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# Mechanical Comparison of 10 Suture Materials before and after *in Vivo* Incubation

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**The material properties of ten 2-O suture materials were evaluated tensiometrically at time = 0 and again after 6 weeks incubation in rats. All suture material was incubated and tested without knots. Specialized machinery was used with a custom securing apparatus to pull suture material apart at constant speed. Stress–strain curves were derived, and from these strength, toughness, strain at rupture, and elastic modulus were determined. Sutures tested included Vicryl [poly(glycolide–lactide)], Dexon (polyglycolic acid), Ethibond (polyester), silk, plain gut, chromic gut, Maxon (polyglyconate), PDS (polydioxanone), nylon, and Prolene (polypropylene). Elastic modulus was greatest for braided, least for monofilament, and intermediate for gut sutures, regardless of chemical composition (ANOVA, $P = 0.0001$). Strength, strain, and toughness decreased in all of the sutures over time *in vivo* with the exception of braided polyester (Ethibond), which remained stable. Silk demonstrated the least strength and toughness while PDS and Maxon were the strongest and toughest at time = 0. Vicryl, Dexon, and gut sutures were absorbed to the point that they could not be tested after 6 weeks *in vivo*. Performance tables are provided for all sutures.** © 1994 Academic Press, Inc.

*Thou shouldst draw together for him his gash with stitching.*

Edwin Smith Surgical Papyrus [1]

## INTRODUCTION

The availability of a variety of sutures presents the surgeon with a menu from which to choose the best size, material, and design for the task at hand. The current study was designed to provide mechanical information to assist in that choice.

Sutures are categorized by size, material, design, and behavior. Absorbable and nonabsorbable materials are further divided into synthetic versus natural products, some of which can be fabricated in braided and/or monofilament form. Most sutures come in many different sizes, and most are available on a variety of needle types. Nonabsorbable sutures can be made from nylon, polypropylene, stainless steel, silk, cotton, Teflon, polyester, Dacron, and a variety of less commonly used synthetic materials. Each of these can be manufactured in different sizes, and many are available with or without coatings. The advantage of these sutures is that they remain permanently in place and that they elicit little tissue reactivity.

Absorbable sutures include plain gut (made from the submucosa of sheep intestine and the serosal layer of cattle intestine), chromic gut (plain gut precipitated with chromium salts), synthetic polymers of polyglycolic acid (Dexon), poly(glycolide–lactide) (Vicryl), polydioxanone (PDS), and polyglyconate (Maxon). Gut sutures are constructed primarily of interlacing collagen molecules; Maxon and PDS are monofilaments; Dexon and Vicryl are prepared as braids. These absorbable sutures are used when their presence is required temporarily. They incite varying degrees of tissue response and are degraded by hydrolysis (Dexon, Vicryl, PDS, Maxon) and enzymatic digestion and phagocytosis (gut). Each of these sutures behaves differently in the surgeon's hands and in host tissues.

There are many ways to evaluate the properties of these materials. Tissue reactivity [2, 3] and wound strength [4, 5] analysis provide complimentary information, especially if viewed in light of the mechanical properties of the material used to close the wounds. The current study was designed to catalog the mechanical properties of 10 commonly used suture materials and to compare their performance over time in an *in vivo* model. Sutures behave differently if they are stretched, knotted, kinked, nicked, or otherwise damaged. Furthermore, knot types and number of throws can influence whether a knot will slip before it will break under load. To minimize the effects of these variables, all sutures were incubated and tested in unknotted and undamaged form.

