and better periprosthetic BMD induced by stress loading [112].

10. What is the role of cement and cementing technique in the development of RLL?

The occurrence of implant loosening has decreased following improved cementation techniques. Fehring et al, observed a decreasing rate from 40% to 25% of revisions in case of well-balanced cemented TKA [81]. Initial fixation of cement by adequate preparation of the bone surface is paramount for avoiding long-term failure of the tibial component [79, 116].

The intrinsic and extrinsic properties of bone cement such as preparation and application techniques are among many factors that affect the strength and stability of the bone–cement–implant interface [76].

a. Cement properties

Polymerization of bone cement occurs by mixing 2 copolymers, polymethyl-methacrylate powder and the methyl-methacrylate monomer, forming the crystal PMMA during an exothermic reaction. This polymerization progresses through four phases: a mixing phase, a waiting phase, a working phase and a hardening phase. This late phase can continue four weeks after implantation [108].

These 4 phases can be modified by properties of the cement, such as the porosity [116]. High viscosity cement (HVC) has relatively shorter mixing and waiting phases due to a fast polymerization process.

The amount of temperature created by an exothermic reaction is correlated with a faster polymerization process and a shorter setting time [117]. High Viscosity Cement has a longer working and hardening phase in comparison to lower viscosity cements, diminishing the depth of bone penetration to almost the double [56, 64, 76, 108] as shown by Rey et al [56].
Secondly, these properties will also affect the strength of cement, stronger with compressive forces than compared to shear and tensile forces [38]. These properties can lead to the development of micro fractures, which could contribute to crack propagation and debonding at the cement–implant interface [76, 108].
Thirdly, thermal bone necrosis is temperature and time exposition dependent [88, 94]. Below 47°C, literature reports no osseous injuries, but when the bone is exposed at temperatures between 47-50°C for 1 minute or more, bone absorption, fat cell degeneration and vascular necrosis injuries occur [64, 77, 108]. Furthermore, higher saw blade temperatures on sclerotic bone may induce necrosis [77].

Animal models show that thermal necrosis occurs after an exposition of > 1 minute above temperature of 53° leading to bone remodeling 35 weeks after thermal event. The exothermic reaction of the polymerization of 100 G of methyl methacrylate monomer used for cemented implants produces 13Kcal of heat, equivalent to in vivo bone temperatures of greater than 100°C. Modern techniques of cementation, such as cooling the cement permits to obtain better penetration of cement, with narrow thermal safety margins (36.81± 4.71) as shown on cadaveric models suggesting that increased cement penetration did not augment mantle temperatures and bone necrosis [77].

b. Cement penetration

Cement penetration into the microstructure of cancellous bone leads to implant fixation [79]. Component stability is obtained by achieving micro-locking with trabecular bone [77]. In case of poor cement penetration, an early nonprogressive RLLs under the tibial component following cemented TKA can occur [80]. The development of third generation cementation techniques has shown to improve cement penetration in the cancellous bone and decrease the rate of implant loosening [79, 80]. Ritter et al demonstrated that the proper preparation of the cancellous bone and pressurization of the cement reduces the initial occurrence of RLLs [80].

Multiple studies, have shown that an adequate technique of cementation depends on the cement and its application, but also on the bone quality and its preparation [64, 80, 108, 116]. Bone quality depends on the preoperative bone status but also on the tibial cut. A lower tibial cut leads to a smaller surface and another type of cancellous bone less compatible with cement penetration [64, 80].

In case of medial sclerotic bone, studies have shown that drilling the sclerotic bone [64, 108] with a 4.5 mm drill bit, allows better cement penetration and enhances tibial fixation with an occurrence rate of RLLs of 5.5% at 24 months postoperative compared to 20% with a 2.0 drill bit [71]. The RLLs vary in size and location according to the technique of pressurization, with progressive RLLs commonly associated with early failure [79, 80, 88].

The degree of penetration depends on the quality and porosity of the cancellous bone. In osteoporotic bone, Van Lommel et al observed an insufficient penetration with isolated application of cement onto the tibial component and excessive penetration when using a cement gun and confirmed the adequate cement penetration by spatula or finger packing [64, 116].

Krause and Walker demonstrated in the past, that timing of application of cement after mixing is inversely proportional to the depth of penetration [64] and that the better technique involved mixing for 4 minutes and fenestration of the tibial cancellous bone. Bone preparation consists of cleaning all debris and blood with a pulsed lavage because it is a more effective debridement than manual flushing [63, 64, 116] and drying with sponges and suction [64, 79, 80, 108] because the presence of blood reduces shear strength of cement up to 50% [64] .

Previous studies have shown that hand mixing tends to be inferior to vacuum mixing in terms of increasing porosity and decreasing tensile forces, but it is superior in antibiotic elution [108].

Based on radiographs and biomechanical experiences, Walker et al , suggests a mantle of 3-4 mm as the optimum depth for the penetration of cement [63, 77, 118] into the bone as the limit, with the risk of having collagen destruction if more penetration than 5mm occurs and substantial bone loss at time of revision [63-65, 88, 116].

Currently, there is some debate about the best application of cement and its technique [116]. There are many possibilities to prepare and apply cement, hand mixing and application or with a cement gun vacuum-packed.

Based on a recent study about cementing techniques [64], it's recommended to use a low or medium viscosity PMMA, hand packing, with a time to application of 3-4 minutes, and low storage temperature [76, 116].

Guha demonstrated in his study [79] that a single stage cementing technique may be superior to the two-stage technique in avoiding RLLs in the immediate postoperative TKRs by observing on cemented TKA 52% RLLs, with more significant RLLs in the two stage (68 %) than one stage (36%) with a prevalence of wide category RLLs in zone 1 and 4 [79, 80].

This observation was attributed to the pressurization technique of the cemented implant, being more effective when the leg is placed in full extension for final pressurization as in the one stage technique [79].

The application of cement, only to the tibial base plate or full cementation of the tibial keel still remains controversial [76]. Previous studies claimed that full cementing provides better fixation, less potential for micro movement and higher long-term stability [64, 116]. However, Cawley et al demonstrated in their experimental studies, that fully cemented implants had greater proximal tibial bone resorption by the induction of stress shielding in the proximal tibia and potential bone loss, which could lead to early loosening in the long term [64, 116, 119].

More recent studies showed no difference regarding implant survival between a fully cemented group and an interface cementation group, with a mean follow-up of 8 years and 9 years respectively [119]. This issue is however more complex than a choice between two cementing techniques since the main point will be the need for fixation and that a malaligned TKA in an osteoporotic patient might need two zones of fixation instead of only one.

A recent study by Hazelwood et al observed debonding between implant and cement, with a mean time to revision of 17 months, using Palacos R +G, a HVC, 50% of the tibia implant surface was devoid of adherent cement. The authors speculated that factors inherent to Palacos cement might have contributed to the loosening [76].

11. Motion of components

According to the Knee Society, the definition of implant loosening is identified radiographically as a change in implant position or as the development of a progressive RLL at the bone-cement or bone implant interface [120].

Tibial debonding is a specific type of gross loosening of the tibial component with most of the cement mantle still attached to the bone [16, 56]. Previous studies have shown that patients are little symptomatic, and that debonding can be observed early on radiographs. No correlation was found with overall alignment, component positioning or BMI. This particular mode of failure can be explained by some mechanical theories such as impingement of the post against the box, increasing stress to the modular interfaces of the tibia and could be a cause of failure [85]. Cheng et al described early AL of the tibial component after TKA with debonding between the tibial component and cement mantle and an intact cement–bone interface [56, 76]. They also observed more mechanical debonding with titanium implants than with chrome cobalt [69, 83]. Once debonding is observed, most authors recommend revision of the implant, in an effort to minimize damage to the proximal tibial bone stock [85].

Conclusion

In modern knee arthroplasty, AL is one of the rare reasons of early failure among infection and instability. Radiolucent lines are one of the indicators of potential AL of a component. However not every radiolucency is pathognomonic for loosening and should lead to revision.

This narrative review showed that several factors determine the appearance of RLLs like there are osteoporosis, alignment, type of cement used, level of the tibial cut and the implant utilized. Radiolucent lines that are < 2mm and nonprogressive without signs of instability of the implant should not be considered as a sign of AL. If the RLL are progressive, increasing in size and accompanied by signs of mobility of the implant revision can be considered in the presence of symptoms of pain and swelling for the patient.

Radiolucent lines secondary to osteolysis appear later during the follow-up of the implant and are related to bone resorption as a reaction to particles wear. These are a sign of wear of the implant and revision surgery is indicated in those cases.

Radiolucent lines and aseptic loosening in primary total knee arthroplasty

Chapter III: Aim of this doctoral thesis and its different study hypotheses

Why did we perform this scientific work?

In 2017, after performing the narrative review, it was decided to retrospectively study a cohort of patients operated for TKA, in order to challenge the literature to our daily practice.

The aim of this doctoral thesis was, to obtain more precise information about RLLs, the condition of their appearance, their time to develop, their behavior, why they appear as such, how to manage them and finally, if there was a link with AL.

The first study hypothesis was about RLLs and their non-predictive character in relation to AL, because we had observed RLLs without any clinical consequences on postoperative X-ray's in TKA patients.
It was stated that RLLs depending on the area of the tibial implant where they appear and depending on their evolution could be classified as innocent or at risk for leading to AL. Furthermore, we decided to retrospectively observe patients with RLLs who developed AL in order to understand the process and the progressive signs of a negative evolution, which we would call "predictive signs of loosening".
The aim of these observations would be to identify patients and surgical conditions that would influence survivorship of the implant. These could be bone quality of the proximal tibia, but also alignment and immediate fixation issues of the implant.

The second study hypothesis was inspired by the concept of three zone fixation in revision TKA and more particular of the proximal tibia.
Innovation during the last decade in knee arthroplasty, brought us new anatomical implants giving better epiphyseal coverage surface. We hypothesized that better epiphyseal coverage would lead to better epiphyseal fixation and therefore to less RLLs. Furthermore, the new knee design came with a more squared tibial keel than the previous knee design used and therefore it would allow us to study the difference in metaphyseal fixation of these two designs and the impact on RLLs or AL.

The third hypothesis of this thesis was that if we would augment the tibial fixation in the metaphyseal area, we might influence the rate of RLLs and of AL. Therefore, we retrospectively studied two groups of patients with the same anatomical implant offering the same potential epiphyseal coverage and fixation, but a different mode of metaphyseal fixation with either the standard tibial keel or a short stubby stem extension of 14 x 30 mm that can be added to the primary component.

Radiolucent lines and aseptic loosening in primary total knee arthroplasty

Chapter IV: Appearance and evolution of radiolucent lines below the tibial implant in primary total knee arthroplasty

What did we learn from this scientific work?

Before starting this scientific work, the authors had several clinical questions for which they didn't necessarily find the answers in the available literature, despite of an extensive narrative review.

A first series of questions was: Why do some patients develop early RLLs?
Why do they occur, since it cannot be because of PE wear in such an early stage? Under which condition do they occur? Is there a typical patient profile?

The second clinical question was: What strategy can we apply to RLLs?
Can I predict what type of RLL will behave badly and link it to a poor evolution for the implant? Identifying this type of RLL would help us in selecting which patient should be closely followed-up and which patient will be at risk to develop an AL of the tibial component.

The third clinical question was: How can I do better, as a surgeon, for my next patient? Can I interfere by my surgical technique or by my choice of the implant in the rate of RLLs depending on the patients' individual risk factors?

With the resources available to us, a large data base of TKA patients operated by arthroplasty-trained surgeons, applying a common surgical philosophy for several years before modifying some elements and with a highly recognized radiology department performing standardized radiographs since decades, we decided to retrospectively review a cohort of patients operated for OA with a cemented PS TKA and analyze their post operative X-ray's, clinical information and evolution with time.

The purpose of the first part of this scientific work, was to study the morphology and apparition time of RLLs, according to their clinical, surgical and mechanical factors, and to search for a correlation between RLLs and AL.

In reviewing the post operative X-rays, we issued two hypotheses for this first retrospective study:

(1) RLLs may have different radiological aspects and evolutions in time depending of different factors

(2) Signs of micro- and/or macro-mobility of the implant are necessary before diagnosing AL of the tibial component

Appearance and evolution of radiolucent lines below the tibial implant in primary total knee arthroplasty

Adapted from: Wautier D, Thienpont E. Appearance and evolution of radiolucent lines below the tibial implant in primary total knee arthroplasty. Arch Orthop Trauma Surg. 2023 Oct 25.

Abstract

Background The aim of this study was to evaluate TKA radiographically to detect the occurrence of RLL under the tibial base plate and to determine what type of RLL may have a correlation with AL. The study had two hypotheses: (1) RLLs may have different radiological aspects and evolutions in time depending of different factors (2) Signs of micro- and/or macro-mobility of the implant are necessary before diagnosing AL of the tibial component.

Methods Retrospective cohort study of 774 patients operated with a Vanguard TKA (Zimmer Biomet, Warsaw, IN, US) from 2007 to 2015. RLLs were recorded in a database and described according to their radiological aspect, localization, time of apparition, progression and eventual evolution to AL. Other collected parameters were pre and postoperative HKA angles, amount of postoperative HKA correction, surgical, clinical and demographic data.

Results 178/774 TKAs (23%) showed RLLs under the tibial base plate including 9 (1.2%) tibial implants needing revision for AL. Three different types and two aspects of RLLs were observed. Important deformity corrections or under-corrected implants were recognized as a mechanical risk factor for loosening. Elderly women with osteoporosis and young men with important preoperative deformities were identified as clinical risk factors for RLLs.

Conclusions RLLs are frequently present at the epiphyseal bone/implant interface after TKA, but do not mean the implant is loose. They can be considered a sign of reduced epiphyseal surface fixation due to micro-mobility of the tibial implant. Aseptic loosening can be observed radiologically when signs of macro-mobility of the implant are present at the metaphyseal level.

Level of evidence III.
Keywords Radiolucent lines · Aseptic loosening · Total knee arthroplasty · Survivorship · Revision TKA

Introduction

Radiolucent lines in TKAs are radiologically defined as lucencies with either an osteolytic or osteosclerotic effect [53], between the cement/implant interface and the bone [121]. RLLs under the tibial base plate are the most frequent localization [56]. With the improvement in materials, other mechanisms than osteolysis [122] might be responsible for these periprosthetic radiolucencies.

The mechanical implications of RLLs are a reduction in the surface of fixation of the tibial implant and the potential development of micro- or macro-mobility. Aseptic loosening is the progressive disappearance or absence of stable fixation between the cement/implant bone interface in the documented absence of infection. Aseptic loosening remains an important cause for revision [34-40, 123].

Morgan Jones et al. have demonstrated in revision TKA that there are three zones of fixation [124]. The same principle can be applied to primary TKA, where these three zones are also anatomically present, but have not been modified by previous knee arthroplasty or a mode of failure. Especially, the epiphyseal and metaphyseal zone of fixation will be crucial in primary TKA.

Three factors determine the potential of fixation in primary TKA: (1) TKA design factors, such as the coverage area of the epiphyseal tibial surface and the design of the tibial keel (shape, size and length) for metaphyseal fixation; (2) Patient factors, such as osteoporosis offering less construct support and sclerotic bone allowing less cement penetration and (3) Surgical technique factors, such as level of tibial resection, coronal alignment philosophy, amount of constraint and ligament balancing.

Depending on their time of apparition, RLLs can be related to surgical factors [17, 62, 125-129], postoperative alignment [15] or micromotion of the implant [33, 122]. Because the literature is not clear about defining RLLs [125], in case of apparition on routine radiographs, it often remains a subjective decision to declare a component with RLLs loose. This perception-based decision can lead to higher revision rates in registries for the index surgeon or the individual implant [127, 130, 131], but also to disappointing results for the revised patient.

Therefore, the value of the radiological observation of the apparition and progression of RLLs, a description of the type of RLLs that could behave badly in the future and the description of radiological signs of AL remains important.

The purpose of this scientific work was to study the morphology and time to apparition of RLLs, for one TKA design, according to patient's and surgical technique factors, while searching for a correlation between a specific type of RLL and AL.

