2 Biological Properties of Suture Materials

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Suture is a general term for all materials used to stitch torn tissues. Sutures can be synthetic or natural and have a monofilament or braided construction. Through the history of mankind, various materials were tried to serve this purpose. Plants such as flax, hemp, and cotton and animal tissues such as hair, tendon, silk, and intestines are some examples. The oldest, known suture was on a mummy in ancient Egypt on 1100 BC, and the first written description on surgical wound suturing belongs to the Indian physician Sushruta in 500 BC.

In this chapter, the biological properties of commonly used suture materials will be discussed. Sutures may cause different host reactions in living tissues. While the suture remains in the tissue, it can trigger the inflammation cascade through different pathways such as degradation, a foreign body reaction, an allergic reaction, or abrasion. Sutures can remain inert, be partially degraded, or be totally degraded by the host. The amount of degradation is dependent upon the absorbability of the specific suture material. Generally a suture that loses its tensile strength within 60 days is considered absorbable. However, the new generation of absorbable suture materials may hold their tensile properties far beyond this limit. The absorption rate may vary due to the suture composition or the tissue sutured. Host reactions and infection also affect the absorption process. Nonabsorbable sutures do not biologically degrade but can also lose their integrity over time. Sutures that are commonly used in orthopedic procedures are listed in Table 2.1.

The biological response of the local tissues against sutures can be influenced by different factors (Table 2.2). The suture material and its absorbability, configuration, and size in particular are important. Natural materials such as catgut and silk are more immunogenic than synthetic materials because they are degraded by proteolysis in contrast to synthetic sutures, which are degraded by hydrolysis. Hydrolysis is a less immunogenic process compared to proteolysis. Nonabsorbable sutures cause less inflammation in contrast to absorbable sutures and usually induce a fibrous layer formation around the suture, which prevents a host response. More irritation is seen with braided suture than with monofilament sutures. This can be explained by the surface topography of the suture. The smooth texture of monofilaments causes less response in

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Table 2.1 Biological and structural properties of common sutures used in orthopedic procedures

	Brand name	Material	Architecture
Absorbable	Dexon	Polyglycolic acid	Monofilament or braided
	Dexon II	Dexon coated with polycaprolate	Monofilament or braided
	Vicryl, polysorb	Polyglactic acid—polyglactic 910	Braided
	Vicryl rapide	Different form of polyglactin 910	Braided
	PDS	Polyester poly (*p*-dioxanone)	Monofilament
	Maxon	Polyglyconate	Monofilament
	Caprosyn	Polyglytone P6211	Monofilament
	Panacryl	Caprolactone/glycolide	Braided
	Monocryl	Poliglecaprone 25	Monofilament
	Phantom fiber	Poly-4-hydroxybutyrate	Braided
Partially absorbable	OrthoCord	UHMWPE and polydioxanone	Braided
Non-absorbable	Ethibond	Polypropylene	Braided
	Ethilon	Aliphatic polymers Nylon 6 and Nylon 6,6	Monofilament
	Fiber wire	UHMWPE core with a braided jacket of polyester and UHMWPE	Braided
	Force fiber	UHMWPE	Braided
	HiFi	UHMWPE	Braided
	MagnumWire	UHMWPE	Braided
	MaxBraid	UHMWPE	Braided
	Prolene	Polypropylene	Monofilament
	TiCron	Polyester	Braided
	UltraBraid	UHMWPE	Braided

Table 2.2 Effect of suture properties on local tissue reactions

	Local tissue reaction	
	Less	More
Material of the suture	Synthetic	Natural
Architecture of the suture	Monofilament	Braided
Picks per inch in braided suture	More	Less
Twist angle in braided suture	High	Low
Size of the suture	Thinner	Thicker
Type of suture	Non-absorbable	Absorbable

the host. As discussed later in the text, the internal architecture of braided suture is another variable that may cause abrasion to the host tissue. Regardless of the material, as the suture size increases so does the tissue reaction. In addition, a true allergic response to a suture material may also occur. Foreign proteins found in natural materials usually trigger this type of response.

Choosing the most appropriate suture for a specific surgery is a very important issue. Any biological response to the suture material should be limited because exuberant inflammatory reactions delay or prevent tissue healing, cause scar formation, and predispose to infection.