## METHODS AND MATERIALS

Ten different 2-O suture materials were evaluated: Dexon, Vicryl, gut, chromic gut, PDS, silk, Maxon, Pro-

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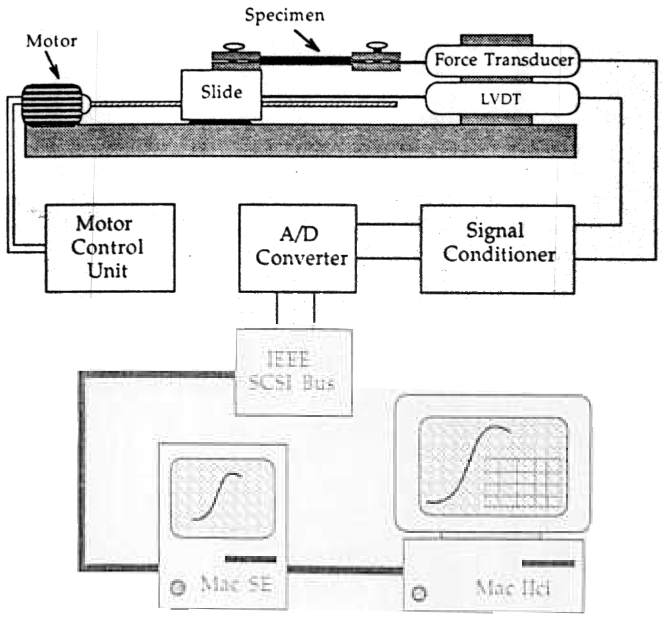


**FIG. 1.** Tensiometer. Specimen is distracted (pulled apart) as slide tray is moved by screw powered by high-torque, constant-speed motor. Applied force and distance distracted are monitored by force transducer and LVDT, respectively. Noise is reduced and analog data is amplified by the signal conditioner. Analog data is sampled at 10 Hz for digital conversion by the A/D converter. Digital data are sent to the first CPU by the IEEE-SC-SI Bus. The second CPU transforms force-displacement curves into stress-strain curves. Analysis of stress-strain curves yields strength, toughness, elastic modulus, and strain data.

lene, nylon, and Ethibond (braided polyester). Suture material was donated from current stock by the University of Chicago operating room. Twenty-five individual sutures of each type were randomly selected from single lots. Five of each suture type were sent to an industrial testing facility (Ethicon Laboratories, Somerville, NJ) where suture diameter was measured optically to USP standards (accuracy: $\pm 10^{-6}$ m) [6]. Ten of each suture type were tested mechanically until rupture (see below); the remaining ten sutures were tested after a 6-week period of *in vivo* incubation in rats.

Twenty male adult Sprague-Dawley rats (250–300 g) were anesthetized with ether. Circumferential full-thickness wounds through skin and panniculus carnosus were created sharply under sterile conditions around the middle of each animal. Suture material was carefully wrapped around each animal without tension and in a nonconstricting way. Wounds were closed with surgical wound clips, taking care to avoid kinking. Each animal had a total of five randomly chosen sutures placed. Animals were allowed to recover under a warming light, and were then individually housed under standard laboratory conditions for 6 weeks (14-hr light, 10-hr dark cycle; 30% humidity; 72°F; food and water available *ad libitum*). All animals were then sacrificed (lethal intraperitoneal injection of pentabarbital) and the wounds were opened. Remaining suture material was carefully removed and tested as described below.

### *Mechanical Testing*

Suture specimens were tested on a motorized slide tray (Fig. 1). Grip-induced failure through stress concentration was avoided with the use of specially constructed clamps (Fig. 2). Suture ends were stretched apart at constant speed (2 cm/min) until rupture. Applied force (load) and distance pulled (displacement) were monitored by force transducer (Lucas Shaevitz, Pennsauken, NJ; accuracy: ±0.02%) and linear variable differential transformer (LVDT; Lucas Shaevitz; accuracy: ±0.01%), respectively. Output signals were amplified and noise was reduced by a signal conditioner (Omega Engineering, Inc., Stamford, CT). Analog data was sampled at 100 Hz for digital conversion (IO Tech, Inc., Cleveland, OH). Digital data were sent through a computer interface unit (IEEE-SCSI Bus; IO Tech, Inc., Cleveland, OH) to a Macintosh SE CPU for real-time, two-channel acquisition. Custom software was used to format the data for analysis by a second Macintosh CPU (Mac IIci). The compliance of the machinery was subtracted, and Poisson's ratio (0.5 assumed) was used to normalize the data for specimen dimensions.