The hypotheses for this retrospective study were that (1) RLLs may have different radiological aspects and evolutions in time depending on patients and surgical technique factors (2) Signs of micro- and/or macro-mobility of the implant are necessary before diagnosing AL of the tibial component.

Methods

The authors present a single center retrospective cohort study on 774 TKAs, implanted between 2007 and 2015 for primary osteoarthritis by two surgeons using the same surgical technique and the same type of implant [Vanguard, PS cemented device (Zimmer Biomet, Warsaw, Indiana, US)]. Surgical indication for TKA was preoperative osteoarthritis of the knee with Kellgren–Lawrence grade 4 in more than two compartments, based on preoperative radiographs (AP, lateral, 30° axial patellar view) and a standing full leg alignment view. All components in this study were cemented and the patella was resurfaced when the surgeon considered it necessary.

High viscosity cement was used in a one stage procedure for tibia and femur, with pulse lavage cleaning before cementing and drilling of the sclerotic surfaces allowing cement penetration when needed. Intramedullary alignment was used on the femoral side and extramedullary alignment on the tibial side. Sizing of the components was done intraoperatively according to the surgeons' experience and rotational alignment and gap balancing using a measured resection technique. The alignment target during this study period was adjusted mechanical alignment with 178° for the preoperative varus patients and 182° for the preoperative valgus patients [6, 10, 28, 132]. All patients underwent routine postoperative clinical and radiological controls at 3, 6, 12, 24 weeks, as well as 1, 2 and 5 year(s) postoperative.

In accordance with the conventional radiological guidelines, the leg was positioned for the AP view with the patella facing towards the X-ray beam to be tangential to the tibial base plate and with controlled rotation of the leg. For the lateral view, the patient was lying on the operated knee, which was flexed at 30°. For the patella view, the beam was classically positioned at 30° from the floor with the knee flexed at 45°.

Demographic data (age at time of surgery, gender and BMI), clinical data about diseases at risk for poor bone quality (endocrinological or rheumatologic pathologies, renal disease, positive history of alcohol abuse or smoking and medication or treatments with a potential bone remodeling impact (steroids)), were recorded from the hospital medical data file system. The level of tibial resection, PE thickness and tibial base plate size were also collected from the surgical procedure and included in the data base.

The authors studied the apparition of RLLs on the tibial implant because of the scarcity of RLLs observed around the femoral implant in this series, potentially because of superposition of the femoral component in the AP plane.

All x-rays were reviewed by one observer (DW) with a mean follow-up of 9 years (5–13 years). 178 TKAs presented tibial RLLs and were studied in more detail. The measurement system from PACs software (Carestream, Rochester, New York, USA) was utilized with an accuracy tolerance of 0.1 mm for RLLs size measurements and 0.1° for the HKA angle measurement.

This author read the same radiographies more than five times at different time intervals. The Cohen's Kappa was almost perfect agreement with an intra-observer agreement score of 0.926 for the radiological RLLs screening.

Localization of RLLs under the tibial baseplate was classified in zones according to the Knee Society Scoring System [54, 55].

Radiolucent lines were classified as either being osteolytic and as an irregular and unclear (radiolucent) line between the implant/cement interface greater than 2 mm or as osteosclerotic when an osteodense area (white sclerotic line, thin layer of lamellar bone) was visible under the radiolucent area.

In this series, the time to apparition was defined by the authors as immediate when the RLLs appeared within 6 weeks postoperatively, early if the RLLs appeared within 3 months and late if the RLLs appeared at more than 3 months postoperatively. Their modification over time (still visible or disappearance) was noted as unchanged, progressive or resolved.

When a RLL was present in one compartment only (medial or lateral compartment of the tibial component) it was defined as an Isolated RLL.
When it was bicompartmental and the RLLs were present simultaneously in both compartments, it was called a Combined RLL.
If the RLL was present in one compartment first, followed by the other compartment later in time sequentially, it was called a Sequential RLL.

In case of sequential apparition of RLLs, the authors identified the time of apparition of the first RLL as Time 1. For the time of apparition of the second RLL, the authors used the term Time 2.

For all TKAs with RLLs (178/774), the following parameters were studied: mean loadbearing preoperative and postoperative HKA angle (varus < 178° or valgus > 182°). The overall postoperative standing mechanical alignment was analyzed for its effective correction (under or overcorrection, i.e. preoperative valgus becoming postoperative varus or vice versa).

The mean HKA correction realized was called "delta of correction" defined by the authors as a mathematical difference between the preoperative and the postoperative HKA angle.
For each TKA, the amount of correction in degrees was measured, but also whether a positive delta (positive difference = postoperative HKA angle < preoperative HKA angle) or negative delta (negative difference = postoperative HKA angle > preoperative HKA angle) of correction was present.

The percentage of patients with a postoperative HKA angle of more than 3°, outlier from the neutral mechanical axis of 180° was noted. For each type of RLL, the authors compared the demographics, clinical and radiological variables, to understand the differences between them.

To assess and describe the radiological signs of AL, the authors retrospectively reviewed the successive X-ray's and clinical symptoms of 9 TKAs needing revision of the implant for tibial AL. The authors have observed postoperative modifications around the tibial base plate that they qualify as signs of AL. The authors compared the group of patients with signs of AL and those without for demographics, clinical and surgical variables, to understand the differences between both groups.

All TKAs with RLLs were collected in a database, including their date of surgery, last consultation in our center and whether the TKA was revised or not (revision in or outhouse), the date (time from index surgery) and the reason for revision as noted in the National Joint Registry.

Descriptive statistics were used for demographics, clinical and surgical data and sample characteristics are presented as numbers, means and standard deviations; categorical variables are presented as percentages. For continuous variables, violations of the normality assumption were tested using the Shapiro–Wilk test. The Cohen's Kappa method was used to obtain the intra-observer reliability. Between group differences were tested using unpaired *T* tests and chi-squared test was used for categorical variables. The authors used the Kaplan–Meier method to evaluate cumulative survivorship of the implant with the absence of revision as an endpoint. A multiple logistic regression was used to observe a statistic link between variables observed and the apparition of signs of AL. GraphPad Prism software 8.0 (GraphPad, La Jolla, CA, US) was used for statistical analyses, and a p value < 0.05 was considered as statistically significant.

Result

Isolated RLLs (Fig. 1a) are the most frequent RLLs in this series. They appear most frequently on the medial side of the tibial base plate (Table 1). A statistically significant correlation (p=0.016) was found between the preoperative HKA angle and the side of the Isolated RLL (Fig. 2a). A preoperative varus knee, most often presents with a medial Isolated RLL.

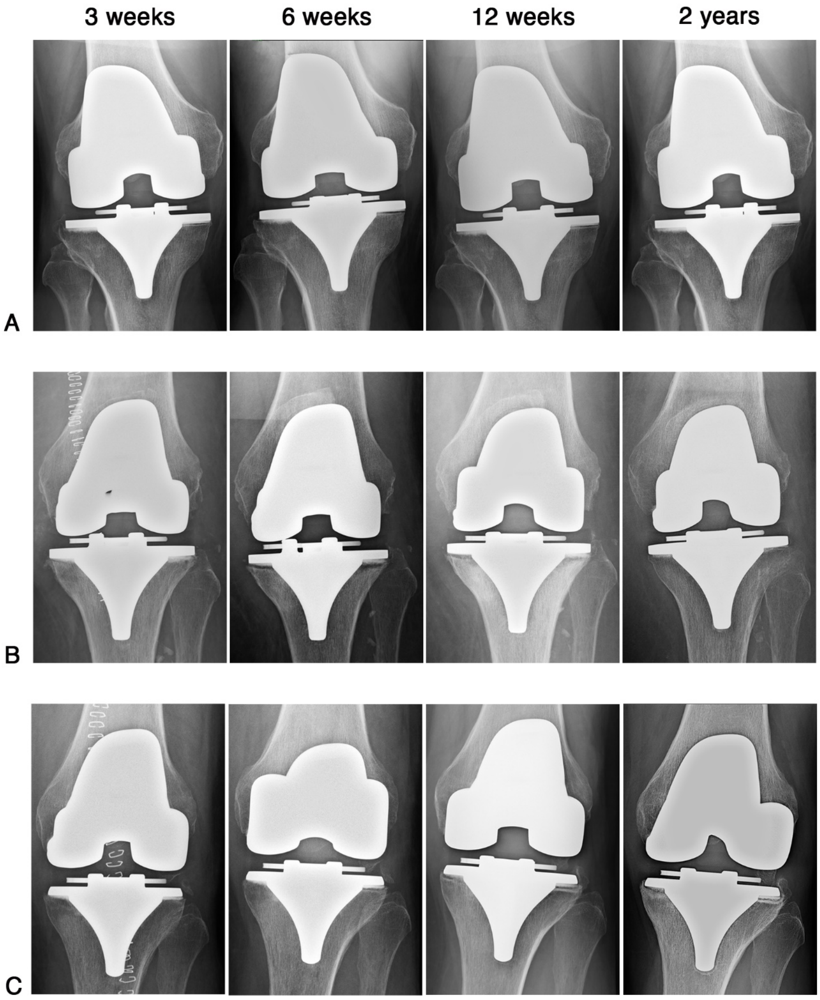

Fig.1 *Radiolucent lines aspect and characteristics on successive postoperative X-rays at 3, 6, 12 weeks and 2 years,* ***a.*** *Isolated RLL, sclerotic type, on the medial side visible at 6 weeks,* ***b.*** *Combined RLL under the medial and lateral side simultaneously at 6 weeks, osteolytic aspect,* ***c.*** *Sequential RLL with a first RLL on the lateral side at 6 weeks and the apparition of a second RLL on the medial side at 12 weeks*

If the preoperative bone aspect is sclerotic on the concave side of the deformity, the aspect of the RLL postoperatively will also be osteosclerotic in a significant manner (p = 0.008) (Fig. 2b). Over time, 42% of Isolated RLLs disappear at 2 years postoperatively, the other RLLs are often still visible, but without size modification (Table 1).

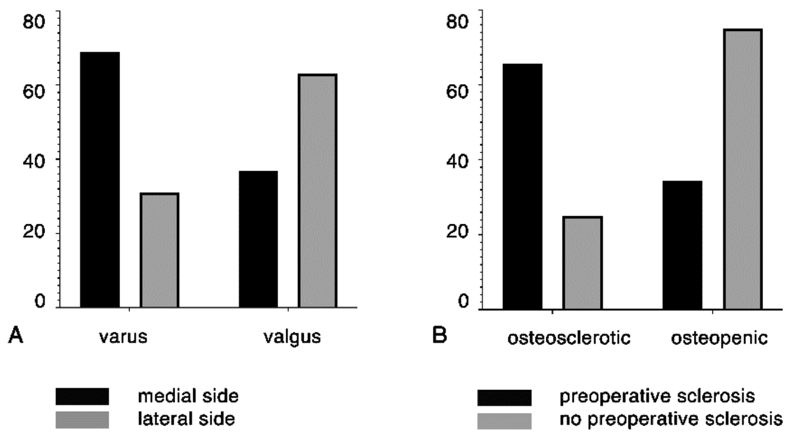

Fig.2 *Isolated RLL characteristics with X-ray's representing radiolucent lines with their location under tibial plate,*
a. *The graphs represent the proportion of RLLs on the medial and lateral side relative to their preoperative HKA angle (varus/valgus), 63% of lateral RLL are relative to preoperative varus and 69% of medial RLL are relative to preoperative varus.*
b. *Proportion of preoperative bone sclerosis or not in the osteosclerosis and osteolytic RLL, 66% of sclerotic RLL are relative to preoperative bone sclerosis and 75% of osteolytic RLL are relative to non-sclerotic preoperative bone*

Combined RLLs (Fig. 1b) are the second most frequent RLLs in this series with a similar time of apparition as Isolated RLL and a majority of osteolytic lines (Table 1). Sequential RLLs (Fig. 1c) represented 18% of RLLs in this series.

The side on which appears the first RLLs in the sequential group does not show a correlation with the preoperative or postoperative HKA angle. The Sequential RLLs display a significantly earlier time of apparition of the first line (p = 0.017) and a delayed apparition of the second RLL (Table 1).

Table 1 Radiolucent lines: proportion, time characteristics, aspect and evolution

Variables	Number of patients *N* (%)	Postoperative time of apparition of RLLs (in weeks)		Side of apparition	Radiological aspect	Radiological evolution at 5 years
		Time 1	Time 2			
TKAs without RLL	596/774 (77%)	–	–	–	–	–
TKAs with RLL	178/774 (23%)					
Isolated RLL	77/178 (43%) 77/774 (10%)	11 ± 14	-	70% medial 30% lateral	64% osteosclerotic 36% osteolytic	2% of RLLs disappear
Combined RLL	69/178 (39%) 69/774 (9%)	10 ± 9	–	Both sides	Osteopenic	52% disappear
Sequential RLL	32/178 (18%) 32/774 (4%)	6 ± 5 *	24 ± 19	Both sides	Both aspects	12% disappear

Values are expressed as Mean ± SD; Time is expressed in weeks by Mean ± SD. * Significant value

Isolated RLLs appear in patients with a moderate preoperative HKA angle and good alignment correction. Combined RLLs are seen in patients with a high preoperative HKA angle and a significantly higher ($p = 0.003$) positive delta of correction and with thicker PE sizes ($p = 0.013$), than other types of RLLs (Table 2).

Sequential RLLs were typically present in younger patients ($p = 0.010$) and patients with more clinical risk factors for poor bone quality ($p = 0.004$). A higher proportion of negative deltas of correction was significantly correlated with this type of RLLs ($p = 0.012$), but this group remained overall under-corrected.

For all three types of RLLs, the percentage of TKAs with postoperative HKA angle outliers and the amount of deviation was not significant (Table 2).

Table 2 Type of radiolucent lines: demographic data, surgical and mechanical values of the cohort of RLLs

Variables	Isolated $N=77$ (43%)	Combined $N=69$ (39%)	Sequential $N=32$ (18%)
Demographic data			
Age (years) ± SD	70 ± 10	68 ± 9	65 ± 10 *
Gender female/male	59/18 (3/1)	50/19 (3/1)	24/8 (3/1)
BMI (kg/m2)	30 ± 6	30 ± 5	29 ± 7
Patient with clinical risk factors for poor bone quality (%)	34/77 (44%)	40/69 (58%)	20/32 (63%) *
Implant size			
Tibial base plate (mm)	71 ± 4	71 ± 5	71 ± 4
Polyethylene (mm)	11 ± 2	12 ± 2 *	11 ± 2
Mechanical data (degrees)			
Pre-operative angle			
Varus	174 ± 4	171 ± 6 *	175 ± 5
Valgus	188 ± 4	188 ± 4	188 ± 6
Post-operative angle			
Varus	177 ± 2	176 ± 3	176 ± 3
Valgus	183 ± 2	183 ± 1	183 ± 3
Proportion of knees with positive delta of correction in the varus–varus group			
Proportion (%)	21/77 (27%)	21/69 (30%)	12/32 (38%)
Delta of correction (degrees)	3 ± 4	6 ± 6 *	1,5 ± 4
Proportion of knees with negative delta of correction in the varus–varus group			
Proportion (%)	7/77 (9%)	3/69 (4%)	8/32 (25%) *
Delta of correction (degrees)	2 ± 0	3 ± 0	2 ± 0
Proportion of knees with a post-operative HKA angle > 3 degrees of 180°			
Proportion (%)	(22/77) 28%	(16/69) 23%	(11/32) 34%
Post-operative angle (degrees)	175 ± 2	174 ± 3	174 ± 2

Values are expressed as Mean ± SD; *Significant value

The authors found 31 TKAs presenting with potential radiological signs of AL (Table 3) in patients with RLLs.

