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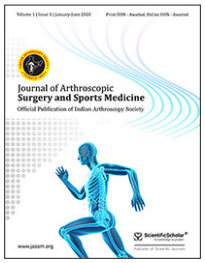

Knee *Review Article*

History of anterior cruciate ligament surgery

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ABSTRACT

The history of the anterior cruciate ligament (ACL) surgery is a very fascinating tale subject to constant evolution, as a path marked by multiple progresses and various long-lasting intuitions and ideas. Along the centuries improved anatomical, physiological and biomechanical knowledge has led to progressively better understand ACL ruptures and evolves from the initial conservative cast immobilization treatment of the past centuries to surgical repair and reconstruction. These reparative and reconstructive techniques have undergone constant evolutions and developments. From the eighties, the advent of arthroscopy enabled minimizing surgical invasiveness, adopting new, stronger and safer fixation devices and promoting quicker, safer, and more aggressive rehabilitation. Several reasons have led to an increase in the success rate, including rapid diagnosis and early treatment, factors that prevented the occurrence of associated meniscal and cartilaginous injuries which, often can cause complications, worsening of results and development of early osteoarthritis. Actually, conventional reconstructions using autologous hamstring tendons or bone-patellar tendon-bone grafts are the procedures most popular today, along with the use of quadriceps tendon grafts and allografts. Orthopedic surgeons have in the last years shown greater interest on understanding and reproducing more precisely ACL's femoral and tibial insertions and this has opened up new horizons leading to increased studies toward biological reconstructions with preservation of ACL remnants through partial reconstructions procedures and all biological reparative procedures, including cell culture techniques, tissue engineering, and gene therapy.

Keywords: Anterior cruciate ligament, Autografts, Allografts, Repair, Reconstruction, Bone-patellar tendon-bone graft, Hamstring: biological enhanced repair, Growth factors, Platelet-rich plasma, Mesenchymal stem cells

INTRODUCTION

The history of the anterior cruciate ligament (ACL) surgery is a very fascinating tale subject to constant evolution, as a path marked by multiple progresses and various long-lasting intuitions and ideas.

From the first surgical interventions to the therapeutical solutions adopted today, considerable steps have been taken, as shown by the brief historical excursus that follows.

FROM CLAUDIUS GALEN TO TWENTIETH CENTURY

If nowadays ACL reconstruction operation is one of the most practiced in joint surgery, recognition of the ACL dates around 170 A.D. starting from the description of the joint environment made from Claudius Galenus of Pergamon (Pergamon, 129 A.D. - Rome, 210 A.D.) in his treatise "On the usefulness of various parts of the body," written between A.D. 165 and 175 and known for centuries just in Greek, Latin, or Arabic. Galenus was the first to describe the ACL as being a structure that supports the joint and prevents abnormal knee motion. He called the cruciate ligaments "*ligamenta genu cruciata.*"[1-3]

From Galenus times, many centuries have passed without further developments or in-depth anatomical or biomechanics studies on the knee structures. In fact, just in the 19th century the ACL began to arouse considerable interest in the field of knee surgery and to be the subject of considerable researches on its structure, its possible injuries and their treatment.

Two German natural scientists brothers, Wilhem Weber, Professor in Göttingen and Eduard Weber, Prosector in Leipzig, in 1836, published a booklet "Mechanik der Menschlichen Gehwerkzeuge" (Mechanics of the Human Walking Apparatus), considered the first comprehensive theory of the kinematics of walking and running, translated to English just in 1992, containing 17 plates of anatomical illustrations. By their treatise, they initiated the modern study of human movement by combining rigorous experimental methods and techniques innovative at that time, optical instruments and experiments with cadavers. In their drawings they identified the ACL as constituted by two different and independent bundles, with different tension in flexion and extension, that when cut gave origin to anterior translation of the tibia respect the femur, thus anticipating the anterior drawing sign.[4]

At the beginning of 1800's clinicians did not still understand that many symptoms and functional impairment consequence of a knee sprain were caused by an ACL rupture.

