STRESS, STRAIN AND SUTURES*

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TWO BRIDGES ARE ILLUSTRATED in Figure 1: One is constructed without definite knowledge of the strength of component parts and without consideration of the load to which it may be subjeced; the other, in contrast, is a product of engineering skill and art in which the strength of every bolt and cable, strut, beam and column is known, where each structural part is adjusted to meet calculated stresses and strains with ample margins of safety. What will happen to the toy bridge when Junior steps on it is anybody's guess, but the safety of the engineer's bridge is no guesswork; every day thousands of people unhesitatingly entrust their lives to it.

In operative surgery there are also potentially dangerous stresses and strains and practical problems of mechanical forces. It is often literally true that the life of a patient hangs by a thread.

The tensile strength of sutures, in the strand and at the knot, depends upon the size of the thread and the material of which it is composed. (Fig. 2). Given the same material, tensile strength varies with the square of the diameter of the thread; double the diameter and you quadruple the strength. Knot breaking strength, as a rule, is about 70 per cent of the tensile strength of the strand away from the knot. Brittle material like silkworm gut is relatively weak at the knot. Size for size, the weakest suture material is wet catgut. This material is distinctive also in that, after implantation in tissues, it rapidly loses what strength it has.

Table I shows how badly is needed a uniform gage for all suture material. A gage, based, let us say, upon thousandths of an inch diameter would enable the surgeon, by quick reference to an appropriate chart, to determine the tensile and knot-breaking strength of any given thread, and to suit the sort and size of sutures to his immediate purposes.

The strength of sutures depends not alone upon the tensile strength of the strand, but also upon the security of the knot. Each of the horizontal stripes in Figure 3 represents a set of 20 tests. None of the five commonly used knots represented there is safe when the ends are cut very short; indeed, the only dependable knots are those with three throws, the ends being cut 2 or more mm. long. Similar results are obtained with cotton (Fig. 4); nor is the pattern of these tests altered significantly by wetting the thread with water or serum, by waxing or oiling the thread, or by using boiled or autoclaved thread. Results with catgut are much the same (Fig. 5). Steel wire knots are very prone to slip. Particularly unreliable are those knots which tighten down when the second throw is pressed home, and the knot which ends-off a continuous suture, in which two strands are tied to one.

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Table I.

COMPARATIVE SIZE (DIAMETER) OF SUTURE MATERIAL

Diameter 1/1000 inch	CATGUT Dry	CATGUT Wet	SILK Surgical	SILK Commercial	NYLON Surgical	NYLON Commercial	COTTON Surgical	COTTON Commercial	WIRE Tantalum	WIRE Steel
28		No 1								No 22
26										
25	No 2		No 2							
24		No. 0								
23					No. 3					
22	No 1				No 2					No 24
21										
20			No 1							
19	No 0	No 00								
18										No 26
17							"C"			
16	No 00							"8"		
15			No 0					"10"		
14		No 000								No 28
13					No 00		"B"	"20"		
12	No.000							"30"		No. 30
11		No 4-0								
							"A"			
10			No 000		No 000		No. 0	"40"		
	No. 4-0	No. 5-0								
9								"50"		No. 32
	No 5-0							"60"		
8			No. 4-0	"A"		"A"				
							No 000	"80"		
7										No. 34
			No. 5-0							
6										
5									.005 in	No. 35
			No. 6-0							
4										No. 36
3									003 in.	

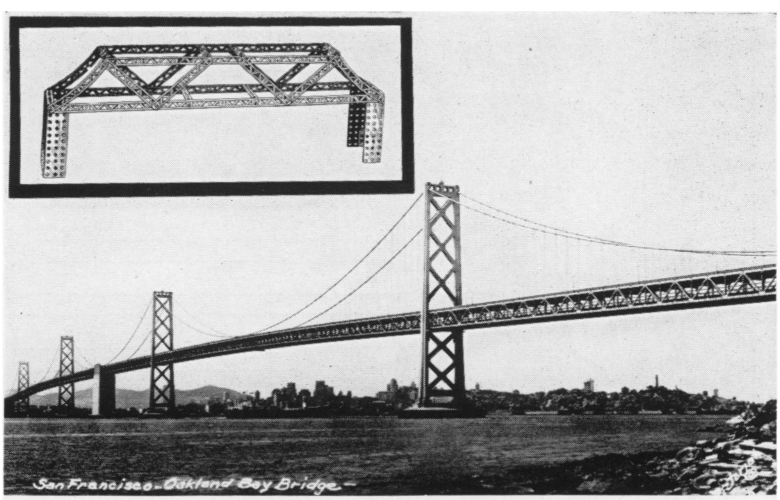

Fig. 1.—A splendid example of engineering skill, contrasted with a toy bridge (inset) which is constructed without regard to principles of engineering.