Table 3 Signs of aseptic loosening: proportion and time of apparition

Variables	Number of patients (%)	Time of apparition of signs of AL (months)
Radiolucent lines around the keel	31 (100%)	8 ± 5
Metaphyseal densification and epiphyseal bone apposition	15 (48%)	10 ± 6
Increase in HKA-angle	17 (54%)	18 ± 11

Values are expressed as Mean ± SD; *Significant value

The first sign was a RLL around the tibial keel, seen as a white sclerotic line around the keel (Fig. 3a). Second, in 48% of patients with signs of AL, the authors observed the apparition of metaphyseal bone densification under the tibial base plate and epiphyseal bone apposition on the side of the deviation (Fig. 3b). Finally, 54% of patients with signs of AL, presented a progressive mean increase of their postoperative HKA angle of 4 ± 4 degrees (Fig. 3c), appearing within a mean of 18 ± 11 months postoperatively (Table 3).

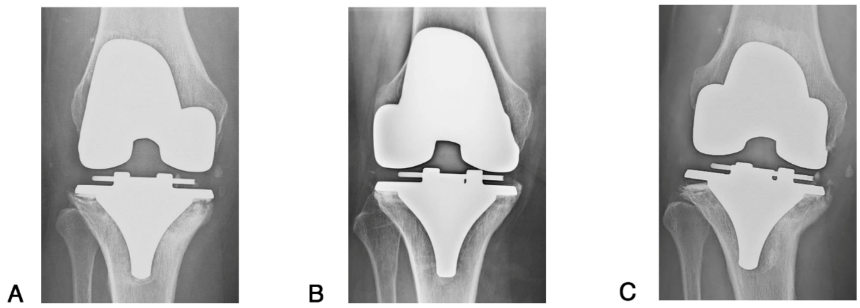

Fig.3 *Signs of aseptic loosening on post operative X-ray's.*
a. *Radiolucent lines around the tibial keel with bone densification and sclerosis at 1 year postoperative follow up;*
b. *Metaphyseal densification and epiphyseal bone apposition on the medial side at 1.5 years;*
c. *Tilt of the implant with medial collapse at 3 years leading to revision*

The majority of RLLs represented in this group of patients with signs of AL were Combined RLLs (Table 4). The Isolated RLLs were sufficiently followed-up, from 5 to 13 years, to be certain they were not Sequential RLLs. For Sequential RLLs, the first RLL was immediate with a mean general time of apparition significantly earlier in this group of patients (6 ± 4 weeks for Time 1 (p = 0.028) and 16 ± 14 weeks for Time 2 (p = 0.078)) (Table 4). In the group of patients with signs of AL, the authors did not observe any major increase in size of the RLLs under the tibial base plate.

Table 4 Total knee arthroplasty with radiolucent lines without and with signs of aseptic loosening and revision cases: time characteristics and time to revision

Variables	Number of patients (%)	Postoperative time of apparition of RLLs (weeks)		Postoperative time to revision of the implant (months)
		Time 1	Time 2	
TKA without signs of AL	147 (83%)	10 ± 12	28 ± 20	-
Isolated RLLs	74 (50%)	11 ± 14	-	
Combined RLLs	51 (35%)	11 ± 10	-	
Sequential RLLs	22 (15%)	7 ± 5	28 ± 20	
TKA with signs of AL	31(17%)	6 ± 4*	16 ± 14*	
Isolated RLLs	3 (10%)	3	–	
Combined RLLs	18 (58%)	7 ± 5	–	
Sequential RLLs	10 (32%)	4 ± 2	16 ± 14	
Revision cases	9 (5%)	4,7 ± 3	18 ± 19	55 ± 31

Values are express by Mean ± SD; * Significant value

In the group of AL, women were more represented (p = 0.028) (Table 5) with a higher risk of loosening associated with female gender (OR = 3.73, p = 0.038) (Table 6). Eighty percent of patients had clinical risk factors for poor bone quality (p = 0.001) (Table 5) with an OR = 4.21 (p=0.002) (Table 6). The tibial base plate was smaller 69 mm (p = 0.007) (Table 5) and the multiple logistic regression showed that a bigger tibial implant size significantly positively influenced the absence or development of signs of AL (OR = 0.86, p = 0.009) (Table 6). The PE size was significantly thicker (p = 0.014) (Table 5). Each increase of 2 mm of PE thickness, increased the risk for signs of AL by a factor 1.3 (OR = 1.3, p = 0.019) (Table 6). The mean preoperative HKA angle in the group of AL was significantly higher for both the varus (p = 0.008) and valgus (p = 0.002) group (Table 5). The majority of patients (29/31) with signs of AL had a postoperative varus angle, 11/31 were overcorrected from valgus to varus, and 18/31 were under-corrected varus.

The postoperative HKA angle value was significantly ($p = 0.002$) higher in his group, and the analysis of the delta of correction showed that all patients with an increased postoperative HKA angle were in the postoperative varus group (Table 5). Forty eight percent of patients in the AL group presented with a residual postoperative varus of the tibia of more than 3 degrees, compared to 22% for the group without signs of AL, and this difference was significant ($p < 0.001$) (Table 5).

Table 5 Signs of aseptic loosening: demographic data, surgical and mechanical alignment values

Variable	Radiolucent lines without signs of AL $N = 147$ (83%)	Radiolucent lines with signs of AL $N = 31$ (17%)
Demographic data		
Age (years)	69 ± 9	66 ± 9
Gender female/male	105/42 (3/1)	29/3 (9/1) *
BMI (kg/m2)	30 ± 6	29 ± 6
Clinical risk factor of Poor bone quality (%)	(67/147) 46%	(25/31) 81% *
Implant size		
Tibial base plate (mm)	72 ± 4	69 ± 3 *
Polyethylene (mm)	11 ± 1	12 ± 2 *
Mechanical data		
Pre-operative angle		
Varus	174 ± 5	170 ± 6*
Valgus	187 ± 4	181 ± 5*
Post-operative angle		
Varus	177 ± 2	175 ± 4 *
Valgus	183 ± 2	182 ± 0
Proportion of knees with a post-operative varus HKA angle > 3 degrees at 3 months		
Proportion (%)	39/177 (22%)	15/31 (48%)
Post-operative angle (degrees)	175 ± 2	172 ± 4 *
Proportion of knees with increased post-operative HKA angle at 4 years		
Proportion (%)	–	17/31 (54%)
From Valgus to Varus	–	7/17 (41%)
From Varus to Varus	–	10/17 (59%)
Delta of evolution (degrees)	–	4 ± 4

Values are expressed as Mean ± SD; * Significant value

The multivariable logistic regression shows no significant increase of the risk for signs of AL according to age (p = 0.2648) or BMI of the patient (p = 0.4294). A postoperative HKA angle outlier > 3 degrees, significantly influenced (OR = 1.264, p = 0.047) the risk for signs of AL (Table 6).

Table 6 Multiple variable regression: clinical or surgical risk factors and signs of aseptic loosening

Variable	OR	IC	*P* value
Age	0,98	[0,94;1,02]	0,2648
Women	3,73	[1,24;16,19]	0,0378 *
BMI	0,97	[0,91;1,04]	0,4294
Clinical risk factor of poor bone quality	4,21	[1,79;11,13]	0,0018 *
Polyethylene size	1,3	[1,04;1,61]	0,0187 *
Tibial implant size	0,86	[0,76;0,96]	0,0089 *
Post-operative HKA angle > 3 degrees	1,264	[0,78;3,86]	0,047 *

*Significant value

Three TKAs (0.4%) were considered in need for revision because of loosening of the implant in our institution, because they combined clinical symptoms with radiological signs of AL (Table 4). Based on the National Joint Registry, six other TKAs with RLLs were revised for AL in other centers. Three TKAs of that group only showed signs of RLLs and three other TKAs have indeed radiological signs of AL. This implies a survival rate of 98.4% for the entire cohort and 94. 9% in the series of 178 TKAs with RLLs under the tibial base plate (Fig. 4). It also implies that 33% of patients in this series were revised for RLLs and not for radiological signs of AL.

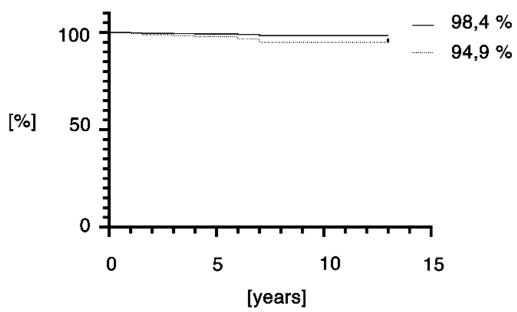

Fig.4 *Kaplan–Meier curve presenting survival of implant (absence of revision) as the endpoint in our series. The solid line: 98.4% of survival in the series of 774 TKAs; The dotted line: 94.9% of survival in the cohort of patients with RLLs*

Discussion

Fixation of all components, and more particular for this study, of the tibial component is a crucial factor to obtain pain relief and good functional outcome after TKA. Micro-mobility of the implant implicates the inability of the bone/implant interface to offer good early fixation. This can lead to macro-mobility of the implant when the bone is unable to compensate with remodeling and it will eventually lead to tilt and AL of the implant over time. In the recent literature there are, to the best of our knowledge, only rare descriptions and definitions of RLLs, their evolution and the difference with AL at the tibial level component in TKA [56, 99].

The authors identified three types of RLLs, at the level of the tibial component, different by their radiological aspect (osteolytic or osteosclerotic), location, time of apparition and evolution. These observations at the epiphyseal bone/implant interface were, to the best of our knowledge, not described in literature before. Isolated RLLs were the most frequent type of RLL, followed by Combined RLLs and Sequential RLLs. Isolated RLLs appear early on the concave side of the corrected deformity, where the osteoarthritic wear was present. The medial side is, therefore, the most frequent location observed in this study, because of a higher proportion of preoperative varus cases in this series [130, 131].

Combined RLLs appear early in both compartments under the tibial base plate at the same time and are observed in patients with bigger preoperative deformities. They are probably explained by a simultaneous change of load on the epiphyseal bone on both sides under the tibial base plate. A higher amount of correction and the use of thicker PE sizes in these cases, because of a lower tibial cut, can be the origin of this observation [133, 134].

Sequential RLLs appear on both sides under the implant, but sequentially in time. First, an early RLL is observed at the convex side of a residual postoperative deformity, corresponding with distraction forces. The second RLL is later observed at the concave side of the deformity with a compression of the tibial bone. These conditions were found more often in under-corrected patients, such as in constitutional varus or when the surgeon positioned the implants in varus on the tibia [129].

In Sequential RLLs, the observation of the apparition of the second line, some weeks after the first line, is important.

Despite of the relative earlier apparition time of a lucent lines in this type of RLLs, the apparition of a RLL in one compartment does not make it an Isolated RLL as it can always evolve to a Sequential RLL. Therefore, radiological follow-up remains important up to 1 year after surgery. In this study, the apparition of all types of RLLs, was within the first postoperative year, and more specifically within the first 3 months after surgery, in contrast to previous studies [36, 123, 127, 130, 135].

The authors observed two types of RLLs without any consequences on the survival of the implant. The most frequent radiological aspect was an osteosclerotic RLL, much more represented in Isolated RLLs, probably due to the absence of cement penetration at the side of preoperative sclerotic bone in minimal tibial resections, as previously observed in the literature [121]. The other aspect is the osteolytic RLL, a radiolucency of 2 or 3 mm, associated with a metaphyseal densification under the RLL. The authors have observed a decrease in size and disappearance after 2 years by bone remodeling in a stable implant [122, 136]. Osteolytic RLLs are most often observed as either an Isolated or a Combined RLL. In the Combined RLLs, the osteolytic RLL does not disappear for 50% of patients, but remains stable if metaphyseal densification appears. The authors did not observe more cases of AL in patients with osteolytic RLLs, so they do not consider this radiological aspect as a higher risk factor for loosening, in contrast to the past where osteolysis was a clear sign of PE wear and secondary loosening [54, 121].

The authors demonstrated three progressive signs of AL appearing in a specific order and visible on successive postoperative X-ray's, with different rates of representation for each patient (1–3 signs), depending on the level of progress of AL in each case. These signs appear later, after first apparition of RLLs under the tibial implant, testifying of a progression of the micro-mobility to macro-mobility of the implant, at each apparition of a new sign. To the best of our knowledge, this sequence of apparition of signs of AL as the authors observed, has not previously been described in the literature. The authors only found one study, reporting patterns of migration without radiological description [137]. In this series, the first sign observed was a RLL around the keel, considered by the authors as the progression of the micro-mobility of the implant from the epiphyseal zone (RLL under the implant) to the metaphyseal zone (RLL around the keel).

This aspect appears a few months after surgery due to an increase of the bone mineral density, inducing a mineralization of the mobility chamber, visible and stable for years as a white border around the keel [32, 138, 139].

The second sign observed, was an epiphyseal bone apposition on the loadbearing side of the postoperative HKA angle (medial for varus alignment). Easily explained by the modification of the cancellous bone elasticity (Wolff's Law) [140, 141], this reaction may be sufficient to compensate and "stabilize" the implant as observed in this and other studies [142, 143].

The third sign observed, was the increase of the postoperative HKA angle visible on successive standing full leg radiographies. The authors believe that this sign, visible from the second to the fourth year after surgery, is the most objective and pejorative sign of progression of the macro-mobility [144] and measurable by a medial shift of the loadbearing axis [145]. Ritter, described this mode of failure as the inability of the bone to compensate for the increased contact stress on the medial side, as observed in knees aligned in varus leading to failure by tibial collapse [89, 143].

The concept of potential AL observed by an increased size of RLL is a previous literature concept. Indeed, increases of RLLs is defined as a potential sign of AL, but in this study, the authors have found that only osteolytic RLLs showed small modifications in size: this can be both increase and decrease without necessarily an evolution to AL. The apparition of signs of macro-mobility as defined by the authors: RLL around the keel, periosteal epiphyseal apposition and increases in HKA angle, are objective radiological signs of AL.

In this series, some patients showed a slow increase of the HKA angle (< 3 degrees) and apparent progressive stabilization by epiphyseal and metaphyseal bone apposition on the side of the postoperative deformity. In the absence of pain and without a progression in their HKA angle, they were not revised. Other patients, presenting with a sudden and important increase of the HKA angle without apparition of bone apposition, often being painful, were revised by the authors because of AL. Full leg standing radiographs are not performed in all institutions, but this study emphasizes their importance as a load bearing analysis of the progression of deformity and the need for revision.

The signs of AL were observed in patients with early Sequential and Combined RLLs presenting clinical risk factors of osteoporosis and female gender, confirming previous studies [18]. AL might be explained as macro-mobility, after suboptimal epiphyseal fixation allowing micro-mobility of the implant, caused by more important constraints on poor bone quality, by the final alignment (varus) or by the more important lever arm on the implant induced by a lower cut and a thicker PE, as previously observed [136, 142].

In these patients, the authors suggest to be attentive for the apparition of the first signs of macro-mobility, by following the postoperative HKA angle and the evolution of the mechanical pain. Therefore, clinical and radiological follow up seems indicated.

In case of the presence of preoperative risk factors for AL, such as in women with clinical risk factor for osteoporosis and more important deformities, the authors suggest to adapt the surgery to the patient by choosing the best epiphyseal coverage possible and with more metaphyseal stability, as described for newer anatomic implants or by the use of short stem extensions [124, 136, 138].

This cohort study carries several limitations. First, it is a retrospective study, with all limitations of such a study design, because the study protocol had no impact on the quality control of specific incidences of the postoperative X-ray's. Fortunately, our radiology department has since many years been looking specifically for RLL on coronal X-ray's and knows the importance of rotation in the coronal plane. Furthermore, the exact timing of the radiological follow-up was less rigid than if this would have been a randomized controlled trial, but for 2 decades long all patients were seen at 3, 6, 12 and 54 weeks post operatively, allowing some standardization. Some osteosclerotic RLLs may have disappeared, because of a wrong position of the beam more than a physiological evolution of the line, without CT or fluoroscopic evaluation impossible to say. Second, only two experienced knee surgeons were involved in the surgeries, what might have led to a reduction of alignment outliers despite of conventional instrumentation. Their alignment target was 178° HKA in the varus and 182° in the valgus knee [26] with one surgeon aiming for tibial neutral and femoral under-correction and the other for tibial varus of 3°. This study overall alignment outlier cases included extraarticular deformities at the tibial or femoral level ranging from old fractures, bowing or constitutional varus of the tibia. Individual component positions were not measured as tibial or femoral coronal angles. Third, these findings potentially only apply to the Vanguard implant, which is known to have good survivorship [140]. The keel design, with a cruciate finned tray, is intended to be press-fit and used without cement application, but does not allow for a stem extension to the primary components. Fourth, although our series contains 774 patients, the authors found only a small amount of RLLs (4%) with predictive signs of AL and only 9 cases needing revision (1.2%). Fifth, in this study, the absence of clinical data collection and individual component positioning for patients without RLL, did not allow the authors to use that group as a control for statistical comparison.