In 1845, in the "Traité des maladies des articulations"[5] the author, the primary Lyon surgeon Amédéé Bonnet, treated joint injuries that could cause internal bloodshed, focusing on injuries that involved the knee in particular. He perceived the importance of ACL lesions and with regard to acute ones, Bonnet, on the basis of his clinical experience and anatomic studies carried out on corpses, wrote: "In patients who have not suffered a fracture, irrefutable signs of a knee ligament injury are the sound of a break, an hemarthrosis and the loss of function." He proposed conservative treatment, at the same time also encouraging early motion because he perceived that prolonged cast immobilization was detrimental to cartilage. Bonnet's work was unfortunately not translated into English and consequently his work remained unknown for a long time.

It is for this reason that the first recorded description of rupture of the ACL is attributed to James Stark, Fellow of the Royal College of Physicians of Edinburgh that, in 1850, published "Two Cases of Rupture of the Crucial Ligament of the Knee-Joint."[6] Describing the first of the two cases, he wrote "Mr S., on the evening of June 8, 1839, was wrestling in sport with one of his friends, when their legs got interlocked, and something gave way in his right leg with a snap, audible to the others in the room and he fell down…He therefore attempted to rise, when he found he had completely lost the power of supporting himself on the right leg…When he assumed the erect posture, the knee-joint was found to be preternaturally moveable; and whenever any weight was endeavored to be thrown on the right leg, the knee fell against the left leg, and bent with equal facility forward or backward…I resolved to fix it in a nearly, but not quite, straight position with a strong flat steel spring." Both cases were treated conservatively by 3 months of cast and 10 months of semi-rigid brace that unfortunately did not allow to regain normal joint function.

In the second half of 19th century scientists better understood clinical signs and symptoms due to ACL injuries, their pathological mechanisms and their importance.

In 1875, in the thesis entitled "Entorse du genou,"[7] written by the Greek doctor Georgios K. Noulis, the author explained how to evaluate the ACL rupture on the knee near to full extension. He wrote "fix the thigh with one hand, while with the other hand hold the lower leg just below the knee with the thumb in front and the fingers behind. Then, try to shift the tibia forward and backward. When only the ACL is transected, this forward movement is seen when the knee is barely flexed, whereas a backward movement is noted when the posterior cruciate ligament is transected." It is easily understood from these words that the test proposed by Noulis is quite similar to what is now known as the "Lachman test."

In 1879, Segond, a surgeon from Paris, reporting his discoveries in "Recherches cliniques et expérimentales sur les épanchements sanguins du genou par entorse"[8] he described the characteristics of the fracture that involves the anterolateral portion of the tibial plateau and that Segond himself stated to be possibly accompanying ACL injuries and considered as a pathognomonic component of the injury to the ACL. Segond also specified the symptoms of an ACL rupture: The sound of a "pop," pain, joint effusion, and anterior instability.

TWENTIETH CENTURY: FROM LIGAMENT REPAIR TO RECONSTRUCTION

As seen, due to limited resort to open surgery, the 19th century ACL rupture treatment modality was generally conservative through several months of immobilization that conducted patients to satisfactory stability in most cases but not to normal function.

Fifty years after the conservative ACL repair described by Stark, exactly at the beginning of the 20th century, in 1900, the English doctor WH Battle,[9] in a case of knee dislocation occurred 2 years before, made an ACL repair while in 1903 his English colleague from Leeds, Sir Mayo Robson, reported the case treated in 1895, with 8-year follow-up, of a direct suture of both cruciates made by applying sutures at their original femoral anchor sites, with the 41-year-old patient able to go back to work in a mine and after 6 years describing

the operated knee as "perfectly strong and resistant," thus being able to allow him not only to walk but also even to run.[10]

These authors were the first to actuate a direct ACL repair and, obviously, both of them claimed the "paternity" of the ACL repair intervention and a long battle developed.

Hubert Goetjes, in 1913, in a detailed review of ACL lesions, suggested direct repair of both acute and chronic ruptures and was the first to suggest to examine the patient under anesthesia to ascertain the diagnosis.[11]

Trying to improve direct suture results at that times unfortunately not so predictable, Georg Perthes proposed to join the ligament to the bone with a bronze and aluminum wire that was passed from the ligament stump to the outside of the femoral condyle through drill holes.[12]

Suture repair has been continued until the 80, supported by results obtained by David McIntosh and John Marshall, but was then abandoned due to better results published on ACL reconstruction techniques developed at that times.