2.1 Nonabsorbable Sutures

Common nonabsorbable sutures used in orthopedic procedures are listed in Table 2.1. Natural materials like silk are not routinely used in orthopedic surgery because their foreign proteins can cause severe reactions. Nowadays the sutures most commonly used in orthopedic procedures are synthetic. Synthetic sutures can be divided into two groups: monofilament and braided. In monofilament group, Prolene and nylon are generally used for soft tissue approximation, nerve, and vascular repairs. Braided sutures in orthopedic surgery are generally used for tendon and ligament repairs and bone fixations. Until the development of ultrahigh molecular weight polyethylene (UHMWPE) suture materials, braided polyester sutures such as Ethibond were commonly used for these procedures. Nowadays different UHMWPE-containing sutures are preferred for tendon and ligament repairs due to their high strength and handling characteristics.

Nonabsorbable sutures used in orthopedic procedures seldom cause significant host reactions. However they are not trouble free. Some of these include tissue abrasion, infection, and foreign body and allergic reactions.

Abrasion is a mechanical irritation causing tissue inflammation. The architecture of the suture is the main factor in abrasion. Monofilament sutures are made of a single strand, whereas multifilaments are composed of several strands and usually braided. Nonabsorbable monofilament sutures such as Prolene (Ethicon, Somerville, NJ) made of polypropylene and Ethilon (Ethicon, Somerville, NJ) made of long-chain aliphatic polymers Nylon 6 and Nylon 6,6 cause minimal abrasion because of their smooth surface. However most of the braided sutures do cause some degrees of abrasion due to their surface topography [1, 2]. Braided sutures are woven by twisted strands. Physical characteristics such as picks per inch (PPI) and the twist angle of these strands affect tissue abrasiveness [3] (Fig. 2.1). As the PPI and twist angle decrease, abrasion of the tissue increases [3]. Williams et al. reported that the latest generation high-strength sutures such as FiberWire, Phantom Fiber BioFiber, Collagen Coated FiberWire, and Ti-Cron are more abrasive than OrthoCord, Force Fiber, MaxBraid, and UltraBraid [3]. Some braided sutures are coated with Teflon, silicone, or wax to improve knot tying. These coatings may also affect the abrasiveness of sutures.

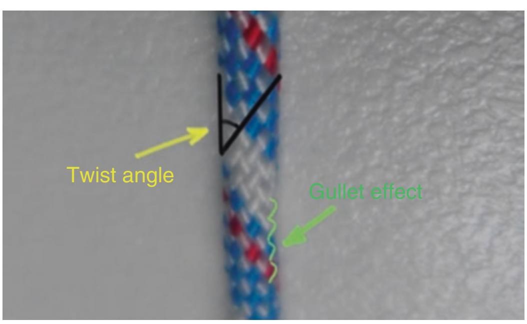

Fig. 2.1 In a suture with fewer external fibers (lower PPI), fibers must take a steeper angle to cover an inch of suture (lower twist angle). Lower twist angle creates a deeper groove between each bundle, like an increased gullet depth on a saw blade

Suture architecture may also cause an increased predisposition toward infection. Fowler et al. showed bacteria adhere less to monofilament sutures than to braided ones. The authors reported that a barbed monofilament suture (Quill) caused less bacterial adherence compared to Vicryl and Vicryl Plus braided absorbable sutures [4]. This suggests that monofilament suture might be better suited for use in surgical areas which are prone to infection.

Adverse events are occasionally reported with nonabsorbable sutures. A foreign body reaction is an early physiological response seen in all types of sutures. Microscopically an inflammatory zone forms around the suture composed predominantly of multinucleated giant cells [5]. While a normal healing response, this response in some cases becomes severe and may result in aseptic drainage. More intense foreign body reactions are commonly seen with absorbable sutures [6]. Esenyel et al. showed that a foreign body reaction is more severe with braided polyester than polypropylene and polyethylene suture [5]. In an experimental study, Carr et al. compared foreign body reactions for eight different braided sutures [7]: Ethibond (Ethicon, Somerville, NJ), Ti-Cron (Tyco, Waltham, MA), HiFi (Linvatec, Largo, FL), UltraBraid (Smith & Nephew, Memphis, TN), MaxBraid (Biomet, Warsaw, IN), OrthoCord (Mitek, Raynham, MA), MagnumWire (Opus Medical, San Juan Capistrano, CA), and FiberWire (Arthrex, Naples, FL). These authors reported that MagnumWire and Ti-Cron demonstrated a more intense inflammatory response than the others in a rabbit model.