Another limitation would be that the authors have observed RLLs only on a AP and not on lateral views because of the ease of observation, the presence of a validated Knee Society Classification System for the coronal plane and sometimes the absence of true lateral views. A combination of a RLL in two planes might have another impact than only in the coronal plane, but the end result of an AL should than be observed anyway. A final limitation is that the description of RLLs of the femoral component was not performed in this study, because the authors rarely observed RLLs around the femoral implant in this series.

Conclusion

RLLs about the tibial implant are frequent (23%) and do not necessarily mean that the component is loose and should be revised. These radiological lines are indicative of bone remodeling around the implant, induced by the surgery. Combined and sequential RLLs could be behaving badly and should be closely followed at least for 1 year after surgery with radiographs. Isolated RLLs can be considered stable, if no change appears after 3 months. Radiological signs of AL, as described in the current study, in the presence of pain should be considered an indication for revision. For the same implant, surgical and patient risk factors for loosening are lower levels of tibial resection, under-corrected varus deformities in the young and active person and overcorrected valgus deformities in the osteoporotic elderly female patient.

Radiolucent lines and aseptic loosening in primary total knee arthroplasty

Chapter V: Tibial implant design in primary TKA: retrospective comparison of two designs for the occurrence of radiolucent lines and aseptic loosening

What did we learn from this scientific work?

Not all patients develop RLLs and not all TKAs develop AL.

Aside patient factors, we wanted to know if the design of the tibial implant could make a difference and so we decided to study this in the same patient group for the same arthroplasty-trained surgeons after introducing a new morphometric implant into their treatment strategy.

The initial implant the surgeons were using, had a symmetrical tibial component and the new generation would be an anatomical, morphometric component. Knee design has an influence on the potential for fixation in the epiphyseal- and metaphyseal zone of the proximal tibia. The notice of epiphyseal anatomy has been discussed over the past few years as the concept of coverage and anatomical matching with the native knee anatomy.

The impact of the metaphyseal design has been less a point of interest, since most surgeons consider these decisions made by engineers as sufficiently tested and proven in vitro. However, in vitro studies don't include surgical, biological and patient factors.

After the previous study, that allowed us to classify different types of RLL and their evolution over time, as well as the description of the individual parameters of AL, we decided to compare 2 models of implants, the classical implant described in the previous study, the Vanguard knee system with a new anatomical implant the Persona knee system, and to observe whether the design of the implant may have an influence on the rate of RLLs and AL.

The hypotheses for this retrospective study were:

(1) Persona tibial implant design offers better epiphyseal bone coverage than Vanguard tibial implant and results in less RLLs

(2) Better epiphyseal coverage and a more squared metaphyseal shape of Persona tibial design reduces micro and macromotion of the implant observed as less radiological signs of mobility in TKA

(3) Better metaphyseal fixation, because of a different keel geometry, especially in cases of poor epiphyseal bone quality, reduces the radiological signs of macro-mobility or AL in TKA

Tibial implant design in primary TKA: retrospective comparison of two designs for the occurrence of radiolucent lines and aseptic loosening

Adapted from: *Wautier D, Thienpont E. Tibial implant design in primary TKA: retrospective comparison of two designs for the occurrence of radiolucent lines and aseptic loosening. Arch Orthop Trauma Surg. 2023 Sep 21.*

Abstract

Introduction The purpose of this retrospective study was to study the effect of tibial implant design on the occurrence of RLLs and AL by comparing two different TKA designs.

Materials and methods Two types of TKA, different for tibial shape, size and keel design were compared, 255 for the first and 774 for the second. The occurrence of RLLs and radiological signs of micro- and macro-mobility and AL was analyzed. Demographic data were compared, as well as the type and rate of RLLs, occurrence of AL and the presence of potential risk factors.

Results The first implant design is morphometric and has a squarer keel than the second implant TKA. The overall rate of RLLs was similar (21% vs 23%), despite of a significantly lower rates of radiological signs of macro-mobility of the tibial component with the first implant (2% vs 17%). Survivorship of both designs was overall comparable (99.6% vs 98.8 %) the first implant group had more potential risk factors for poor bone quality than the second group ($p < 0.05$).

Conclusion A morphometric design is more anatomic and offers better bone coverage of the epiphyseal tibial surface. RLLs, as a sign of implant micro-mobility, were equally present in both designs. Radiological signs of macro-mobility at the metaphysis were less frequently observed in squared keel design. The morphometric implant did not show improved survivorship compared with a symmetric implant.

Level of evidence III.
Keywords Morphometric implant · Radiolucent line · Aseptic loosening · Revision TKA

Introduction

Not all patients are satisfied with their TKA and residual pain might be a cause [146, 147]. Pain can be related to obvious mechanical failure mechanism such as malalignment, instability or AL of the components. Sometimes no apparent cause can be determined and then the diagnosis for residual pain or dissatisfaction becomes more difficult [148].

In the absence of obvious implant failure, subtle variations of radiological normality might be interpreted as a cause for dissatisfaction. Examples are malalignment of a component outside the conventional ± 3° [132, 143], more than 2 mm of medial component overhang [149] or the presence of RLL around different components [55, 129, 150].

The potential impact on patient outcome of radiological variations depends on the subjective interpretation by the surgeon. One of those can be periprosthetic RLLs that are known to occur around well-functioning implants, but can also be considered signs of loosening by some. Facing a dissatisfied patient and depending of the knowledge about chronic pain [146], the expertise with painful TKAs [150] and the personality of a surgeon [151], the presence of RLLs might lead to revision TKA for so called AL.

However, in patients with other causes of pain, revision surgery might increase the suffering [152, 153]. It was the authors believe that RLLs, in modern TKA designs, should be explained by other reasons than AL due to PE wear and that a better knowledge about clear signs of loosening would help improve quality of care.

Radiolucent lines are more frequently observed around the tibial implant [154, 155]. Potentially, because there are more variations in the level of resection of the tibia and the proximal tibia seems to be more prone to local osteoporosis with its conical shape. The mechanical constraint that the tibial component undergoes can be important and is related to postoperative alignment, soft tissue balancing, the weight of the patient and their activity level.

Because epiphyseal fixation alone at the tibial implant/bone interface is not sufficient, a tibial keel of different shapes was added to the metal backed tibial component.

Current trends in TKA design have been moving toward the development of smaller keels to respect the concept of proximal bone stock conservation and to avoid stress shielding [110, 156]. Two types of patients might be in need for better metaphyseal fixation. The young and active patient, with a high mechanical demand of his implant [54, 157] and the elderly, more fragile patient presenting with osteoporotic changes of the proximal tibia. The quality of the bone might also change over time because of general health conditions or secondary to inflammatory processes.

The purpose of this study was to understand the influence of tibial design on the presence of RLLs and signs of AL.

The hypotheses for this retrospective study were:
(1) Persona tibial implant design offers better epiphyseal bone coverage than Vanguard tibial implant and result is less RLLs

(2) Better epiphyseal coverage and a square metaphyseal shape of Persona tibial design reduces micro and macromotion of the implant

(3) Better metaphyseal fixation, because of a different keel geometry, especially in cases of poor epiphyseal bone quality, reduces the radiological signs of macro-mobility or AL in TKA.

Methods

The authors retrospectively reviewed 328 TKAs operated from 2013 to 2018, for primary OA using the same surgical technique and one type of arthroplasty [Persona, PS cemented device (Zimmer Biomet, Warsaw, Indiana, USA)] and compared these with 781 TKAs operated from 2007 to 2015 with a second type of arthroplasty [Vanguard, PS cemented device (Zimmer Biomet, Warsaw, Indiana, USA)]. All patients underwent routine postoperative clinical and radiological controls at 3, 6, 12, 24 weeks, as well as 1, 2 and 5 year(s) postoperative, if it was possible. After 5 years of follow-up, only 23 patients had missed 1 or 2 X-ray controls in the Vanguard group and none in the Persona group. 9 patients with history of infection were excluded from this study, 2 patients in the persona groups and 7 in the Vanguard group, and 71 Persona implants were excluded from this study because of the use of a stubby stem extension. Finally, 255 Persona and 774 Vanguard implants were retrospectively reviewed.

All implants were cemented in one session with the keel cemented for both designs with a high viscosity, antibiotic loaded cement (Refobacin Bone Cement, Zimmer Biomet, Warsaw, US).

To answer the study hypotheses, the authors retrospectively compared the clinical and radiological outcome of these two implants.

For the first hypothesis, the authors compared the sizes in millimeters of the tibial base plate of both implants. The referencing size of the tibial base plate of Persona is represented by a letter from A to J. In order to compare the size of the implant, the authors converted the letter references in millimeters, using the size references from the manufacturer's technical brochure from Zimmer Biomet. The authors described the differences in size (A/P and M/L), thickness of the baseplate, shape of the keel and tibial design of both implants. The authors have described the geometrical difference of the tibial tray and keel of the Vanguard (Fig. 1a) compared to the Persona implant (Fig. 1b).

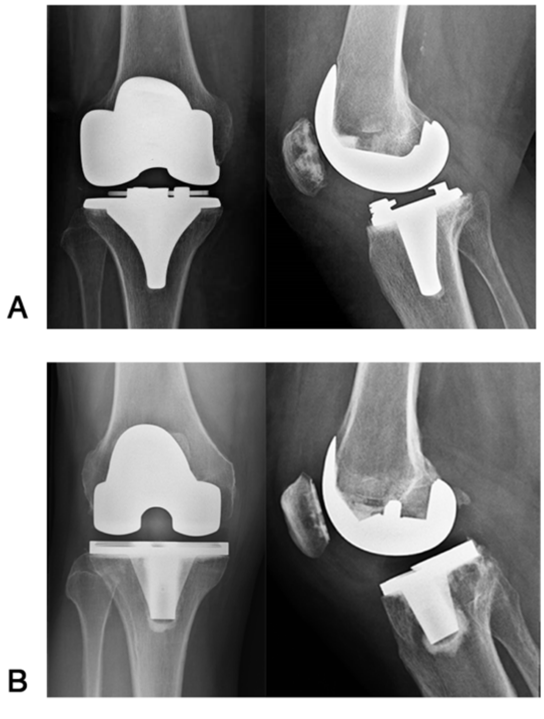

Fig. 1 *Postoperative X-rays of both implants with same mediolateral size showing the differences between both designs of the tibial base plate and keel (shape and length):* ***a.*** *Vanguard implant* ***b.*** *Persona implant*

Manufacturer's data collected for both implants are presented in Table 1.

Table 1 Manufacturer's design characteristics of the Persona and Vanguard implants

Variables	Persona	Vanguard
Tibial base plate		
Design of baseplate	Asymmetric morphometric	Symmetric
Baseplate thickness	3.7 mm	4 mm
Coverage surface of baseplate	92%	81%
Inclination of baseplate	5°	0°
Stem		
Design of stem	Cylindrical shape	Cruciate finned tray
Size of stem (mm)	31.4–39.7	40
Keel medialization	Medialization of 1 mm for each increase of 2 sizes of tibial implant	No
Stubby stem	Yes	No

Persona tibial base plate is asymmetrical with a more developed medial side in the AP direction, compared to its lateral side. The Vanguard implant is symmetrical with the same AP size on the medial and lateral side. The keel of Persona is larger and more squared with robust fins compared to the cruciate and sharp finned tray of the Vanguard keel (Fig. 1). For each increase in size of the tibial implant of Persona, the keel is medialized 1 mm.

Based on these observed design features, the authors hypothesized that the difference in epiphyseal bone coverage and metaphyseal keel size and geometry may have an effect on the primary fixation of the implant, especially in patients at risk for poor bone quality, with an impact on the appearance of postoperative RLLs or signs of macro-mobility or AL.

In order to answer the second hypothesis, one author (DW) reviewed, all the postoperative X-rays (AP, lateral, 30° axial patellar view and standing full leg) up to a minimum of 3 years postoperative for Persona and 5 years for Vanguard TKA. The measurement system utilized for this study was the Carestream Pacs software (Rochester, NY, US), which gives a high degree of accuracy, with a tolerance of 0.1 mm for RLLs size measurements and 0.1° for the angle measurements. The intra-observer difference was reconciliated by reading the same radiographs more than 5 times. The Cohen's Kappa was almost perfect agreement with an intra-observer agreement score of 0.88.

Radiolucent lines were detected by reviewing post operative X-rays. The number of RLLs observed in each group was noted. Localization of RLLs (area under the tibial baseplate) was classified in zones according to the Knee Society Scoring System ,KSRES by Ewald [54]. RLLs can be osteolytic or osteosclerotic. They can appear early or late and can be isolated (one side of the tray) or combined (both sides). The sequence of appearance on both sides of the implant can be simultaneously (both present from the start) versus sequentially (first one side and then on the other side). In case of sequential appearance of RLLs, the authors identified the time of appearance of the first RLL as Time 1. For the appearance of the second side RLL, Time 2 was used. The size in mm and the evolution (still visible or disappeared) was noted according to guidelines [90]. Based on the radiological follow-up, three types of RLL were defined based on localization (medial, lateral or both sides), the sequence of appearance simultaneously or sequentially: Isolated RLLs (appearance on one side only), Combined RLLs (appearance on both sides simultaneously) and Sequential RLLs (appearance on both sides sequentially).

Finally, the authors also observed postoperative changes around the tibial component that they qualify as signs of macro-mobility: progressive RLLs around the keel, epiphyseal bone apposition on the compression side of the tilted implant and progressive tilting of the implant with distraction on the opposite side of the tibial implant on successive postoperative radiographs. Radiological signs of macro-mobility combined with pain and reduced functional outcome can be considered AL.

In order to answer the third hypothesis, the authors compared these observations in the Persona group with those in the Vanguard group.

All radiographs of both study groups were analyzed for the presence of RLLs. In the group of RLLs, signs of macro-mobility and AL were described. The following parameters were collected for all study patients: mean preoperative and postoperative HKA angle (varus < 178° or valgus > 182°). Demographic data, such as the age at time of surgery, gender and BMI were recorded as well. Furthermore, clinical data about diseases with a risk for poor bone quality (endocrinological pathologies, rheumatologic pathologies, renal disease, positive history of alcohol or smoking and medication or treatments with a potential bone remodeling impact (steroids)) were retrieved from the hospital medical records system.

The level of tibial resection, PE thickness, tibial base plate size and potential complications such as per-operative fractures was also collected from the surgical procedure and included in the data base.

All TKAs with RLLs were collected in a database, including date of surgery, last follow-up at our center and whether the TKA was revised or not, revision in or outside our hospital, the date (time from index surgery) and the reason for revision, as noted in the National joint register.

Descriptive statistics were used for demographic, surgical and mechanical data and sample characteristics are presented as numbers, means and standard deviations; categorical variables are presented as percentages. For continuous variables, violations of the normality assumption were tested using the Shapiro–Wilk test. The Cohen's Kappa method was used to obtain the intra observer agreement. Between group differences were tested using unpaired *t* tests. Kaplan–Meier method was used to evaluate cumulative survivorship of implants. GraphPad Prism software 9.0 (Graphpad, La Jolla, CA, US) was used for statistical analyses, and a p value < 0.05 was considered as statistically significant.

Results

The metrics analysis of both implants are represented in Table 2 and confirm that the Persona implant has a significantly larger surface coverage thanks to its higher medio lateral size ($p = 0.0212$) and a higher anteroposterior size on the medial side ($p < 0.0001$), than offered by the symmetrical Vanguard implant. The mean length of the Persona keel was 11.1 mm, statistically significantly shorter than for Vanguard 12.2 mm ($p < 0.0001$) (Table 2).