In fact, the beginning of the 20th century sees the evolution toward ACL reconstruction techniques, transplanting for the first times fascia lata an

d subsequently hamstring and patellar grafts. Patients at that time generally presented to doctor's offices with chronic lesions with dated instabilities unsolved by the conservative treatment attempts.

In 1907, Fritz Lange presented the results of four cases in which he used an artificial ligament made by woven silk support that he connected to the tendon of the semitendinosus and semimembranosus, to create a ligament substitute.[13] The ligament failed, but the new reconstruction idea was launched.

In 1917 Ernest William Hey Groves, who edited the British journal of Surgery for 27 years from its beginning, performed the first ACL reconstruction using a graft taken from the fascia lata and publish it in "The Operation for Repair of the Crucial Ligaments."[14] The approach involved a "wide anterior horseshoe incision made across the joint, the lowest point being below the tibial tubercle, and the lateral ends running up to the lines of the hamstrings on each side" and subsequent osteotomy of the tibial tubercle, to turn upward the patella and ensure excellent exposure of the joint. The incision extended laterally so as to allow the removal of a strip of iliotibial band. In the initial technique, the graft was detached from the tibia, passed through the femoral and tibial tunnels created by $^1/_4''$ twist drill and, on its exit from the second tunnel, it was sutured to the periosteum and aponeurosis.

In 1919, the Italian orthopedic Vittorio Putti presented his case history of reconstruction of the ACL on the occasion of the 26th Congress of the Society of Surgery in Trieste. Putti described two operations performed on a patient who had ankylosis of the knee following a war wound: In the first surgery, knee arthroplasty was performed with interposition of the fascia lata; in the second, performed for the serious residual instability, the reconstruction of the collateral ligaments and of the ACL with flaps of the fascia lata was carried out. Vittorio Putti concluded by saying that "5 months after the operation, the patient walks quickly without the need for prostheses".[15]

In 1934 the Italian surgeon Riccardo Galeazzi, pioneer of ACL reconstruction with hamstrings, described the use of the semitendinosus tendon, released from its musculotendinous junction, brought intra-articularly through a 5mm tibial tunnel drilled in the tibial epiphysis and a tunnel drilled through the lateral femoral condyle, where it was fixed to the periosteum. Galeazzi used three incisions: One for harvesting of the semitendinosus tendon, another for arthrotomy, and a third laterally for fixation. He used a cast for 4 weeks and partially weight bearing for 6 weeks. He reported on three cases. One operated in 1932 had a follow-up of 18 months, and the final outcome was a stable knee with full extension and only a mild reduction of flexion. Galeazzi was the first that ever published the usage of hamstrings tendon autograft in ACL reconstruction.[16]

Galeazzi's technique was revisited by Robert Merle d'Aubigne'[17] in the 50 using pedicled semitendinosus while gracilis was passed through a transfemoral tunnel. Max Lange and Kenneth Cho added further modifications to the technique.

In 1935 Willis C. Campbell of Memphis, who coined the term "giving way," first described the use of a tibia-based graft composed by the medial one-third of the patellar tendon, the prepatellar retinaculum and a portion of the quadriceps tendon in his article "Repair of the ligaments of the knee: Report of a new operation for the repair of the ACL"[18] on 17 patients, most able to go back to sports.[16] Furthermore, in this case, the procedure involved the preparation of two tunnels and the graft was anchored to the periosteum at the exit of the femoral canal. Following the operation, a period of immobilization of the limb was foreseen, which was subjected to splinting for 3 weeks. Campbell's work dealed with 17 cases of ACL reconstruction in as many subjects, most of them practicing sports. Of them, nine had an excellent result and were able to return to playing football 6–10 weeks after the surgery. Campbell deduced that among athletes there was the primary need to provide for an immediate reconstruction of the injured ligament and that the procedure used had to be completed quickly avoiding counterproductive intra- or extra-articular reactions.

The first decades of 1900 saw the launch of new ideas, but it has been only since the 60 that the treatment of ACL ruptures

gained great evolution. Many of these procedures represent the referral of the autologous grafts in use today for ACL reconstruction.