Rarely delayed allergic reactions can occur. In a case report, Al-Qattan and Kfoury reported a delayed allergic reaction to polypropylene in a flexor tendon repair [8]. In this special entity, patients usually do not have a history of allergy to sutures. In delayed allergic reactions, the main histopathological findings are foamy histiocytes, lymphocytes, and plasma cells. A skin test is needed to confirm the diagnosis [8]. Suture removal is usually required for resolution.

For nonabsorbable sutures, monofilaments such as nylon and Prolene cause less host reaction than braided sutures like Ethibond or the new generation of UHMWPE-containing sutures. Natural materials such as silk can cause severe foreign body reaction because of their foreign proteins.

2.2 Absorbable Sutures

Absorbable sutures degrade over time and therefore have a complex interaction with the host tissue. Depending upon the material, the time needed for degradation may be as little as 6 days up to several months. Other factors affecting the time needed for suture degradation are the presence of infection and the surgery site. Since the historical catgut suture, many synthetic absorbable sutures have been developed. The common absorbable sutures used in orthopedic surgery and their characteristics are listed below.

2.2.1 Older Materials (Chromic, Gut)

Catgut was the first absorbable suture. It is made by twisting together purified strands of collagen taken from the submucosal or serosal layers of healthy ruminants' (sheep, cattle, and goats) small intestine or beef tendon. Amino and carboxyl groups of collagen are sensitive to pH levels. Alterations in tissue pH may weaken the fiber structure, further causing loss of strength and mass in highly acidic and alkaline conditions. Thus, the strands are treated with formaldehyde to resist the pH alterations and enzymatic attack and twisted together forming the "plain gut" suture. When further processed with chromium trioxide, "chromic gut" is created which is more resistant to absorption and has less tissue reaction.

The plain gut suture retains its tensile strength for 7–10 days and fully absorbs over 60–70 days. In contrast, chromic gut retains its tensile strength for 10–14 days. Fast-absorbing gut is created when plain gut suture is heated to begin the collagen breakdown within the suture prior to use. This suture retains its tensile strength for 3–5 days [9].

2.2.2 Newer Materials

(a) Polyglycolic acid (Dexon), (Dexon II Bicolor): Polyglycolic acid was the first synthetic absorbable suture polymerized either directly or indirectly from glycolic acid. Because of its predictable absorption characteristics and low tissue reaction, it often replaced the use of catgut [10]. It maintains 89% of its tensile strength at 7 days, 63% at 14 days, and 17% at 21 days [11]. Full absorption of polyglycolic acid is reported to occur in 90–120 days [12, 13]. Due to hydrolytic absorption, Dexon has minimal tissue reaction, compared to surgical gut which is degraded by proteolytic enzymes [13]. Polyglycolic acid is available as in a monofilament and a braided form as well as either coated or uncoated. Dexon II is the polycaprolate coated form allowing for easier handling and smoother knot tying. The coating also decreases the risk of bacterial colonization [14]. Dexon sutures were also shown to maintain vascular integrity long enough to permit healing of small canine femoral vein grafts and performed well compared to Prolene [15].

(b) Polyglactic acid (polyglactin 910), (Vicryl, Polysorb): Polyglactin 910, a copolymer of glycolide and L-lactide, is a synthetic braided suture material mainly introduced to take the place of polyglycolic acid. The high concentration of the glycolide monomer in polyglactin 910 (90:10 molar ratio of glycolic to levo-lactic acids) is crucial in maintaining the mechanical and degradation properties. The level of crystalline or amorphous structures impacts the tensile force and retention rate of the suture [13, 14, 16]. Less amorphous structures result in longer strength retention times and stronger tensile properties in sutures.

The primary absorption of polyglactin 910 occurs by hydrolysis. Because of its hydrophobic properties, polyglycolic acid maintains 75% of its strength at 2 weeks and 50% at 3 weeks [13]. It is totally absorbed between 60–90 days [17]. The commercially available polyglactin 910 is either dyed or undyed. If the violet or dyed version is used, cutaneous applications should be avoided because the colored suture may be visible clinically [18]. A lubricant coated form with polyglactin 370 and calcium stearate is also available to ease tissue passage. Vicryl Rapide is another form of polyglactin 910 for cutaneous usage. This suture is a partially hydrolyzed form and does not need to be removed because it is spontaneously absorbed within 7–14 days [19].