Table 2 Implants size characteristics in the series of patients with RLLs in the Persona and Vanguard cohort

Variables	Persona	Vanguard	
Tibial base plate			
ML size (mm)	73 ± 5	71 ± 4	$p = 0.0212$*
Antero-posterior medial size (mm)	52 ± 4	46 ± 3	$p = 0.0001$*
Antero-posterior lateral size (mm)	46 ± 4	46 ± 3	
Keel length (mm)	36 ± 3	40 ± 0	$p = 0.0001$*
Medialization (mm)	2 ± 1	NA	
Polyethylene			
Thickness (mm)	11 ± 1*	12 ± 2	$p = 0.0001$*

Values expressed as means ± SD

*Significant value

The authors have observed a similar Gaussian repartition of the tibial implant sizes in the Persona group (Fig. 2a) and in the Vanguard group (Fig. 2b).

The authors did not observe (Table 3) significant differences in the occurrence of RLLs in both groups of patients with a rate of 53 RLLs/255 TKAs (21%) for Persona and 178 RLLs/774 TKAs (23%) for the Vanguard group. The time of appearance of RLLs was comparable in both groups (Table 3).

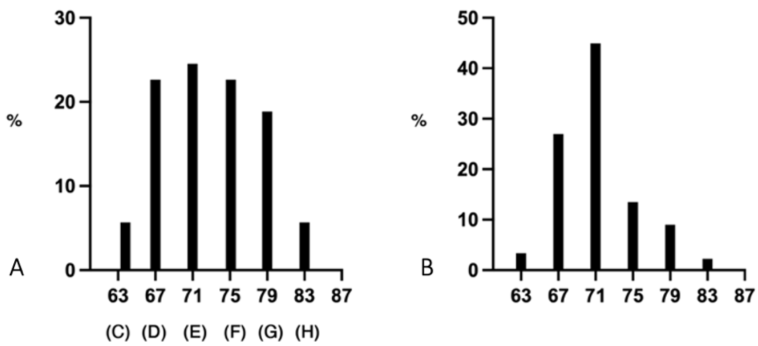

Fig.2 *Gaussian repartition, of the mediolateral size of the tibial implant with RLLs*
a. *Persona implant mediolateral size expressed as a letter (i.e., D or E) converted into millimeters*
b. *Vanguard implant mediolateral size in millimeters*

In the Persona group, Isolated RLLs were most frequently present with a rate of 64%, followed by 25% for the Combined and 11% for the Sequential RLLs. This compared to 43% Isolated, 39% Combined and 18% Sequential RLLs, respectively, for the Vanguard group (Table 3).

Table 3 RLLs in both groups of implants: number, proportion and time of appearance

Variable	Persona	Vanguard
Number of implants studied	255	774
Number of RLLs (%)	53 (21)	178 (23)
Isolated RLLs (%)	34 (64)	77 (43)
Combined RLLs (%)	13 (25)	69 (39)
Sequential RLLs (%)	6 (11)	32 (18)
Time of apparition		
Time 1 (weeks)	10 ± 11	9.7 ± 11
Time 2 (weeks)	17 ± 8	24.7 ± 19

Values expressed as means ± SD

The proportion of Combined and Sequential RLLs in the Persona group was significantly ($p = 0.0081$) lower than in the Vanguard group. For the Isolated RLLs, the authors found a correlation ($p = 0.0188$) between the presence of osteosclerotic RLLs and the preoperative deformity. Varus deformity leads more often to medial Isolated RLLs and valgus to lateral RLLs (Fig. 3).

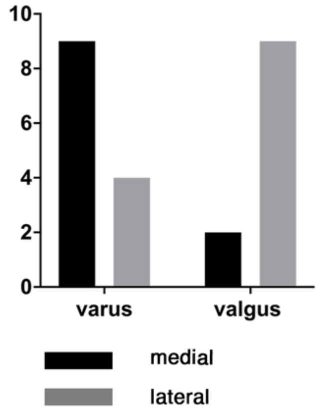

Fig.3 *Isolated RLL characteristic with X-rays representing radiolucent lines with their location under the tibial plate. The graphs represent the proportion of sclerotic radiolucent lines on the medial and lateral side relative to their preoperative HKA angle (varus/valgus)*

In the Persona group, the authors observed some differences, concerning the time of appearance of Sequential RLLs (earlier than Isolated and Combined RLLs), the age at time of surgery (younger patients in the Sequential RLLs group), and mechanical data (higher preoperative HKA angle in the Combined and Sequential RLLs), but these differences were not significant, due to the small group of Combined and Sequential RLLs (Table 4).

Table 4 Demographics, implant size and mechanical data of RLLs in the Persona group

Variables	Isolated $N=34$ (64%)	Combined $N=13$ (25%)	Sequential $N=6$ (11%)
Time of apparition (weeks)			
Time 1	11 ± 2	13 ± 3	6 ± 4
Time 2	–	–	17 ± 8
Demographic data			
Age (years) ± SD	68 ± 10	66 ± 11	64 ± 15
Gender female/male	2/1	2/1	2/1
BMI (kg/m^2)	32 ± 8	28 ± 6	31 ± 5
Clinical risk factor/patient (ratio)	25/34 (0.7)*	15/13 (1.2)	6/6 (1)
Implant size			
Tibial base plate (mm)	71 ± 6	73 ± 5	71 ± 6
Polyethylene (mm)	11 ± 1	10 ± 1	11 ± 2
Mechanical data (degrees)			
Pre-operative angle			
Varus	174 ± 3	174 ± 4	171 ± 4
Valgus	188 ± 5	189 ± 6	191 ± 0
Post-operative angle			
Varus	178 ± 2	178 ± 2	174 ± 3
Valgus	184 ± 2	182 ± 2	181
Proportion of knees with positive delta of correction in the varus-varus group			
Proportion (%)	20/34 (59%)	5/13 (38%)	4/6 (67%)
Delta of correction (degrees)	4 ± 3	4 ± 4	5 ± 2
Proportion of knees with a post-operative HKA angle > 3° of 180°			
Proportion (%)	(10/34) 29%	(4/13) 31%	(2/6) 33%
Mean angle (degrees)	5 ± 1	4	8

Values are expressed as mean ± SD

*Significant value

However, in the Persona group, the ratio of 1.2 clinical risk factor for osteoporosis for the Combined and 1 clinical risk factor for Sequential RLLs was significantly higher ($p = 0.0383$) than the 0.7 clinical risk factor per patient for the Isolated RLLs in this group (Table 4).

The authors observed a significant difference (p = 0.0032) in the rate of signs of macro-mobility with only 1 patient (2%) in the Persona group compared to 31 patients (17%) in the Vanguard group (Table 5).

Table 5 Radiographic signs of loosening and revisions in both RLLs study groups

Variable	Persona	Vanguard	p
Number of patients with signs of loosening	1/55	31/178	0.0032
Number of revisions	1/55	9/178	0.3024

The sign of macro-mobility in the Persona cohort was only one RLL around the keel, compared to 31 lucent lines around the Vanguard keel, combined with 15 epiphyseal bone appositions and 17 cases of tilt of the implant. This case in the Persona group was a 72 years-old woman, with a change of alignment with an HKA angle of 186 degrees to an HKA angle of 174° (correction from valgus to varus), and with a clinical risk factor for osteoporosis. This TKA presented a combined RLL and was not revised, because she was not painful.

Table 6 Demographics and mechanical data of the patient with RLLs in the Persona and Vanguard cohort

Variables	Persona	Vanguard
Number of patients with RLLs	53/255	178/774
Demographic data		
Gender M/F	20/33	45/133
Age (years)	68 ± 11	68 ± 10
Gender female/male ratio	2/1	3/1
BMI (kg/m^2)	31 ± 7	30 ± 6
Patient with clinical risk factor (%)	32/53 (60)	90/178 (51)
Number of clinical risk factor/patient (proportion)	46/53 (0.9)	127/174 (0.7)
Mechanical data (degrees)		
Pre-operative angle		
Varus (64%)	174 ± 4	173 ± 5
Valgus	188 ± 5	188 ± 5
Post-operative angle		
Varus (77%)	179 ± 2	177 ± 3
Valgus	183 ± 2	183 ± 2

Values expressed as means ± SD

The authors observed similar data about age, BMI and gender between both study groups (Table 6). The proportion of clinical risk factors per patient showed a significant difference (p = 0.0261) between the two groups of implants with a ratio of 0.9 clinical risk factor per patient in the Persona group, compared to a ratio of 0.7 clinical risk factor per patient in the Vanguard group.

The authors observed an excellent medium-term survivorship for both implants (Fig. 4). Based on National registry data, in the Persona group, 1/255 TKAs (survivorship of 99.6%) with an Isolated RLL was considered loose by a surgeon in another center and revised. Nine out of 774 Vanguard (survivorship of 98.8%) were revised. Three were considered retrospectively to need a revision for loosening of the implant in our center, and 6 were considered as presenting AL by surgeons in other centers and revised.

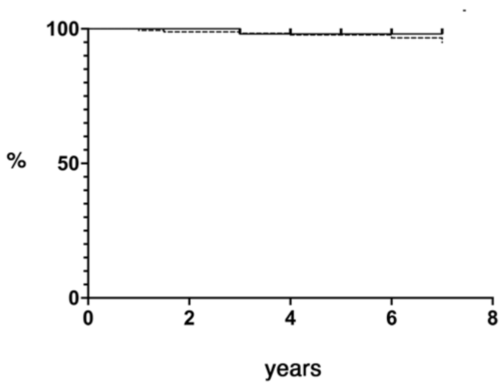

Fig. 4 *Kaplan–Meier survivorship curve of the implant in both series.*
Survivorship of the implant with revision for aseptic loosening as an endpoint.
Upper line: Persona implant with a survival rate of 99.5%;
Lower line: Vanguard implant with a survival rate of 98.8% (99.6%) is significantly better (p = 0.0116) than that of Vanguard with 31/774 TKAs (96%).

However, if the authors consider the appearance of radiological signs of macro-mobility as an endpoint, the survivorship of the Persona implant 1/255 TKAs (99.6%) is significantly better (p = 0.0116) than that of Vanguard with 31/774 TKAs (96%).

Discussion

In knee arthroplasty, it still remains a dilemma whether kinematics and alignment or implant design play a major role in clinical outcome [158]. Good survivorship of the implant will depend on the fixation of the implant to the host bone, which in difficult technical conditions (important surgical corrections, poor bone quality, high BMI, or high levels of activity) might be compromised. The literature still reports 20% of patient dissatisfaction [158-160], most of time due to residual pain and still a large amount of revisions due to loss of fixation [38, 161].

The choice of the implant itself can be important in patients at risk for loosening [159, 160]. The most important finding of this study is that RLLs are present in about 20% of cases, independently of the knee design. They can be considered a sign of micro-mobility at the epiphyseal level of the tibia. The tibial keel plays an important role in the metaphyseal fixation of the implant and the design can reduce the radiological signs of macro-mobility.

The observations made by the authors confirm previous studies [162, 163]. Persona implant is a morphometric implant with an asymmetric, side specific base plate, with a large panel of small increments in mediolateral sizing, giving a large number of available sizes [164] and a larger anteroposterior size on the medial side of the tibial tray.
This implant is well recognized to improve coverage in both mediolateral and anteroposterior dimensions compared to symmetrical implants, such as Vanguard [149, 165, 166]. Persona implant has 92% of coverage of the epiphyseal tibial bone compared to 81% with Vanguard and this observation has been confirmed by several other studies [149, 165, 166].

Another particularity of Persona is a correlated increase in size of the tibial tray and the keel. Medialization of the keel of Persona, offers a unique position in the metaphyseal bone compared to the Vanguard implant for each size of the implant [163]. The geometry of tibial keels with a rectangular cross section are more efficient than others [167].

The surgical and cementation technique used in this study were the same for both implants groups with a short surgical time and a good management of hemostasis with the use of the tourniquet during all surgical procedures until the cement was hard.

The type of cement was also the same and may not explain the differences in rates of AL between both groups [154, 161]. This finding confirms previous studies that stated that cementation technique, type of cement and the use of tourniquet may not explain differences in survivorship both implants [154, 155, 161].

With comparable results for both groups concerning demographics, and mechanical data, as observed in the literature [168], the rate of RLLs was similar in both groups. No cases of debonding were observed in this study. The authors observed that about 20% of TKAs present RLL after TKA independent of the knee design. In the Persona group, mainly Isolated osteosclerotic RLLs were observed on the concave side of the deformity.

However, the higher rate of clinical risk factors for osteoporosis per patient in the Persona group may also explain the presence of Combined and Sequential RLLs in this group. The relative earlier appearance of the second line in the Sequential RLLs of the Persona group may be explained by the age of the patient, younger in the Persona group, with more important HKA angle corrections on a more at-risk bone for poor quality.

The appearance of RLLs comparatively equal for each implant design is an interesting observation, because it demonstrates a poor condition of fixation of the implant into the soft cancellous portion of the epiphyseal tibial surface [149].
Kim et al. compared the Persona implant to the LPS Flex (Zimmer Biomet, Warsaw, In, US) and observed a rate of RLLs in the Persona group that was significantly lower (4.3%) compared to the LPS group (10.3%), and they attributed this difference to the design of the femoral implant of Persona associated with less posterior impingement due to a decreased ROM compare to the LPS [164]. The difference with our findings can lie in the quality of the radiographs and the specific search to find potential RLLs, but they clearly showed a mechanical effect on the presence of RLLs. Galea et al. also observed a lower rate of RLLs of 1.3% at 2 years [150].

In both these studies, the authors did not include any of the mechanical or clinical risk factor for RLLs. In this study, the authors did not observe significant differences between the amount of RLLs between the two implants confirming previous studies [162].

The authors conclude that the design of the implant does not reduce the rate of RLLs between both groups, based on similar mechanical conditions, surgery and amounts of correction.

Yeran Li et al. showed that short stem extensions could share the stress with the cortical bone, and increase the stability of the implant [169] and decrease the rate of RLLs, as observed previously in obese patients [170].

The substantially lower rate of signs of macro-mobility in the Persona group might be attributed to the shape and medialization of the keel. Progressive loosening of the tibial component, by micro- and macro-mobility, happens more often when the component is exposed to shear stress, rather than to axial compression. Compression is well tolerated, except if the compressed side collapses or when tensile forces develop on the opposite side of the component [165].

Under similar patient' conditions, the implant may be considered as a variable, especially in case of poor bone quality, for the appearance of radiological signs of component mobility and AL of the implant [165, 171]. One previous study analyzed the survival of Vanguard implant depending of the PE generation (conventional PE versus highly crosslinked vitamin E-enriched PE), but showed no difference in the number of articular surface fractures nor the frequency of revision for AL at 5 years follow-up [172]. The authors concluded that the benefit of vitamin E enriched PE will be appreciated at 20–25 years postoperatively. In our study, no articular surface fracture was observed at 5 years postoperatively. According to this previous study, the differences in frequency of revision for AL between both groups, may not be due to the type of PE [172].

Previous studies showed that the implant and especially the tibial tray design, with its keel length and geometry, had an influence on the transmission of forces to and stress shielding of the peripheral bone structures [173]. David et al. demonstrated that increasing tibial tray contact surface will reduce the risk of loosening [171]. More than bone quality, the design of the keel of the implant will influence shear forces and transmit them to the peripheral bone [171].

To reduce radiological signs of implant mobility, a combination of correct positioning of the components, maximal epiphyseal contact surface between tray and bone and a reduction of shear stresses by the geometry of the keel and its contact surface (length × diameter) within the bone [170, 171] play a major role.

Epiphyseal and metaphyseal design conditions will improve two zones of fixation as described by Morgan-Jones in revision surgery [138, 169]. The results of this study confirm the same findings in obese patients who show no AL with the Persona implant [170]. The authors have observed an excellent survivorship of both implants, confirming the findings of previous studies [140, 174].