In 1963 Kenneth G. Jones, took up the idea of using a third of patellar tendon taken in the central area with an attached patellar bone block, reporting it in "Reconstruction of the ACL. A technique using the central one-third of the patellar ligament."[19] The tendon was left connected at the tibial site, there was no tibial tunnel and due to the poor length of the graft the femoral canal was performed from the anterior margin of the intercondyloid cavity and the neo-ACL secured to the periosteum at the upper lateral exit of the femoral tunnel. The technique was from, then, modified by several authors (Brückner, Franke and Marshall *et al.*)[20-22] and by the 1990s the free bone-patellar tendon-bone graft (BPTB) harvested from the central one-third of the patella technique became the "Gold Standard" of treatment and referred as the "Jones Procedure." Some authors proposed maintaining some continuity between the patellar tendon and Hoffa's ligament to improve its vascularization. Others proposed associating it with a lateral tenodesis[23,24] to protect the graft during the process of "ligamentization" and final results furtherly improved by the use of interference screws, after the biomechanical study on fixation methods conducted by Kurosaka *et al*.[25]

In 1973 McIntosh[26] and in 1976 Torg *et al*.,[27] one of Lachman's students, changed the clinical evaluation of ACL lesions till then diagnosed mainly by the anterior drawer test in external and internal rotation and neutral position, introducing, respectively, the "Pivot Shift" test and the "Lachman Test" dynamic evaluation.

The comprehension of knee rotatory instability, already years before thanks to Slocum and Larson, brought to the development of various extra-articular techniques that gained popularity in late 60 and 70, where they gained maximum interest (Franke, 1969 – patellar tendon with the respective patellar and tibial bone blocks, for the first time totally detached graft; McIntosh, 1972 – fascia lata graft passed extra-articularly under lateral collateral ligament and fixed, in first technique [McIntosh "1"] on the tibia and in the second technique [McIntosh "2"] intra-articularly inside a tibial tunnel; Lemaire, 1975 – tensor of fascia lata muscle in "Lemaire laterale" procedure).[28-30]

Late 70 and 80 viewed a renewed interest on ACL conventional reconstruction procedures.

In 1979, MacIntosh and Marshall revolutionized the nature of the material used as a graft in the procedure known as "MacIntosh 3," deciding to collect a third of the entire extensor mechanism centrally, including a large portion of pre-patellar aponeurotic tissue. The graft was conducted beyond the upper part of the lateral femoral condyle ("over the top") and anchored with suture or with a metal staple; the terminal part was then stretched posteriorly to be hooked to Gerdy's tubercle.[22]

The problems encountered with BPTB technique – bone block passage, patella fractures, and anterior knee pain – has led, in last decades, to new popularity on the hamstring technique initially introduced by Galeazzi and furtherly modified from Cho in 1979[31] and from Perugia and Puddu,[32] who developed a more medial positioning of the extra-articular tibial tunnel in a manner to preserve the internal rotational action of the semitendinosus and detached hamstrings tendons distally from the tibia, reinforcing them with a PDS tape. Lipscomb, from Nashville, published the technique that used both semitendinosus and gracilis tendons in 1982.[33] There on many variations – being free or attached at its distal end, be it single (2 strands), or double (4 strands) bundled – have been proposed. In 1988, M. J. Friedman first experimented with an arthroscopically assisted self-grafting technique that used four ligament strands.[34,35] He was followed in 1993 by Howell,[36] Rosenberg,[37] and Pinczewski.[38] The hamstring graft success was related to less invasiveness, easier post-operative regimen and rehabilitation, lower risk of stiffness, and reduced anterior pain.

The 70 and 80 have also to be remembered for the development, parallel to conventional autograft procedures, of the augmentation and arthroscopic procedures and the use of allografts. Jack Kennedy, in 1970,[39] introduced the synthetic ligament in polipropilene, known as "Kennedy-LAD" and afterwards as Leeds-Keio and Lars; in 1971, the Cardiff group started using the carbon grafts for their biologic and mechanical potential, which will be abandoned from 1980 for their complications.

David J. Dandy from Cambridge has to be reminded as the first to execute an arthroscopic reconstructive procedure and implanting a carbon fiber ligament in 1981 combined with a lateral plasty with McIntosh technique.[40,41] Probably precisely because of the lack of experience and knowledge in this regard, the results were quite disconcerting: unfortunately traces and carbon deposits were detected in the synovial membrane and in the liver, a contraindication that definitively put an end to the use and possible evolution of the technique.