Apparent true stress–strain curves were generated (Fig. 3). Strength was defined as peak stress; toughness was defined as energy absorbed (calculated as the integral of the stress–strain curve from strain = 0 to strain at maximum stress). Strain = 0 was chosen as the first point in the stretch where load was 5% over background. The elastic modulus was calculated as the slope of the stress–strain curve taken at 50% maximum strain. Data outside the zone of interest was eliminated until a least squares regression of remaining data points yielded a coefficient ($r^2$) > 0.99 (minimum strain range = 0.1).

Statistical significance was analyzed by ANOVA (StatView II for Macintosh; Abacus Concepts, Berkeley, CA).

## RESULTS

Mean peak stress (strength), mean energy absorbed to rupture (toughness), strain at rupture, and elastic modulus data are presented graphically in Figs. 4–6 and in tabular format in Table 1.

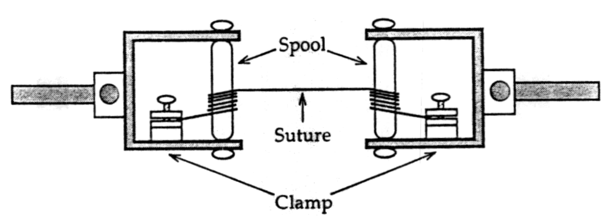


**FIG. 2.** Grip design. Suture material is wound five times around nonrotating spools (4.75-mm diameter) and secured to clamps. Stress concentration is minimized.

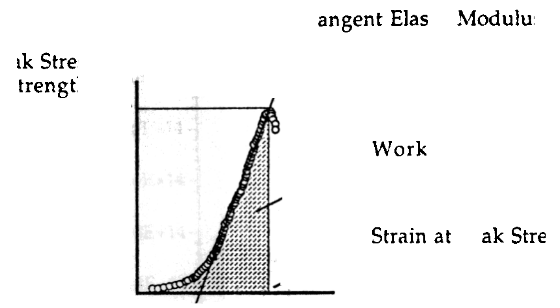


**FIG. 3.** Representative stress–strain curve. Stress represents instantaneous force divided by instantaneous cross-sectional area of the specimen; units are N/m². Strain, calculated as the natural log of instantaneous length/starting length, is reported in units. Strength is defined as peak stress. Toughness is defined as the energy absorbed by the specimen before rupture and is calculated as the area under the stress–strain curve (integral); units are J/m³. Strain at peak stress is indicated. Tangent elastic modulus is the slope of the greatest part of the stress–strain curve and indicates the "stiffness" or resistance to stretch of the specimen; units are N/m².

*Time = 0*

Elastic modulus evaluation (Fig. 4) revealed that suture material behaved according to suture design: monofilament sutures had similar tangent elastic moduli, as did all of the braided materials, both of which were different from gut and chromic gut sutures (ANOVA, $P$ = 0.0001). The braided sutures demonstrated the least compliance (greatest modulus of elasticity: $2.6 \times 10^8$ N/m²), while monofilament sutures were the most compliant ($1.3 \times 10^8$ N/m²). Gut sutures were intermediate ($1.5 \times 10^8$ N/m²).

The monofilament absorbable sutures Maxon and PDS were the strongest and toughest (Figs. 5 and 6), while silk was the least strong and least tough (ANOVA, $P$ = 0.0001). Strain at rupture (Fig. 7) was greatest for PDS, followed by nylon and Prolene (ANOVA, $P$ = 0.0001). All of the monofilament sutures were more extensible (demonstrated the greatest strain at rupture) than all of the braided sutures (0.663 vs 0.253, Fischer PLSD, $P < 0.05$). Gut sutures were intermediate (0.372, Fischer PLSD, $P < 0.05$).

*Time = 6 Weeks*

None of the Vicryl, Dexon, or gut sutures survived the 6-week *in vivo* incubation period. Some remnants of the Vicryl and Dexon sutures were visible in the wounds but lacked sufficient structural integrity for removal and testing. With the exception of braided polyester, all remaining sutures were less strong and less tough when compared to time = 0 controls (Fisher PLSD, $P < 0.05$). Changes in toughness accompanied a decrease in maximum strain for each suture (Fisher PLSD, $P < 0.05$). The tangent elastic modulus was unchanged in all of sutures except silk, Maxon, and PDS, all of which demonstrated an increase in compliance (decreased modulus) after 6 weeks (Fisher PLSD, $P < 0.05$).