This study has several limitations. First of all, this is a retrospective study without randomization of the implant. A selection bias might have happened in the period where both implants were used. The senior surgeon felt from 2013 on that the Vanguard implant with its finned keel design seemed less stable in osteoporotic patients and therefore he selected Persona for those cases. This created a selection bias from that moment on, putting more osteoporotic patients in this group. This was observed by a higher mean of risk factors for osteoporosis in the Persona group. This emphasizes even more the finding that Persona has good primary fixation, since only one patient had signs of macro-mobility in this more osteoporotic group. Secondly, the number of TKAs in both groups were not similar, because in the second study period both Vanguard and Persona were both utilized. This might play a role in the potential occurrence of patients with risk factors for loosening. However, both groups were substantial and the minimal follow-up was longer than 2 years. Thirdly, the mean follow-up time of the Persona group was 4.5 years compared to 9 years for the Vanguard. Most papers in the literature showed however that AL is a cause for early revision and probably would manifest itself within two years after surgery [175]. Finally, patients undergoing revision in another institution, were not contacted to know whether they were revised for radiological signs or for clinical symptoms and if they were doing better after their revision. Radiological follow-up for patients without complaints remains advisable.

Conclusion

A morphometric TKA design, such as Persona is more anatomic and offers better bone coverage of the epiphyseal tibial surface compared to a symmetrical implant. RLLs, as a sign of implant micro-mobility, were equally present in both designs. Radiological signs of macro-mobility at the metaphysis were less frequently observed in a squared keel design, despite more patients at risk for poor bone quality. In cases of observed less optimal epiphyseal bone quality, an implant with better metaphyseal fixation, can reduce the risk for macro-mobility by two zone fixation. The morphometric implant did not show improved survivorship compared to a symmetric implant.

Chapter VI: Survivorship of primary total knee arthroplasty in a modern anatomic implant with or without a short stem extension

What did we learn from this scientific work?

The combined findings of the previous two studies allow us to conclude that better epiphyseal coverage of the tibia with a more morphometric implant doesn't reduce the rate of RLLs, that appears to be around 20% in primary TKA and that must therefore be related to other factors than purely the design of the tibial base plate and its potential for tibial coverage. RLLs are a sign of micromotion and demonstrate a lack of fixation at the micromotion level.

On the other hand, the rate of signs of macro-mobility and AL have decreased consistently, probably thanks to the better contact surface at the metaphyseal level, with a better distribution of loading stresses and potentially a position of the keel in bone of better quality. Biomechanical studies, have proven the capacity of the implant to resist to compression and distractions forces, when the forces are better distributed into the metaphyseal zone. This concept is well known in revision surgery, by adding a third zone of fixation into the diaphyseal bone, if the epiphyseal- and metaphyseal zone have been compromised.

In primary TKA, some implants permit to add a short stem, which will optimize the options for fixation. The Persona knee system, permits to add this type of stem, so we decided to compare the same implant, with and without stubby stem, and to observe the consequences on the rate of RLLs and AL.

The hypotheses for this retrospective study were:

(1) The presence of a short stem will dissipate stress and decrease micro-mobility at the epiphyseal level resulting in less RLLs around the tibial component

(2) Stemmed primary TKA may improve survivorship of the implant in patients potentially at risk for AL

Survival of primary total knee arthroplasty in modern anatomic implant: comparison of one implant with and without a short stem extension

Adapted from: Wautier D, Thienpont E. Survival of primary total knee arthroplasty in a modern anatomic implant with and without a short stem extension.
Submited to Arch Orthop Trauma Surg in January 2024, under review

Abstract

Introduction: Primary TKA has two areas of fixation for the tibial component; the epiphyseal and metaphyseal zone. In most cases, two zone fixation will be sufficient for survivorship of the implant, however AL remains one of the main causes for revision. The importance of radiolucent RLLs around TKA and their role in the development of AL is still not clear. The hypotheses for this retrospective study were (1) The presence of a short, stubby stem will dissipate stress and decrease micro-mobility at the epiphyseal level resulting in less RLLs around the tibial component (2) Short stem primary TKA may improve survivorship of the implant in patients potentially at risk for AL.

Materials and Methods: Retrospective cohort study of 326 patients operated with a morphometric implant between 2013 and 2018. A short stubby stem was added to the tibial implant, if at the time of the tibial cut, the surgeon judged the epiphyseal bone quality to be poor or a smaller tibial size was necessary. All primary TKA were radiographically evaluated. RLLs were recorded and described according to their radiological aspect, localization, time of appearance and their progression over time. Mechanical, surgical, clinical and demographic data were recorded.

Results: 71 TKAs out of 326 (22%) were stemmed. Of the 255 TKAs without stem, 53 (21%) showed RLLs under the tibial base plate and 1 case (0.4 %) was revised for potential AL of the tibial implant. No RLLs were observed in the group of stemmed implants and no revisions for AL were needed. Patients with stubby stems were elderly women with risk factors for osteoporosis or young men in need for correction of big coronal deformities.

Conclusion: A short stubby stem extension can drastically reduce the rate of RLLs and AL in primary TKA, probably by adding metaphyseal fixation to the classic epiphyseal fixation of the tibia and by a reduction in micro and macromotion of the tibial component.

The decision to add a short stubby stem to a primary component can be made during surgery when risk factors for good epiphyseal fixation appear to be present and the used knee system allows this option.

Level of evidence III

Keywords: Zones of fixation; Stemmed primary TKA ; Aseptic loosening ; Revision

Introduction

The three zones of fixation in revision TKA were described by Morgan-Jones. In revision TKA, these three zones are usually influenced by the previous surgeries [124]. In primary TKA, the same three zones of fixation exist and the tibial component usually utilizes two of those zones of fixation; the epiphyseal and metaphyseal zone [124]. In primary TKA, these zones of fixation are not influenced by a previous implant, but do not always present under the same optimal conditions. The epiphyseal zone of the tibia can suffer from osteoporosis with fragile cancellous bone, inflammatory bone cysts or reduced contact surfaces in cases of more important wear. The metaphyseal area can also present with osteoporosis, inflammatory bone cysts, with the presence of metal hardware (screws, staples or plates) that need to be removed and alter the mechanical load resistance of this area or by metaphyseal wear in more advanced osteoarthritis [134]. On the other side of the spectrum, important areas of bone sclerosis or reduced surfaces of epiphyseal bone coverage can also reduce epiphyseal zone 1 fixation [176].

It remains, to the best of our knowledge, a question whether different knee designs offer different levels of fixation. If that would be the case, both the epiphyseal contact surface and the extension into the metaphyseal area can play an important role in primary fixation. The development of more morphometric implants, with more anatomical tibial trays could offer better coverage of the proximal tibial bone. Furthermore, different tibial keel designs could offer different metaphyseal zone distribution of compression forces or different resistances to distraction forces, therefore altering the primary component fixation [177] . This difference in primary fixation could potentially explain why some knee designs present with early failure, because of AL, more often than other designs [149, 165, 167, 174]. Concepts of fixation can be tested under laboratory conditions with mechanical testing [171, 178] or in observational studies looking at survivorship of different implant designs [177, 179].

Independently of implant design, patient conditions can also determine the fixation of the implant. At the epiphyseal level, fixation can be determined by contact surface and the quality of the bone supporting the implant construct. Identifying potential risk factors preoperatively as a proxy for clinical osteoporosis could be considered an important part of the surgical planning. The same can be said for coronal deformity analysis and the potential for correction of the total deformity with an intra-articular osteotomy, called total knee arthroplasty. The resulting postoperative mechanical axis can predict the area of the tibial epiphysis that will be undergoing compression or distraction forces, resulting into micromotion.

Also, for patients with reduced epiphyseal areas of contact surface (small size tibia or metaphyseal wear extension resulting in a lower tibial cut), metaphyseal zone extension with a short stubby stem for better primary fixation might be key. If the implant design offers the flexibility of adding a stem extension during surgery, where the conditions of epi- and metaphysis can be evaluated, the final decision can be taken by the surgeon to optimize the options for fixation.

To the best of our knowledge, there are no studies yet, comparing the survival of Persona Total Knee Arthroplasty (Zimmer Biomet, Warsaw, Indiana, US) with or without short stem extension.

The purpose of this study was to understand the influence of a tibial stem extension in primary TKA on the micro and macromotion of the implant, observed as RLL on postoperative radiographs, as a proxy for micromotion.

The hypotheses for this retrospective study were (1) The presence of a short, stubby stem will dissipate stress and decrease micro-mobility at the epiphyseal level resulting in less RLLs around the tibial component (2) Short stem primary TKA may improve survivorship of the implant in patients potentially at risk for AL.

Methods

The authors retrospectively reviewed 328 TKAs operated between 2013 and 2018, for primary osteoarthritis (OA) using the same surgical technique and one type of arthroplasty (Persona, Postero-Stabilized (PS) cemented device (Zimmer Biomet, Warsaw, Indiana, US)). All patients underwent routine post-operative clinical and radiological controls at 3, 6, 12, 24 weeks, as well as 1, 2 and 5 year(s) postoperative, if it was possible.

Were excluded from this study, 2 patients with a history of infection. Finally, 326 TKAs were retrospectively reviewed. 255 TKAs (78%) were without a stubby stem, and 71 TKAs (22%) with a stubby stem and both groups were studied comparatively. The surgeon, with his own experience, decided during surgery to add a stubby stem, depending of the observed epiphyseal bone quality.

When it was estimated osteoporotic, a short stubby stem was added to improve the metaphyseal and proximal diaphyseal fixation (high zone 3). All implants were cemented in one session including the keel and stem, when it was added, with a high-viscosity, antibiotic-loaded cement (Refobacin Bone Cement, Zimmer Biomet, Warsaw, US).

To understand survivorship of these implants and to answer the study hypotheses, the authors retrospectively compared the clinical and radiological outcome of the Persona implant, with and without short stem.

For the first study hypothesis, the authors reviewed the differences between the design of Persona with and without a stubby stem using the characteristic references from the manufacturer's technical brochure from Zimmer Biomet. The authors describe the size (A/P and M/L), thickness of the base plate, shape of the keel and stubby stem characteristics. Manufacturer's data collected for both groups of implants are represented in Table 1.

Persona's tibial base plate is asymmetrical with a more developed medial side in the antero-posterior (AP) direction. The keel of Persona is larger and more squared with robust fins. For each increase in size of the tibial implant, the keel is medialized 1 mm and the keel length increased from 31.4 to 39.7 mm. Use of a short, stubby stem increases the total length of the keel from 63.8 to 72.1 mm (Table 1).

Table 1 Manufacturer's design characteristics of the Persona implant

Variables	Persona
Tibial base plate	
Design of baseplate	Asymmetric morphometric
Baseplate thickness	3.7 mm
Coverage surface of baseplate	92 %
Inclination of baseplate	5°
Keel	
Design of keel	Cylindrical shape
Size of keel (mm)	31.4 – 39.7
Keel medialization	1 mm for each increase of 2 size of the implant
Stubby stem	
Characteristic: Diameter x Length	14 x 30 mm
Lengthening of the fixation system	32.4 mm
Total length of the Persona keel with short stem extension	63.8–- 72.1 mm

Based on these design features, the authors hypothesized that the presence of a stubby stem, by adding a second zone of fixation to the metaphyseal keel, may have an effect on the primary fixation of the implant by a reduction of micromotion and a decrease in RLLs observed on postoperative radiographs.

One author (DW), reviewed all the post-operative X-ray's (AP, lateral, 30° axial patellar view and standing full leg) up to a minimum of 4 years postoperative. The measurement system utilized for this study was the Carestream PACS software (Rochester, NY, US), which gives a high degree of accuracy, with a tolerance of 0.1 millimeter (mm) for RLLs size measurements and 0.1 degree for the angle measurements. The intra-observer difference was reconciliated by reading the same radiographs more than 5 times. The Cohen's Kappa was almost perfect agreement with an intra-observer agreement score of 0.82.

Radiolucent lines were detected by reviewing post-operative X-rays. The number of RLLs observed in each group was noted. Localization of RLLs (area under the tibial baseplate) was classified in zones according to the Knee Society Scoring System (Knee Society Total Knee Arthroplasty Roentgenographic Evaluation and Scoring System (KSRES)) by Ewald [54]. RLLs can be osteolytic or osteosclerotic. They can appear early or late and can be isolated (one side of the tray) or combined (both sides).

The sequence of appearance on both sides of the implant can be simultaneously (both present from the start) versus sequentially (first one side and then on the other side). In case of sequential appearance of RLLs, the authors identified the time of appearance of the first RLL as Time 1. For the appearance of the second side RLL, Time 2 was used. The size in mm and the evolution (still visible or disappeared) was noted according to guidelines [90]. Based on the radiological follow-up, three types of RLLs were defined based on localization (medial, lateral or both sides), the sequence of appearance; simultaneously or sequentially: Isolated RLLs (appearance on one side only), Combined RLLs (appearance on both sides simultaneously) and Sequential RLLs (appearance on both sides sequentially). All these radiographs analyzed for the presence of RLLs were also evaluated for signs of macro-mobility and AL. Such post-operative changes around the tibial component that qualify as signs of macro-mobility are: progressive RLLs around the keel, epiphyseal bone apposition on the compression side of the tilted implant and progressive tilting of the implant with distraction on the opposite side of the tibial implant on successive post-operative radiographs. Radiological signs of macro-mobility combined with pain and reduced functional outcome can be considered AL [176, 180].Alignment was collected for all study patients as mean pre-operative and post-operative Hip Knee Ankle (HKA) angles (varus < 178° or valgus > 182°).

In order to answer the second hypothesis, the authors reviewed for both groups, demographic data, such as the age at time of surgery, gender and BMI. Furthermore, clinical data about diseases with a risk for poor bone quality (endocrinological pathologies, rheumatologic pathologies, renal disease, positive history of alcohol or smoking and medication or treatments with a potential bone remodeling impact (steroids)), were retrieved from the hospital medical records system. The level of tibial resection, PE thickness, tibial base plate size and potential complications, such as per-operative fractures, was also collected from the surgical notes and included in the data base.

All TKAs with RLLs were collected in a database, including date of surgery, last follow-up in our center and whether the TKA was revised of not, revision in- or out-house, time to revision (from index surgery) and the reason for revision, as noted in the register.

Descriptive statistics were used for demographic, surgical and mechanical data and sample characteristics are presented as numbers, means and standard deviations; categorical variables are presented as percentages. For continuous variables, violations of the normality assumption were tested using the Shapiro-Wilk test. The Cohen's Kappa method was use to obtain the intra observer agreement. Between-group differences were tested using unpaired T-tests. GraphPad Prism software 9.0 (Graphpad, La Jolla, CA, US) was used for statistical analyses, and a p-value < 0,05 was considered as statistically significant.

Results

The radiological characteristics of Persona implant with and without a short, stubby stem are represented in Fig 1.

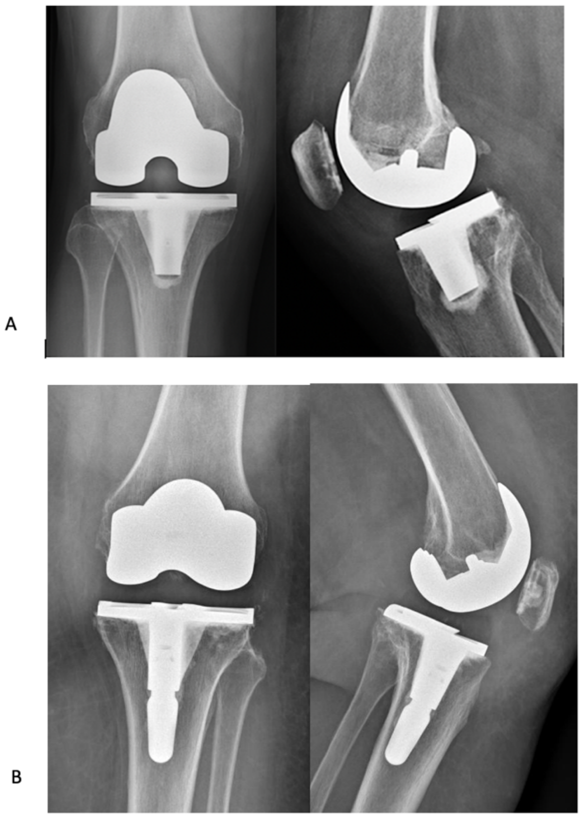

Fig*.*1 *Post-operative X-rays of both implants with same mediolateral size showing the differences between the keel (shape and length) with and without stubby stem.*
a. *Persona implant without stem*
b. *Persona implant with short, stubby stem*

The authors didn't observe any differences between the study groups for the size of the tibial implant or the covered surface area (Table 2), with a similar Gaussian repartition (Fig. 2).