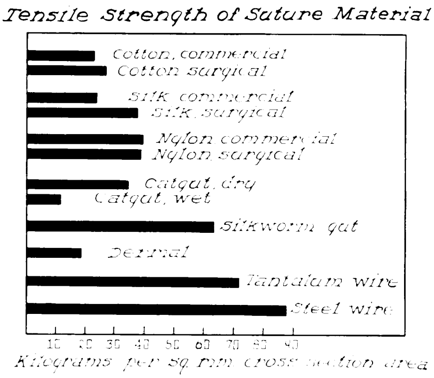

FIG. 2.—Relative tensile strengths of suture materials.

Actually in surgery we deal with loops rather than straight strands. The strength of a simple loop is double that of a straight strand (Fig. 6), and a double loop is four times as strong, presumably because of distribution of tension and friction against the tissues.

In surgery, loops are subject not only to the longitudinal pull indicated in Figure 6, but also to intraloop tensions. For example, a ligature placed around an artery (Fig. 7A) must withstand bursting forces due to the pressure of the blood within the vessel and the expansile elasticity of the arterial wall, and this stress is transmitted to the knot.

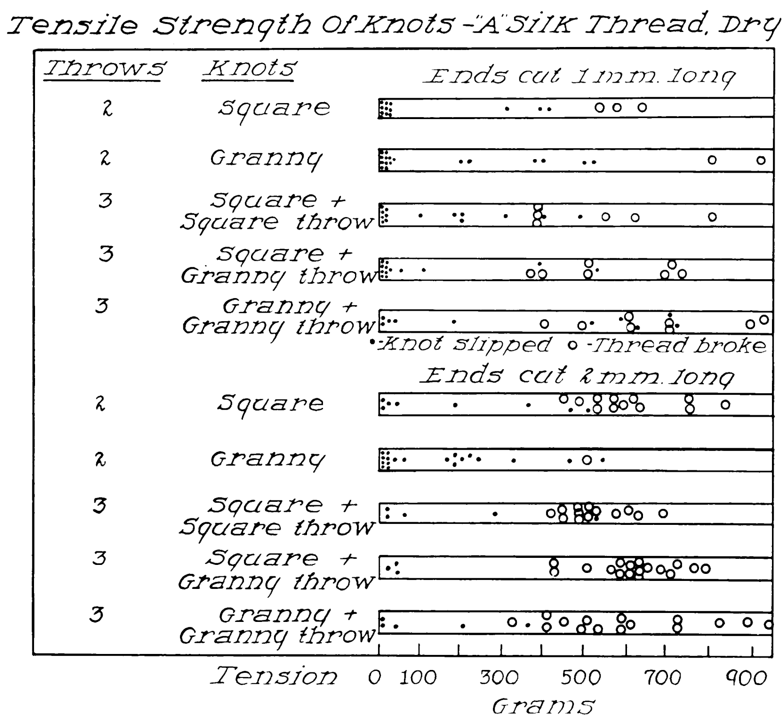

FIG. 3.—Strength and security of knots. Tests made with a tensiometer. Solid dots represent knots which came untied; circles knots which held until the thread broke. The amount of tension required to loosen or break the knot is indicated by the position of the dot or circle.

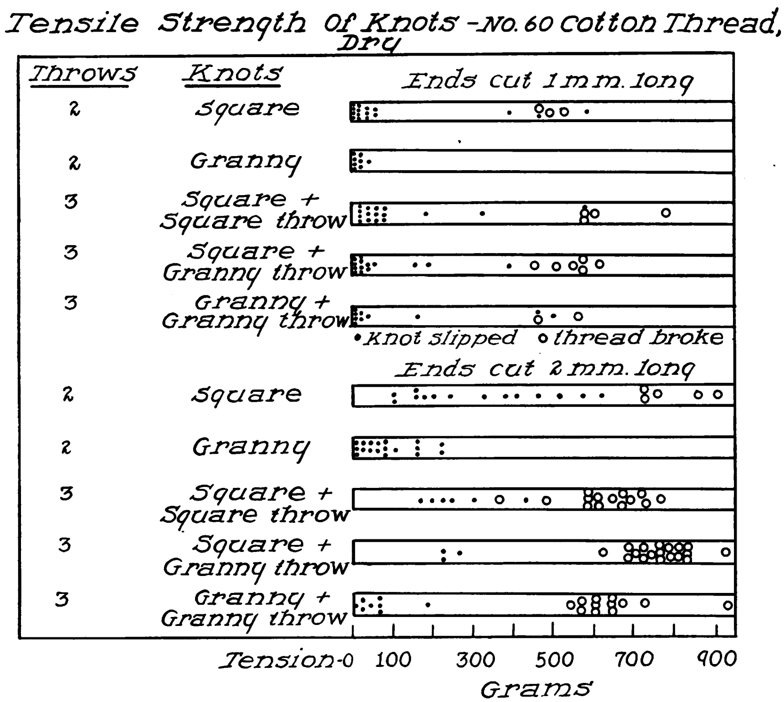

FIG. 4.—Strength and security of knots. Size "A" silk thread, commercial grade.