## DISCUSSION

Force–displacement relationships are easily measured directly. Normalization of forces and displacements is required for comparison of different materials, independent of specimen length or cross-sectional area. The resulting stress–strain curves represent basic mechanical relationships. From these curves derive the parameters

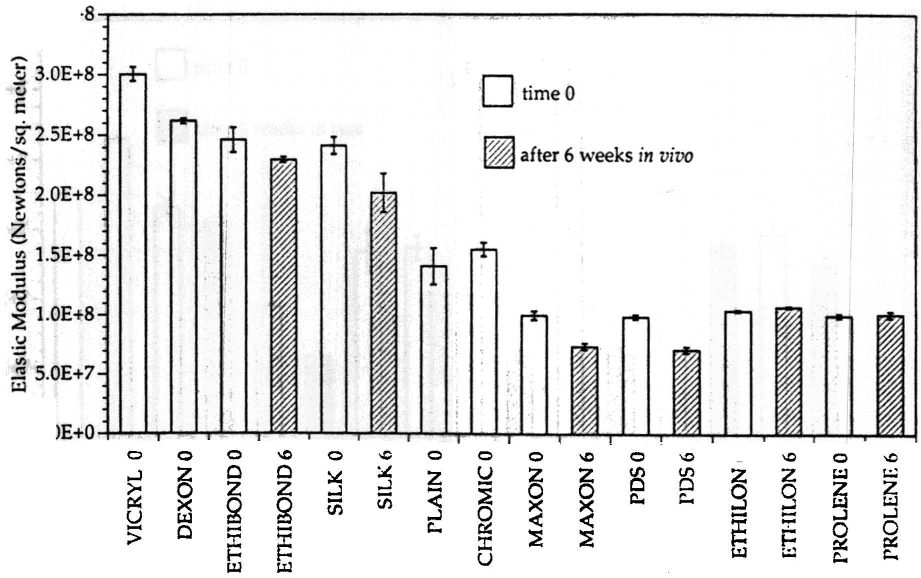


**FIG. 4.** Mean tangent modulus ± SEM.

**TABLE 1**

**Mechanical Data**

| SUTURE | n | STRENGTH | SEM | SEM | | | | |
|---|---|---|---|---|---|---|---|---|
| VICRYL 0 | 8 | 1.42E+14 | 4.56E+12 | 1.48E+06 | 0.234 | 0.005 | 3.00E+08 | 5.92E+06 |
| DEXON 0 | 10 | 3.46E+14 | 6.44E+12 | 7.48E+05 | 0.329 | 0.005 | 2.62E+08 | 2.04E+06 |
| ETHIBOND 0 | 10 | 2.49E+14 | 2.36E+13 | 2.13E+06 | 0.279 | 0.025 | 2.47E+08 | 1.02E+07 |
| *ETHIBOND 6* | 12 | 2.32E+14 | 1.37E+13 | 1.66E+06 | 0.27 | 0.009 | 2.30E+08 | 2.32E+06 |
| SILK 0 | 10 | 8.48E+13 | 4.48E+12 | 6.35E+05 | 0.159 | 0.006 | 2.42E+08 | 6.99E+06 |
| *SILK 6* | 13 | 3.80E+13 | 3.14E+12 | 1.36E+06 | 0.125 | 0.011 | 2.03E+08 | 1.61E+07 |
| PLAIN 0 | 10 | 2.30E+14 | 2.67E+13 | 5.99E+06 | 0.393 | 0.018 | 1.41E+08 | 1.53E+07 |
| CHROMIC 0 | 10 | 2.28E+14 | 1.91E+13 | 3.62E+06 | 0.351 | 0.016 | 1.56E+08 | 5.71E+06 |
| MAXON 0 | 10 | 5.96E+14 | 2.80E+13 | 3.86E+06 | 0.612 | 0.012 | 1.00E+08 | 3.69E+06 |
| *MAXON 6* | 9 | 8.29E+13 | 9.67E+12 | 1.83E+06 | 0.316 | 0.014 | 7.40E+07 | 2.89E+06 |
| PDS 0 | 10 | 7.20E+14 | 4.03E+13 | 3.43E+06 | 0.784 | 0.016 | 9.87E+07 | 1.90E+06 |
| *PDS 6* | 6 | 9.72E+13 | 1.03E+13 | 1.83E+06 | 0.332 | 0.017 | 7.13E+07 | 2.57E+06 |
| ETHILON 0 | 9 | 4.57E+14 | 1.45E+13 | 2.13E+06 | 0.683 | 0.01 | 1.04E+08 | 9.82E+05 |
| *ETHILON 6* | 8 | 2.54E+14 | 7.40E+12 | 8.85E+05 | 0.516 | 0.007 | 1.07E+08 | 9.63E+05 |
| PROLENE 0 | 10 | 4.02E+14 | 4.63E+13 | 4.00E+06 | 0.577 | 0.034 | 1.00E+08 | 2.04E+06 |
| *PROLENE 6* | 8 | 2.99E+14 | 2.59E+13 | 2.66E+06 | 0.479 | 0.019 | 1.01E+08 | 2.77E+06 |