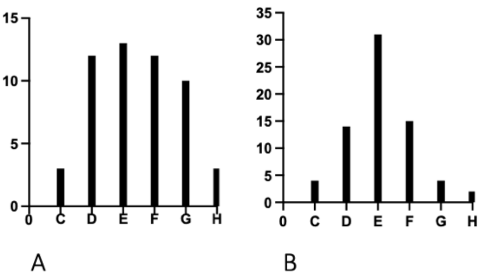

***Fig**.2 Gaussian repartition of the mediolateral size of the tibial implant*
***a.** Persona implant without stem with RLL;*
***b.** Persona implant with short, stubby stem*

Stem length was significantly (p<0.0001) longer in the group with stubby stem extension (Table 2).

Table 2 Implant size characteristics in Persona study groups with and without stubby stem

Variables	Persona	Persona with stem	P
Tibial base plate			
ML size (mm)	73 ±5	71 ±4	
Antero posterior medial size (mm)	52 ±4	51 ±3	
Antero posterior lateral size (mm)	46 ±4	45 ±3	
Keel length (mm)	35 ±3	66 ±8	< 0.0001
Medialization (mm)	2 ±1	2 ±1	
Polyethylene			
Thickness (mm)	11 ±1	11 ±2	0.028

Values expressed as Means ± SD; * significant value

The authors observed a significant (p<0.0001) difference in the rate of RLLs and signs of AL between both groups with 53RLLs/255 TKAs (21%) for the Persona group without stem and 0 RLLs /71 TKAs (0%) for the Persona group with stubby stem (Table 3). No cases of AL were observed in both groups.

Table 3 Number of patients with RLLs, aseptic loosening and revision in both groups of implants

Number of patients	Without stubby stem	With stubby stem	*p*
Total	255	71	
With radiolucent lines	53	0	<0.0001
With signs of aseptic loosening	1	0	0.5985
Revised for loosening of implant	1	0	

Values expressed as Means ± SD; * significant value

The pre and post operative HKA angle values were similar for both groups with mean pre-operative deformities within 10 degrees both for varus (64%) and valgus (36%). Postoperatively, while aiming for adjusted mechanical alignment, 77% obtained this for the varus group and 23% remained in functional valgus alignment (HKA 182°) (Table 4).

Table 4 Demographics and mechanical data of patients with RLLs in both groups

Variables	Persona	Persona with stem	*P*
Number of patients with RLLs	53/255	0/71*	<0.0001
Demographic data			
Age (years)	68 ± 11	73 ± 9 *	0.052
Gender female/male ratio	2/1	5/1*	0.0084
BMI (kg/m2)	31 ± 7	29 ± 5	-
Clinical risk factors for osteoporosis per patient (proportion)	32/53 (0.60)	44/71 (0.62)	-
Mechanical data (degrees)			
Pre-operative angle			
Varus (64%)	174 ± 4	173 ± 4	
Valgus (36%)	188 ± 5	188 ± 5	
Post-operative angle			
Varus (77%)	179 ± 2	178 ± 2	
Valgus (23%)	183 ± 2	182 ± 1	

Values expressed as Means ± SD; * significant value

Demographic data showed that the patients in the group with stem were significantly (p=0.052) older (73 +/- 9 years versus 68 +/- 11 years) and female gender was significantly (p= 0.0084) more represented (5/1 versus 3/1) in this group. BMI was not significantly different in between both groups (Table 4).

The proportion of clinical risk factors for osteoporosis per patient was the same in both groups of implants with a proportion of 0.60 clinical risk factor per patient in the Persona group without stem compared to a proportion of 0.62 clinical risk factor per patient in the stubby stem group (Table 4).

When comparing women to men in the short stem study group, we obtained two profiles of patients. The female gender group was significantly older ($p= 0.004$), than the male group. Clinical risk factors for osteoporosis were high in both gender groups with a proportion of 0.75 clinical risk factor per patient in the male group with short, stubby stem, compared to a proportion of 0.86 clinical risk factor per patient in the women group with short, stubby stem (Table 5). The male group of patients with a stem showed the use of a thicker PE ($p= 0.0058$) and a larger tibial base plate size ($p<0,0001$), than in the female group (Table 5).

Table 5 Demographics, mechanical and implant size characteristics in patients with pre-operative risk factors for osteoporosis

Variables	Male	Female	P value
Number of patients	12	59	<0.0001
Demographic data			
Age (years)	68 ± 11	75 ± 9*	0.0040
BMI (kg/m2)	31 ± 7	29 ± 5	-
Amount of clinical risk factors per patient (proportion)	9/12 (0.75)	51/59 (0.86)	-
Mechanical data (degrees)			
Pre-operative angle			
Varus (64%)	171 ± 5	173 ± 4	-
Valgus (36%)	188 ± 1	185 ± 1	-
Post-operative angle			
Varus (77%)	178 ± 1	178 ± 2	-
Valgus (23%)	183 ± 2	182 ± 1	-
Implant size			
Polyethylene (mm)	12 ± 1	10 ± 1*	0.0058
Tibial base plate (mm)	75 ± 3	70 ± 4*	<0.0001

Values expressed as Means ± SD; * significant value

Based on National Registry data, for the Persona study group without stem, 1/255 TKAs was revised (survivorship of 99.6%). The patient presented with an Isolated RLL and no radiological signs of AL, but was considered loose by a surgeon in another center and therefore revised.

None of the patients in the Persona group with short, stubby stem (survivorship of 100%) were revised, demonstrating excellent survivorship for both study groups (Fig. 3)**.**

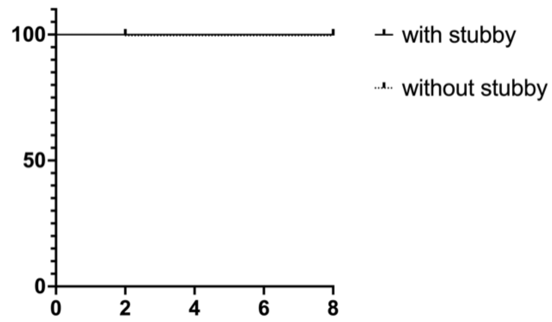

Fig.*3 Kaplan-Meyer survivorship curve of the implant.*
Survivorship of the implant with revision for aseptic loosening as an endpoint.
Upper line: % Persona implant with short, stubby stem with a survival rate of 100%;
Lower line: Persona implant without stem with a survival rate of 99,6%.

Discussion

Primary implant fixation to avoid AL can be crucial for good outcome in total knee arthroplasty [181]. Despite of potentially being the same intervention, patient's surgical and mechanical factors can be very different. These parameters can change the outcome for patient, surgeon and implant.

Is this study, the authors used an anatomical implant known to be morphometric [149, 179] . It offers a better coverage of the tibial epiphyseal zone, compared to a symmetrical implant [180]. The design of the metaphyseal keel gives also a large contact surface within the cancellous metaphyseal bone [171], reducing RLLs occurrence and signs of macro-mobility of the implant [180]. Finally, this implant offers the possibility to add a short, stubby stem, if needed. The "strategy options" for fixation look similar to revision, with three zones of fixation for a primary implant [124, 138, 182].

Radiolucent lines have often been considered as a proxy for AL. Wautier et al. have described the frequency of RLLs (23%) and the different types of RLLs, as well as the radiological signs of AL [176]. They described Isolated RLLs that can be seen either at the medial (70%) or lateral (30%) side of the tibial implant, mostly corresponding to the concave side of the deformity.

The authors also described Combined RLLs that would be present on both sides of the implant from the start (9%) and Sequential RLLs that would start on one side of the implant and progressively develop on the other side (4%). These type of RLLs could behave badly and should be followed-up. Wautier et al. described radiological signs of AL as RLLs around the keel of the tibial implant, as metaphyseal densification and epiphyseal bone apposition and finally by progressive increases in deformity as measured by postoperative HKA-angle increases.

In the present study, the implant without stem presented with the same occurrence of RLLs (21%) as previously described, however the study group with stem presented no RLLs. This finding suggests that RLLs observed on radiographs could be a proxy for micromotion of the implant, without necessarily being a sign of AL. This micromotion at the epiphyseal level and therefore also the RLL observation can be reduced by the introduction of a two-zone fixation with a metaphyseal short stem extension.

Wautier et al. also described previously that two different designs of TKA represent with the same overall rate of RLLs (23%), but that the design of the tibial keel and its impact on metaphyseal fixation can reduce the radiological signs of AL [180]. An important biomechanical characteristic of this implant could be the medialization of the keel in the proximal tibia with increasing size of the tibial tray, known to be an additional element for good fixation [163].

In the present study, adding a short stem extension also confirmed the absence of radiological signs of AL and the need for revision, but more interestingly lead also to a reduction of the RLLs to 0%. In the absence of RLLs none of the study patients were revised in- or out-house, this in contrast to the group without stem where one patient was revised in the presence of an isolated medial RLL. Jin et al. had however shown that an additional stem did not show any difference compared to standard implants, in an in vitro study [149]. However, the limitation of an in vitro study is that it cannot consider the impact of the quality of the bone under the implant and the evolution of the quality of this bone over time, especially in elderly women [183].

Gallo et al. described in a study about osteolysis in knee arthroplasty the combination of biological (bone modification after surgery and reaction to wear particles) and mechanical factors (alignment and stress resistance), both contributing to late loosening. He described the importance of the design of the implant, the quality of the PE, the overall alignment of the limb and the activity levels of the patient [57].

In the present study, the authors confirm by their results that a morphometric implant without a stem leads rarely to AL and that adding a short stem extension reduces RLLs to 0%, even in patients with biological and mechanical risk factors for optimal tibial fixation [184]. The biomechanical explanation, is that stemmed tibial components increase the mechanical stability and allow for a more physiological load distribution with a reduction of 60% of strain in the proximal tibia [183]. It decreases stresses at the cement mantle (compressive stress) by 136% and shear force by 92%, as the stem transfer loads more distally, hence decreases the stress on the proximal metaphyseal region [39, 183, 184]. A stubby stem is therefore key, to obtain a better strain repartition by augmenting the bone contact of the implant and reduce tibial toggling [181].

Retrospectively, the authors identified two different demographic profiles of patients in the group of Persona TKA with a short stem: young men with important preoperative deformities and elderly women with clinical risk factors for osteoporosis. This observation shows the bias of the surgeon who decided to stem or not, because these conditions are well documented in the literature as being major risk factors for loosening of the implant. Radiological studies of the coronal alignment and surgical planning of the different osteotomy levels during TKA was always done in the department. Therefore, the knowledge about the need for a stem in case some extra-articular deformity would not be corrected or the level of resection would be low on the tibia was available. However, the retrospective observation of the presence of several clinical risk factors for osteoporosis, not individually known to the surgeon during the procedure, shows well that the quality of the epiphyseal bone observed during surgery, corresponds to the overall bone quality and the risk for osteoporosis. BMI didn’t appear to be different in between both groups in the present study. Stemmed implants have already shown their efficacy in obese patients, in the presence of high pre-operative deformities [39, 170, 181, 184] and for elderly women with osteoporosis [183].

The same efficacy was observed in this study with 100% survivorship at short-term follow-up (5 years). In this study, the authors found a significant difference in PE size in the group with a short stem between men and women. In the case of an important pre-operative deformity, the need for a lower tibial cut can lead to the use of a thicker PE, which is a well-known risk factor to increase revision rates in TKA [185, 186]. Rajamaki et al. suggested therefore to use constrained knee designs in order to decrease the failure rate [185].

In the present study, there were no implant failures nor revisions, suggesting that a morphometric knee design in the presence of a stubby stem can decrease the risk of failure without increased constraint.

This statement is only true if the knee is well balanced by an experienced knee surgeon. Literature reports that the ideal size for a stem extension, is between 30 and 50 mm maximum, to prevent impingement with the tibial cortical bone. This corresponds to the stem length used in the studied implant since fixation in primary knee remains usually limited to the metaphyseal area of the proximal tibia, without diaphyseal engagement [170, 181, 187]. Surgeons aiming for kinematic alignment will have to plan their surgeries to avoid lateral cortical impingement when correcting bigger deformities needing lower tibial cuts or higher varus medial proximal tibia (MPT)-angles asking for more joint line obliquity.

This study has several limitations. Firstly, it is a retrospective study without the possibility to randomize usage of the short, stubby stem and observe the rate of RLL or AL in two comparable patient groups. Secondly, the choice to add a stem was based on the surgeon's per-operative evaluation of the epiphyseal bone quality and not on a clinical pre-operative diagnosis. It will be interesting for further studies to prospectively identify patients preoperatively who might be in need for a stubby stem extension. According to this study and with survivorship as proxy for the right per-operative choices made, elderly osteoporotic women and younger males with big deformity correction could benefit from stubby stem usage. It might also be interesting to develop a device that measures the epiphyseal bone quality during surgery, helping the decision to use a stem or not. Thirdly, the total number of patients with a stubby stem included in this study was clearly smaller, but a substantial difference in the rate of tibial RLLs was observed (21% vs 0%), leading to a statistical difference. Finally, this study is about only one implant design. It will be interesting to study the recent findings of these authors for other morphometric or symmetrical knee designs.

Conclusion

The usage of a short, stubby stem extension in primary TKA seems to reduce micro and macromotion of an implant observed radiologically as a reduced occurrence of RLLs. Improved fixation in at least two zones of the proximal tibia reduces the rate of AL in patients at risk with correction of important deformities or severe osteoporosis leading to excellent survivorship.

Chapter VII: Summary and general discussion

Radiolucent lines and AL in primary TKA, are a real clinical problem, because it compromises patient satisfaction and survivorship of the implant and therefore has an impact in terms of public health. With the increasing number of TKAs performed around the world and with AL as one of the three main causes for revision, health care providers need to align to have a common evidence-based strategy for this issue [2, 24, 52, 119].

Registry data continue to show that revision rates for AL increase and especially in younger patients. The problem with the diagnosis of AL remains that it is subjective and depends on the surgeons' interpretation of RLLs. Since some RLLs can be innocent and remain stable for the entire life time of the patient, it is important to educate surgeons about RLLs, signs of micro-mobility, signs of macro-mobility and finally the signs of AL [99, 130, 131, 138, 188-190].

If furthermore, a still undetermined percentage of postoperative knee patients suffer from chronic knee pain, it can be easier for the surgeon to consider the RLL as an explanation for their pain, than to study their case further. In chronic pain patients, new and unnecessary revision surgery will only lead to more pain and less patient satisfaction. It is therefore important, as a surgeon, to understand pain mechanism and the mechanism of AL and fixation [146, 176, 180].

From the first descriptions of RLLs, in the 70s-80s until today, the definition and classification of RLLs, prognostic factors or guidelines about follow-up or the management of RLLs in total knee arthroplasty have not evolved, in contrast to our knowledge about the surgical technique, implant design and patient enhanced recovery protocols.

Because of this focus on surgical technique and with the arrival of new surgical trends in this area such as, computer assisted surgery (CAS), small implants (unicompartmental knee arthroplasty (UKA), KA, robotic surgery, surgeons assumed that the key to better patient outcomes and increased survivorship of the implant would be found in these new models of surgery [23, 191] .
In reality, as demonstrated in the literature, survivorship of the implant will depend on multiple factors such as, preoperative alignment and unloading of the convex

disease side, the patient and his level of activity, his comorbidities, the bone quality around the knee, the design of the implant, the postoperative alignment of the limb, fixation choices, quality of the cementing technique, etc [192].
New technologies permit to obtain better positioning of the implant, gap balancing, or more physiological limb alignment, with a better understanding of the choice of the implant and the level of the constraint used according to those conditions, but few focus on bone fixation and changes of the quality of the cement/ bone interface at the time of implantation and over time should be included in the per-operative decision making. With options, such as a short stem extension at our disposal, understanding the quality of the epiphyseal area of fixation should help surgeons to decide whether a metaphyseal fixation component is necessary or not [193].
Radiostereometric analysis studies, give more information about migration profiles, depending of the implant constraint, mode of fixation, but underlying cause of revision are not well studied [18].