(c) Polydioxanone (PDS): Polydioxanone (PDS II®) is a monofilament polymer manufactured from the polyester poly(*p*-dioxanone). The prolonged tensile strength of PDS is its most important advantage over polyglycolic acid (Dexon) and polyglactin 910 (Vicryl) [20]. PDS maintains 74% of its tensile strength at 2 weeks, 50% after 4 weeks, and 25% after 6 weeks [21]. Traces of buried polydioxanone have been found in 6-month postimplantation histologic preparations [22]. The primary usage of PDS is for tendon repair. Because of its slower degradation, it has a low tissue reactivity maintaining its integrity even in the presence of an infection [19]. As a monofilament suture, it retains packaging memory and can remain relatively stiff and present difficulties during knot tying [20, 22]. In subcuticular suturing, polydioxanone was associated with a lower incidence of hypertrophic scar formation compared to polypropylene, nylon, and polyglycolic acid [23].

(d) Polyglyconate (Maxon): Polyglyconate is a synthetic, monofilament absorbable suture material that is a copolymer of glycolic acid and trimethylene carbonate. It is superior to PDS providing a more supple suture handling and smooth knot formation while at the same time providing prolonged tensile strength [24]. It retains 81% of its tensile strength at 14 days, 59% at 28 days, and 30% at 42 days with complete absorption by hydrolysis observed between 180 and 210 days [25]. Maxon has 60% less rigidity than PDS and is significantly easier to handle [24]. Despite its prolonged absorption, tissue reactivity is usually minimal. Though more expensive than Vicryl or Dexon, it is considered as one of the best absorbable monofilament sutures and applicable for large surgical procedures on the trunk or extremities that need prolonged, suture-based approximation during healing.

(e) Polyglytone 6211 (Caprosyn): Polyglytone is composed of glycolide, caprolactone, trimethylene carbonate, and lactide. It can be rapidly absorbed and degraded from the body. Flexibility and superior handling in knot tying are other advantageous properties. It retains its tensile strength for 10 days and is absorbed within 56 days [26].

(f) Caprolactone/glycolide (Panacryl): Panacryl is an absorbable glycolide-L-lactide copolymer suture. It provides significant long-term mechanical strength lasting over 6 months. It retains about 90% of its original in vivo tensile strength at 6 weeks and 60% at 6 months [27]. Complete biodegradation occurs in 2.5 years. In terms of mechanical properties, Panacryl is right in the middle of absorbable and nonabsorbable sutures. The suture is coated by ε-caprolactone/glycolide copolymer for facilitating tissue passage. The braided form allows for excellent suture handling and knot tying with a little concern for knot security [28, 29]. These sutures are mainly used in tissues with slow healing capacity and which demand high tensile strength such as tendons and ligaments. Patients with low tissue healing capacity like diabetics may also benefit from these sutures because of its prolonged strength retention.

(g) Poliglecaprone 25 (Monocryl): Monocryl is an absorbable monofilament suture which is a copolymer of glycolide and ε-caprolactone. At 7 days the suture retains 50–60% of its tensile strength. Absorption is completed by hydrolysis at approximately 90 days post implantation [22]. The initial tensile strength is significantly higher which allows the surgeon to choose a thinner suture size. Monocryl offers good handling characteristics and low tissue reactivity, providing a less reactive scar when compared to Vicryl Rapide [30]. Moreover, poliglecaprone 25 has better knot tying and knot security than other absorbable monofilament sutures [22]. Due to these characteristics, poliglecaprone 25 has become the suture of choice especially in cosmetic cutaneous surgeries.

(h) Phantom Fiber (Wright, Memphis, TN): It is a high-strength absorbable suture composed of poly-4-hydroxybutyrate (P4HB) [3]. It demonstrates approximately 200 N tensile strength at time zero. This suture can retain 50% of its initial strength for 3 months. Poly-4-hydroxybutyrate (P4HB) is fully degraded to water and carbon dioxide in 12–18 months. Because of its high tensile strength, Phantom Fiber is mainly used in tendon repairs.