Just as the carbon fibers were set aside, Dacron and Gore-Tex soon become common in reconstructive surgery, also affirmed thanks to the new arthroscopic technique that could enhance the use of synthetic materials to reconstruct the ACL quickly, with minimal trauma and effectively. However, toward the end of the 80, there was an unacceptable synovitis rate with consequent rupture of the new ligaments that forced the orthopedic community to abandon this reconstructive line.

From the 80 allografts implantation became, after successful use in animals, a positive option which based on their functioning on acting as a collagenous scaffolding for revascularization and fibrovascular creeping substitution. Shino *et al*. did not find implant rejections. From the 90, especially in US, allografts grow in interest and showed good results. Actually autografts are still considered more cost-effective and should represent the first choice in ACL reconstruction.

TWENTY-FIRST CENTURY: PARTIAL, DOUBLE-BOUNDLE AND REGENERATIVE RECONSTRUCTION

During these past 20 years and the previous decade most surgeons have remained faithful to the concept of self-grafting with the difference that compared to the past these procedures could now be practiced in arthroscopy, minimizing surgical invasiveness and adopting new, stronger, and safer fixation devices. There were obviously several reasons that led to an increase in the success rate: Rapid diagnosis and early treatment, factors that prevented the occurrence of associated meniscal and cartilaginous injuries which, often led to complications, worsening of results and development of early osteoarthritis.

As said, conventional reconstructions using BPTB or hamstring autografts are the most popular today, along with the use of quadriceps tendon and allografts. They offer good results also in the long-term follow-up. Studies have although shown a persistence of a positive "Pivot Shift" test in up to 25% of patients.[42] The will to correct this rotatory laxity brought to give greater importance to the reconstruction of the postero-lateral bundle, and not only of the antero-medial one as in the past. With this goal, scientists developed more anatomical reconstruction procedures of the ACL creating the two bundles techniques, originally firstly introduced by Key and Weinstein, in 1973: these authors took a graft from the semitendinosus and the rectus internus, they rotated these tendons, passed them through a single common tibial tunnel and two separate femoral tunnels and finally they fixed the two tendons used for the reconstruction one against the other at their exit. In recent years, Muneta,[43] in 1999, was the first to publish using DB actual techniques, but it was Yasuda's,[44] in 2004, that defined the correct anatomical positioning of the grafts.

More recently, the problems arisen with double-bundle technique have decreased its interest and usage. A recent confirmation comes from last year meta-analysis conducted including five RCTs involving 294 patients that showed no statistically significant difference between single bundle and double bundle reconstructions. Authors concluded that double bundle ACL reconstruction requires longer operation time, expenditure of double fixation materials, and technical difficulty in revision. Furthermore, the DB techniques require excellent surgical skills and a longer learning curve. Given that the SB techniques yield similar efficacy with DB techniques in long-term follow-up and are more cost-effective, the SB techniques may be more suitable as the standard techniques of ACL reconstruction.[45]

Most recent studies state that hamstring reconstruction is followed by most surgeons among the world (45–89%), with BPTB technique used just in 2–41% of cases and preferable in young, highly demanding patients.[46]

The grown interest on understanding and reproducing more precisely ACL's femoral and tibial insertions has, as counterpart to double bundle technique development, also led to greater interest towards the return to biological reconstruction with preservation of ACL remnants through partial reconstructions and the use of cell culture techniques, tissue engineering and gene therapy.

It is a well-known fact that ACL has a low healing capacity, in the past attributed to synovial fluid "hostile" environment and joint movement, that more recently has been retained due to the upregulation of plasmin, through the increased secretion of urokinase plasminogen activator, that would impede fibrin plug formation between ACL wound edges and thus repair of tear.[47]