In this doctoral thesis, we have observed the radiological behavior of this interface with time and the consequences on survival of the implant.
We have demonstrated that RLLs below the tibial component, are a sign of the inability of the bone-implant interface to offer good fixation at the epiphyseal level of the tibia. This type of RLLs, are present in 20 % of TKAs, whatever the design of the implant [158-160, 180]. They are only a sign of micro-mobility of the implant and should not be considered a sign of AL.

Three types of RLLs have been described in our first study [176]. Not previously described in the literature, they are different by their radiological aspect (osteolytic or osteosclerotic), location, time of apparition and evolution. All the RLLs appear during the first year after the surgery, and especially within the first 3 months.

The first type represents the majority of RLLs, appearing early on the concave side of the corrected deformity, most of the time it is osteosclerotic because of the absence of cement penetration at the side of preoperative sclerotic bone in minimal tibial resection.
This type is called an Isolated RLL, because of its unique localization on one side under the tibial base plate, ie on the medial side in a varus knee.

The second type of RLL was observed in patients with high preoperative deformities, needing big corrections, with a lower tibial cut and a bigger PE. Resulting in important changes of load on the epiphyseal bone on both sides under the tibial base plate. This RLL appears most of the time as an osteolytic RLL, with signs of metaphyseal densification under the RLL. This type of RLL was called a Combined RLL.

The third type of RLL, and less common, was the Sequential RLLs, appearing on both sides of the tibial tray, but sequentially in time. Often observed in under-corrected patients or with implants positioned in varus for KA. These RLLs, were most observed in case of AL, can evolve to signs of macro-mobility and need to be followed-up for their evolution in time.

These 3 types of RLLs, were first described in the Vanguard implant in the first study, but were later on also confirmed in the Persona implant during the second study, probably eliminating the design of the implant as the only reason for the presence of RLLs.

The second important observation during this thesis was the description of the predictive signs of loosening. After a first apparition of RLLs, the predictive signs of loosening should be followed on successive postoperative X-rays since they testify of the progression of the epiphyseal micro-mobility to macro-mobility of the implant at the metaphyseal level. We described three signs that may appear successively testifying of the progression of micromotion and the capacity of the bone to adapt to the constraint or signs of macromotion.
The first sign observed is a sclerotic RLL around the keel of the implant showing a mobility chamber. Secondly, bone apposition may appear on the load bearing side of the postoperative axis to stabilize the implant (ie, medial side in a varus aligned TKA). Finally, a tilt of the implant can be observed on successive postoperative standing full leg radiographs, with an increase of the postoperative HKA angle, progressively or suddenly, as previously explain.

This unfortunate progression from micro- to macro-mobility, was mostly observed in patients with important constraint on poor bone quality, such as in women suffering from osteoporosis or in patients with big deformity corrections or with residual varus deformity after surgery.

The known presence of these preoperative patient-specific risk factors, confirms the need to adapt the surgery to the patient by choosing the best epiphyseal coverage as possible and by adding more metaphyseal stability, with a stem extension, where needed.
Signs of macro-mobility can lead to patient dissatisfaction, residual pain and swelling of the operated knee. A combination of radiological signs of macro-mobility combined with clinical symptoms, we consider AL and in these cases revision surgery due to loss of fixation can be indicated.

In this thesis, we have used a PS implant and a MA surgical technique. The PS-implant is known to have more constraint than a CR-implant and stresses the implant-bone interface more, due to the post-cam mechanism [18, 25], potentially leading to a loss of fixation. The use of cement gave the possibility to the surgical construct to increase the implant fixation to the bone. Mechanical alignment, with a tibial base plate parallel to the floor, decreased the valgus and varus constraint on the bone [193]. But those conditions are not sufficient to guarantee fixation, in case of poor bone quality, like tiles on soft ground [18].

The Persona implant studied in comparison to the Vanguard implant in the second study, offers the option to reduce the signs of macro-mobility with a squared keel and the possibility to add a short, stubby stem in primary TKA [180]. This design improves coverage at the epiphyseal level, with adapted AP and mediolateral ratios for each increasing size of the implant and the keel will be more medialized.
The use of a stem extension in the Persona implant in the third study, confirms that RLLs are manifestations of micro-mobility of the implant, without necessarily being a proxy for AL. Using a short stem and improving the two-zone fixation in the metaphyseal bone of the tibia, reduced the number of RLLs observed at the epiphyseal level. Therefore, we can conclude that with improved contact surface and stability of the implant, RLLs disappear.

This doctoral thesis shows that early RLLs about the tibial component are signs of micro-mobility that can evolve to macro-mobility or AL. Initial fixation in primary TKA is a combination of local conditions of the bone (the soil we build our construct on), the contact surface (size of the tibial component), the initial fixation (epiphyseal contact surface and metaphyseal contact surface), the design of the keel (dissipation of contact stresses), the option to extent the metaphyseal fixation lower in the tibia with a short, stubby stem extension and the constraint the tibial construct will undergo.

Signs of micro-mobility can evolve to macro-mobility in cases where the postoperative alignment is loading weak bone (ie, varus alignment in a preoperative valgus knee) or because of suboptimal soft tissue balancing (ie, lateral laxity remaining in an undercorrected varus knee with varus thrust) or small size tibias with a lower tibial cut because of metaphyseal wear extension in obese and osteoporotic female patients [134].

With the knowledge of this current scientific work surgeons can adapt their strategy and plan for correct deformity correction, adequate soft tissue balancing with the appropriate amount of constraint and improve initial fixation with short stem extensions in case of poor bone quality.

To the light of this work, we can understand that surgical technique and the choice of the implant need to be adapted to the patient's condition. We don't need to stem all patients, but stemmed implants are the solution for patients at risk of loosening.

We need to change our paradigm thinking that we have one implant for all the patients into "we have the choice of one of the implants, for one patient".

Chapter VIII: Conclusion and perspectives

Radiolucent lines and AL are two interrelated concepts that can be defined as a sign of micro-mobility and of macro-mobility of the implant, respectively in specific local conditions of the bone and implant fixation.

The presence of RLLs, under the tibial base plate in primary TKA is a frequent phenomenon seen in about 20% of TKAs and does not mean that the implant is loose and should be revised.

The most frequent RLL, the Isolated type is a sign of bone remodelation below the implant immediately after surgery. Other types of RLLs may be more predictive of the important changes of load on the bone, inducing micro-mobility of the implant and need to be closely followed during the first year after surgery. They can evolve with signs of macro-mobility of the implant in case of insufficient epiphyseal and metaphyseal fixation.

An evolution over time of a RLL that develops signs of macro-mobility and that combines clinical complaints of the patient, such as pain on weight-bearing, swelling and coronal deformity of the limb are a sign of AL and revision TKA with an emphasis on better zone fixation should be discussed with the patient.

Depending on the patient and surgical risk factors, it can be advisable to adapt the primary mode of fixation to prevent signs of micro- and macro-mobility. Avoiding these radiological signs can be important in the face of 20% of patients being dissatisfied after TKA. If 20% have RLL, this can be seen by surgeons who go to quick conclusions as the reason for their dissatisfaction and advise revision for AL. Often the implant is not loose in the presence of innocent RLLs and getting the implant out can be hazardous and reconstruction afterwards complicated.

Perspectives

In the coming decade, TKA needs to be adapted to patients and not to surgeons. Too often, going through a residency program, young surgeons are focused on the basic principles of our profession. They want to cut skin, open the joint, cut the bones and implant the different components. We like to do something, act, but rarely we want to think about what we are doing. What is missing, is precision.

Who is this patient? What does he or she expect from his TKA and from us? What is his or her deformity and how should we correct this? Is he or she a high demand physical patient or low demand? How did the disease process impact the tissues, we will have to utilize to heal them? Is there any soft tissue laxity, stiffness of the joint, osteoporosis, etc. How many times this type of questions are discussed about our patients before deciding the type of treatment they need?

Often only one choice is offered to the patient. The surgeon's choice. All types of disease pattern, types of patients and types of deformity get the same therapeutic option. For example, a cemented PS TKA for all, or KA for all patients. But is this how we should see our role in the treatment of each individual patient? It is known that the patient outcome after unicompartmental arthroplasty is better than after TKA, so why not offer this solution, even if it doesn't belong to our technical options? We can always send the patient to a colleague. We need to be less dogmatic and adapt our daily practice to be more efficient.

Coronal alignment is a hot topic today in the orthopedic literature, as if we discover only now, that the distal and proximal anatomy of the femur and tibia are different, and that the individual alignment of each patient is different. Of course, respecting their individual anatomy will make them feel better than when we force them into an awkward position for their joint [24]. But we do it in a typical "ortho way".

Who among us has been exposed during their training to pain specialists? Do we know as surgeons what the mechanisms of acute and chronic pain are and how they are influenced by individual patient factors. Typically younger, female patients who are catastrophizing are at risk for more acute and chronic pain. These are also the patients who sometimes end up with a TKA they never needed because of early disease.

We know for a few years now that TKA before end stage OA, which we call bone to bone disease and expressed as Kellgren-Lawrence grade IV radiological OA, leads to dissatisfied patients. If we know that 20% of TKAs present with a RLL, we should be very careful to use this harmless radiological finding as a reason to proceed to the next more complex and more invasive type of surgery. And let be honest, how often didn't we see a revision TKA done for an Isolated RLL that ended up after revision with a bigger Isolated RLL on the same side, because the revising surgeon ended up lower in the tibia and with less cancellous bone to obtain good cement penetration.

Surgeons should benefit from our legal and moral obligation to continue to educate ourselves and become better doctors and better human beings. Therefore, those of us involved in clinical research, should make sure their message is heard and transmitted across the scientific community.

We advise our colleagues and friends to remember the three simple types of RLL, we described in this doctoral thesis and advise them to follow-up the Combined and Sequential RLLs. If any of these develop signs of macro-mobility and clinical symptoms a revision for AL can be indicated. Before that phase, it could be useless or even debilitating for the patient.

When performing primary TKA, we should remember the basic concepts of three zone fixation and look at our epiphysis after the initial bone cut (often 10 mm from the lateral side, ie in the varus knee) and ask some clinical questions during surgery. What is the quality of my host bone (thumb test)? Do I have any sclerotic zones and what is the surface of this bone compared to my total epiphyseal surface? Do I have any bone cysts with loss of cancellous bone? What is the size of my tibial component? What is the design of my tibial keel and in what type of host bone will it end up (bone cysts, inflammation, hardware, osteoporosis, …). How is my cementation technique (immediate application of the cement to the metallic surfaces, pressurization, etc…).

We should also realize that the decisions about our surgical technique influence fixation. A varus cut of the tibia (3° anatomical alignment) in a valgus knee can lead to subsidence. A neutral cut of the tibia in a varus thrust knee can lead to lateral laxity. A minimal cut in important varus OA, followed by a reduction osteotomy, will lead to a well-balanced low constraint TKA (often CR or PS with low thickness poly), but will present with an Isolated RLL on the medial side because the sclerotic bone was utilized as a strong construct to build the joint upon.

If these concepts can become common knowledge, less patients will undergo useless revision surgery and health care budgets will remain under control.

The current scientific work has identified two patient groups for which we should be attentive to avoid RLLs. One is the younger, male patient undergoing TKA, often because of posttraumatic OA or after sporting injuries (previous ACL, multi-ligament or meniscal surgery).
They often present with more important wear extending into the metaphyseal area or posteromedial wear in the absence of the ACL. They usually have more important deformities that can have an intra-articular origin, because of bone wear or an extra-articular origin because of old fractures. This type of wear and often the sclerotic bone that comes with it might ask for a better initial tibial fixation. Especially, if they will remain very active (work or sports) and if they keep some balancing issues because of previous chronic laxities.
Despite of their younger age, a better mode of tibial fixation might be necessary (uncemented or cemented with short stem). Despite a well-planned surgery, 60% of those patients operated from TKA, still dissatisfied [194].

The other patient group at risk for RLLs lies at the other spectrum of the pathology and are often elderly women with osteoporosis or patients suffering from pathologies affecting bone quality. The quality of the host bone can be insufficient to accept the tibial implant and lead to primary fixation with cement.
Both these groups seem to benefit from a short, stubby stem extension leading to better initial fixation.

The next steps for the future are to manage the surgery by choosing the best alignment possible, the best implant adapted to the type of surgery, a preoperative analysis of comorbidities and trying to know the patient and his expectations before their intervention.
The goal in modern TKA surgery should be to plan the surgery in order to obtain the longest survival as possible, without pain and offering the ability to do normal activities for young patients.
Also, the options for early immediate fixation with uncemented devices should be studied in more detail and especially with the help of new precision-enabling devices and in unicompartmental knee arthroplasty.
The real challenge for the future generation of orthopedic surgeons will be “One patient, one implant”.

The bone quality of the patient, needs to become for the orthopedic surgeon, one of the most important conditions to check before surgery. Biological markers, to analyze BMD before the surgery, need to be more routinely used in our practices, in the case of suspicion of poor bone quality. This bone status screening can be associated to per-operative quality of the bone in order to compare the reliability of those screenings on the bone tibial metaphysis quality.

While going through these reflections of several years of clinical research, it will be crucial to offer some options for future research based on my own experiences.

It will be important to understand where bone scintigraphy or SPECT-CT can add value in the more precise diagnosis of AL. It is our experience that usually these exams are showing an osteoblastic activity in the area that is loaded by the patient. So, on the medial side in a varus aligned postoperative TKA. What amount of bone activity at what stage after surgery can help us understand if the implant has micro- or macro-mobility?

Where can CT-scan with suppression of metallic artefacts help us? With or without the injection of contrast, such as in Arthro-CT. It is our impression today, that the surrounding periost around the tibial component doesn't allow for easy contrast penetration and that the shadow of the metallic component makes it difficult to determine whether there is a real osteolytic reaction around the keel or not.

Where can MRI help us with a special calibration for the presence of the metallic components?

It would be very interesting to obtain images of fluid layers under the components in the presence of micro- or macro-mobility [195-197].

Radiostereometric analysis technologies have improved the comprehension of the migration of the implant, but we can't use those technologies for all TKA and all patients [193].

Can we find a reliable, accessible and less invasive technology to obtain objective measurement of micro- and macro-mobility of the implant? But the question would be, do we need to screen all the patients and if yes, why?
If we screen all patients, would revision for AL be less frequent? In those cases, protocols of screening migration needs to be done, with a clear algorithm of decision.

The advantage of conventional radiography, is the accessibility. If we consider the clinical messages of this doctoral thesis, some signs before loosening can be easily observed on post operative follow up, without particular technologies, indicating if revision is necessary or not.

Where can the analysis of the articular fluid help us? Today we can determine infection with a lateral flow test (Synovasure, Zimmer Biomet, Warsaw, US).
Maybe future developments will show an enzyme typical for AL.

It might also be important to organize a consensus discussion among experienced and expert knee surgeons to determine the clinical and radiological signs of AL.

Clinical signs could be weight-bearing pain, change in limb alignment or starting pain and radiological signs implant migration, increasing RLLs > 2 mm or subsidence.

It will be up to the coming generations of clinical researchers to help us advance with this important problem since AL remains together with infection and instability one of the three main causes for early revision after primary TKA.

We hope to have contributed a little bit to the better understanding of this problem and remain available to support the younger researchers interested in this topic.

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A last thanks to those we forget, those who left, those who have only passed by, those who have shaped me. I am so thankful to the life I am living.

Quelle que soit la rudesse de notre chemin,
l'important est la trace que l'on laisse derrière soi
et qui guidera à leur tour d'autres sur nos pas

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