2.2.3 Partially Absorbable Suture

(a) OrthoCord (Mitek, Raynham, MA): It is a partially absorbable suture, combining UHMWPE and polydioxanone [7, 16, 31]. Depending upon the size, different amounts of polydioxanone will be present. For instance, No.2 OrthoCord contains 38% UHMWPE with 62% polydioxanone, while No. 2-0 OrthoCord contains 45% UHMWPE with 55% polydioxanone. This partially absorbable suture is also coated with polyglactin 910 for improved suture handling. OrthoCord has several advantages including its strength, low tissue abrasion, cut resistance, and flexibility. The main distinction of OrthoCord is the polydioxanone (PDS) core making it partially absorbable. The tensile strength is equivalent to or slightly lower than other UHMWPE-containing sutures and superior to completely biodegradable sutures [1, 32]. Ninety-two percent of baseline tensile strength can be retained through 12 weeks and 90% at 18 weeks. OrthoCord suture has a low bacterial adherence potential compared with other high-tensile sutures [33].

2.3 Biologic Augmentations for Sutures

Tissue healing is a multifactorial process and there are still many questions. Suture type is a significant factor in healing. Various biological materials have been used to increase the efficacy of sutures in different ways. Several different biological enhancement strategies have been used with sutures.

(a) Butyric acid (BA): Butyric acid is a carboxylic acid, formed as a bacterial metabolic product in the gut [34]. In its monobutyrate state, butyric acid has a proangiogenic effect by enhancing DNA transcriptional activity [34]. Leek et al. showed that butyric acid-impregnated sutures improved early Achilles tendon healing in a rabbit model [34].

(b) Polytribolate: It is a polymer of glycolide, epsilon-caprolactone, and poloxamer 188 (Vascufil, Covidien Inc., Mansfield, MA). This material is used as a suture coat in order to accommodate fray resistance, easy handling, less tissue drag, and minimal memory [35, 36].

(c) Growth factors and bioactive substrates: Growth factors and bioactive substrates are known to enhance tendon healing. Various authors studied sutures coated with different growth factors such as epidermal growth factor and basic fibroblast growth factor and reported that the presence of growth factors may facilitate tendon healing [37, 38]. Collagens and amino acids are examples of bioactive substrates. Kardestuncer et al. studied the effect of silk-RGD (arginine-glycine-aspartic acid) on human tenocyte cultures [39]. Their results suggest that the RGD substrate with silk suture increases the adhesion and proliferation of tenocytes.

(d) Mesenchymal stem cells (MSCs): MSCs can effect healing. Pluripotent cells can produce endogenous growth factors and chemotactic agents and differentiate into tenocytes. Yao et al. studied the effect of Ethibond Excel braided polyester sutures (Ethicon Inc, Somerville, NJ) coated with MSCs and bioactive substrate on Achilles tendon repair in a rat model [40]. These authors concluded that MSC-coated suture enhances the repair strength in the early period but shows no significant effect on the later stages. Adams et al. also studied the effect of stem cell and suture combination on Achilles tendon repairs. They reported higher ultimate failure strength with stem cell-coated sutures compared to suture-only repairs in a rat model [41].

(e) Antibacterial suture coatings: Triclosan (5-Chloro-2-(2,4-dichlorophenoxy)phenol) is an antibacterial and antifungal agent that has been used as a hospital scrub. Storch et al. used triclosan-coated polyglactin 910 (Vicryl Plus) suture in an animal study to evaluate the antibacterial effect [42]. The authors showed that bacterial growth was inhibited by triclosan coating without affecting the handling and absorbability of the suture.

Triclosan has also been used on other suture materials including poliglecaprone 25 (Monocryl Plus) and polydioxanone (PDS Plus). In vitro colonization experiments showed that triclosan has an antimicrobial effect against *Staphylococcus aureus* and *Staphylococcus epidermidis* [42, 43].

Li et al. studied the bactericidal and bacteriostatic effects of amphiphilic polymer poly[(aminoethyl methacrylate)-*co*-(butyl methacrylate)] (PAMBM)-coated sutures [43]. These authors reported that PAMBM has a significant bactericidal activity on *Staphylococcus aureus*, while triclosan has mainly a bacteriostatic effect.

Chitin is a natural polysaccharide with an antibacterial effect. Shao et al. reported that an absorbable diacetyl chitin-based suture promotes skin regeneration with faster tissue reconstruction and higher wound breaking strength on a linear incisional wound model [44]. Chlorhexidine, octenidine, caffeic acid phenethyl ester (CAPE), and quaternary ammonium compound (K21) are some new coatings studied in the recent years with good antimicrobial effects [45].