*Note.* Strength (N/m$^2$), toughness (J/m$^3$), strain (units), and tangent elastic modulus (N/m$^2$) data are reported ± SEM. Italics indicate measurements made after 6 weeks of *in vivo* incubation.

fibers (with or without chromiumization), was intermediate. Monofilament, the least resistant to elongation, also included in its ranks the strongest and toughest sutures. The increased stiffness seen with braiding was accompanied by lower peak strains at failure.

An unexpected finding was that even the "nonabsorbable" sutures (except braided polyester) demonstrated changes in mechanical behavior after 6 weeks *in vivo:* strength, toughness, and strain were all lowered. This is obviously a change related to host environment. Madsen [7] studied host response to a variety of suture materials and classified tissue reaction according to degree of inflammation, zone of injury, and collagen formation. Gut and tanned (chromiumized) absorbable suture incited the greatest degree of inflammatory response, with large cellular infiltrates and wide "reaction zones." Nonab-

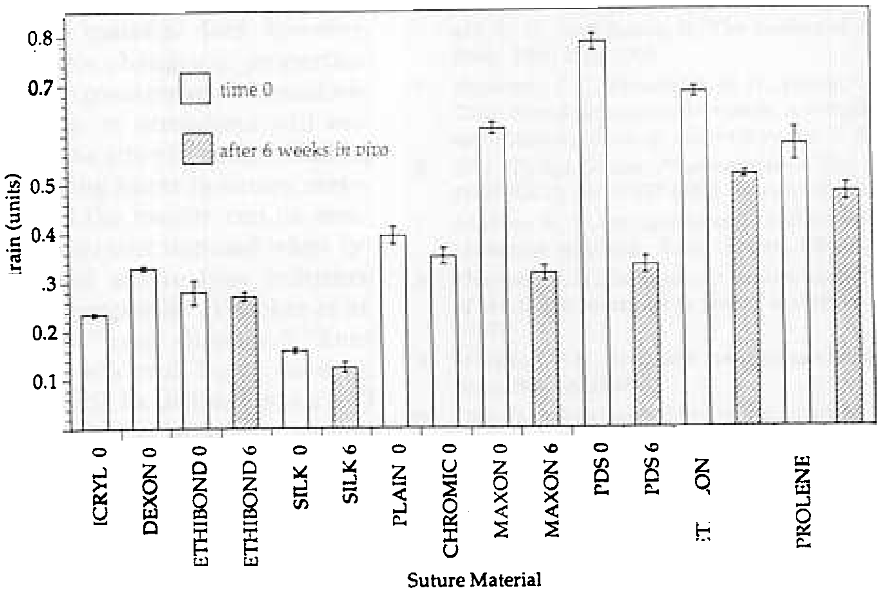


**FIG. 7.** Mean strain at rupture ± SEM.