In the past 5 years, due to more precise imaging diagnosis, more advanced arthroscopic techniques and improved physiology comprehension, new primary augmented repair techniques have been developed, including Internal Brace Ligament Augmentation (IBLA) and Dynamic Intraligamentary Stabilization (DIS) procedures.[48,49] IBLA is based on the use of a 2.5 mm polythethylene tape to bridge from the anatomical attachments of the mid-bundle positions of the ACL on both the femur and the tibia associated to femoral microfracturing. Studies have demonstrated improved stability and graft protection because IBLA works as a load-sharing device, still allowing the graft to see enough stress to undergo ligamentization.[50] DIS uses a threaded sleeve with a preloaded spring in the tibia, from which a 1.8 mm polyethylene wire is passed through torn ACL and made exit out lateral distal femur, where it is secured with a button, also associated to femoral microfracturing. In clinical studies, patients gain near-normal knee function, excellent satisfaction, and return to the previous levels of competition activity in the majority of cases.[51]

Other ongoing possibilities are the biologically enhanced repairs: biological scaffolds, platelet-rich plasma (PRP), PRP+collagen scaffold, growth factors, MSCs injection, and augmentation. Example of bio-scaffold procedures is the bridge-enhanced ACL repair (BEAR) technique.[52] Biological augmented procedures main goal is to accelerate repair

and regeneration, especially thanks to MSCs. The BEAR procedure involves a suture repair combined with a specific hydrophilic extracellular matrix scaffold, composed of extracellular matrix proteins, including collagen and obtained from bovine tissue that is placed in the gap between the two ACL torn stumps and activated with the patient's own blood. The BEAR procedure has recently been demonstrated to give results similar to ACLR with hamstring autografts in the first in-human study and PROMS not inferior to autografts at 2 years follow-up in a prospective multicenter randomized study.[53,54] The findings from all previously mentioned studies are really promising and helping to support the recent paradigm shift in the treatment of proximal ACL tears.[55]

PRP augmentation has given variable results. It should favor graft maturation, but this is not still finally proven, certainly also due to its great differences in harvest, preparation, and location of injection and to variable patient biology. Figueroa *et al*. published a systematic review on 516 patients divided in two groups: 266 who underwent ACL repair versus 250 who underwent ACL repair plus PRP augmentation. At 2 years follow-up they found a tendency to faster graft maturation but not in tunnel healing.

MSCs are perivascular elements[56] proven to be also present in the ACL.[57,58] *In vitro*, bone marrow mesenchymal stem cells have more proliferative capacity than ACL-derived fibroblasts and favor ligamentogenic differentiation with growth factors.[59-61] Animal studies on MSCs in ACL repair have obtained good results, but the translational human studies are still very few.[62,63]

Gobbi *et al*.[64,65] reported the suture repair of proximal partial ACL tear combined with microfracture. Moreover, in a second study, they evaluated also the adjunct of PRP glue injection at repair site. At middle-term results, 78% of 50 athletes could return to their sports activities, clinical scores were sufficient, but four patients experienced re-tear and one patient had residual laxity resulting in a survival rate of 90% at the 5-year follow-up.

Centeno *et al*.[66] performed a prospective trial where patients were treated by fluoroscopic-guided intraligamentary injection of PRP, platelet lysate, and bone marrow-derived stem cells. Seven out of 10 patients demonstrated changes consistent with ACL healing on MRI evaluation at 3 months following the procedure.

The group of Cugat, in 2019,[67] evaluated the effect of autologous derived adipose stem cells (ADRC) injected intra-particularly at the end of ACL BPBT reconstruction procedure and concluded that "patients receiving ADRC at the time of ACL reconstruction significantly improved knee function and healing/maturation of the graft at 12 months. However, this improvement was not statistically significant compared to a control group undergoing ACL reconstruction alone."

In their recent review on ACL repairs, Mahapatra *et al*.[68] have concluded that these techniques are showing promising results in selected patient population and are actually to be considered for proximal avulsions tears – which means Sherman Type 1 –[69] with excellent tissue quality and in the acute phase looking to improve the biological joint environment, thus using a suture system plus PRP or MSCs.

CONCLUSION

This brief representation of the history of ACL surgery confirms the incredible dedication, continuous research and constant commitment of orthopedic surgeons from all over the world to always constantly improve themselves and the services offered with the aim of being able to guarantee patients the most selected and individualized treatment that could offer the restoration of a totally stable joint, the shortest and painless possible recovery times and the resumption of everyday and sport life to which were accustomed before suffering the trauma.

Declaration of patient consent

Patient's consent not required as patients identity is not disclosed or compromised.

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Conflicts of interest

There are no conflicts of interest.

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