(f) Nanoparticle suture coatings: Silver (AgNPs) nanoparticles are commonly used in urinary catheters and wound dressings. Silver's antibacterial effect comes from reactive oxygen species, which directly affects the DNA and cell membrane of the microorganisms. Rare bacterial resistance and a lower risk of toxicity are advantages of silver nanoparticles. Zhang et al. studied the effect of silver nanoparticle-coated sutures [46]. The authors used AgNP-covered absorbable sutures in intestinal anastomoses in mice. Their results suggest that AgNP-coated sutures have good in vitro antibacterial efficacy and show significantly less inflammatory cell infiltration and better collagen deposition in the anastomosis area. These authors also showed that these sutures provide better mechanical properties in the anastomosis.

(g) 1-Ethyl-3-(3-dimethylaminopropyl)carbodiimide hydrochloride (EDC): EDC (Sigma Chemical Co., St. Louis, MO) is a cross-linking agent that covalently bonds collagen molecules. It therefore creates an eyelet of stiffer material that potentially resists suture cutout [47]. In a recent study, Thoreson et al. tested the mechanical and cytotoxic properties of EDC-treated sutures [48]. They reported that EDC-treated 4-0 braided polyblend suture (FiberWire; Arthrex, Naples, FL) provided better in vitro mechanical results in flexor tendons. They also showed that a 10% EDC concentration is a threshold for cytotoxicity.

(h) Drug-eluting sutures: These sutures are produced using various methods including surface coating by the dip method, by grafting, or by an electrospinning process. Tetracycline, levofloxacin, and vancomycin are some antibiotics that can be used with sutures providing desired concentrations. Anti-inflammatory and anesthetic agents can also be used with common sutures. Weldon et al. used bupivacaine with PLGA-based sutures [49]. They reported these sutures released all the drug over the course of 12 days, while the sutures maintained 12% of their initial tensile strength after 14 days of incubation in vitro [49].

In a different study, Casalini et al. showed that lidocaine can be delivered effectively from a poly-e-caprolactone suture and provide an analgesic effect for approximately 75 h [50]. Immunosuppressive agents can also be delivered by sutures. Tacrolimus (FK506, Astellas Pharma Inc., Tokyo, Japan) is an immunosuppressive agent that prevents intimal hyperplasia. In an experimental model, Morizumi et al. studied the effect of tacrolimus-coated 7-0 polyvinylidene difluoride (PVDF) sutures on porcine vascular anastomosis [51]. Their results showed that the suture can effectively inhibit neointimal hyperplasia, the inflammatory response, and granulation tissue formation at the anastomosis site [51].

(i) Smart sutures: Recent studies have been focused on sutures with shape memory and electronic capabilities [45].

2.4 Clinical Performance of Absorbable Sutures

Newer absorbable materials show equal or better clinical results compared to nonabsorbable sutures. For more than 30 years, absorbable sutures have been used widely in various surgical procedures with good and predictable outcomes. Most of these procedures include vascular anastomosis and soft tissue approximation. However bone, tendon, and ligament surgeries are quite different. These tissues usually heal slowly, therefore sutures should retain their mechanical strength much longer. The biological response of the local tissues can also be quite different. Joint fluid may change the regular absorption process of a suture. Barber et al. suggest that meniscal repairs done with absorbable sutures such as Vicryl, Dexon, and PDS may have unfavorable mechanical strength retention because of the rapid suture absorption [52]. Their data showed that inflammatory synovial fluid accelerates the mechanical disintegration of absorbable sutures. These results suggest that nonabsorbable sutures may be the suture of choice in meniscal repairs.

Barbed sutures are widely used in plastic and general surgical procedures. The use of barbed suture for surgical closure has been associated with lower operative times, equivalent wound complication rate, and comparable cosmesis scores. In recent years, orthopedic surgeons have begun to use barbed sutures [4, 45, 53]. In a therapeutic study, Gililland et al. reported a slightly shorter surgery time in total knee arthroplasty cases when barbed sutures were used for wound closure [53]. In the future, barbed sutures may be preferred by more orthopedic surgeons.

Conclusion

Suture materials have different biological properties and may cause various tissue responses. Proper suture selection will affect the clinical outcomes; therefore surgeons should have sufficient amount of knowledge on these properties.

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