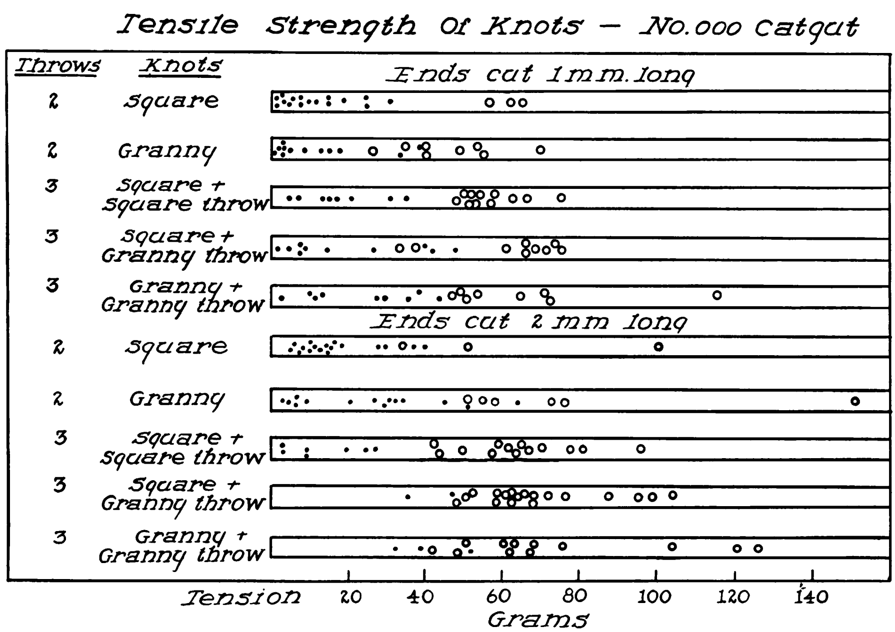

FIG. 5.—Strength and security of knots. No. 000 catgut. Catgut in general is less uniform than other suture material in tensile strength of the strand and in knot-holding ability. Simiular results were obtained with plain and chromic catgun.

Figure 7B illustrates schematically the bursting forces felt by an abdominal incision. The suture represented there has to withstand the cumulative effects of (1) intra-abdominal pressure, (2) the lateral pull of abdominal muscles, and (3) edema or inflammatory pressure within the loop itself. A similar combination of tensions acts also upon lines of suture in the stomach or intestine.

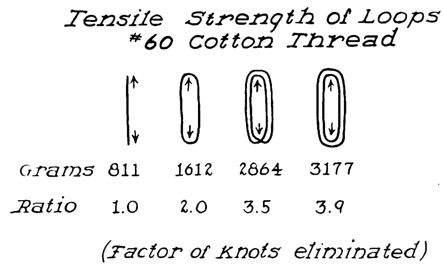

FIG. 6.—Strength of loops.

The bursting strength of a loop is inversely proportional to the area which it encloses; or, to put it more accurately, the tension is proportional to the area which it encloses; or, to put it more accurately, the tension is proportional to the area enclosed. The results shown in Table II were obtained in tests made upon pneumatic tubes and balloons of various sizes, but this law of mechanics, well known to hydraulic engineers, applies to animal tissues also and has wide applications in surgery. Mass ligatures are more apt to break or come untied than ligatures around small bleeding points or isolated vessels (Fig. 8). Large sutures are subject to greater tensions than small sutures. Four-zero silk is more than strong enough to tie a small artery like the thyroid, but might not hold the external iliac artery. The larger the diameter of an organ or cavity, the greater the tension upon sutured incision (Fig. 9).

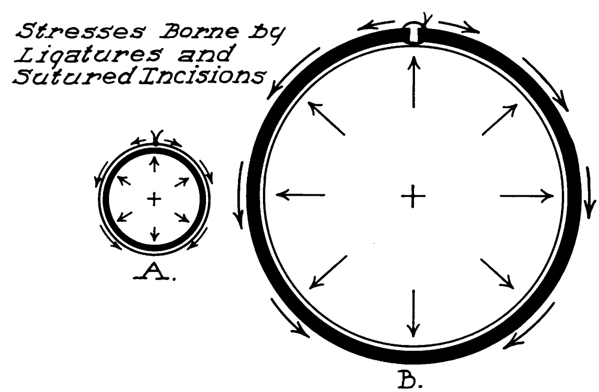

FIG. 7.—Tensions felt by (A) ligatures and (B) sutured incisions.

It follows that the size of suture and ligature material should be selected with a view to the tensions to which it may be subjected. The finest available cotton or silk thread should suffice to ligate ordinary bleeding points.

The operator who places small, closely spaced sutures can afford to use fine suture material, whereas the operator who habitually takes large bites widely spaced must needs use coarser thread. A perforated peptic ulcer is more safely closed with two or three mattress sutures than with a relatively large purse-string suture.

This brings us to a consideration of rows of sutures. Tensions experienced by individual sutures are not easily measured in patients, but they

TABLE II—*Strength of Loops of No.* 60 *Cotton Thread Around Pneumatic Tubes or Balloons (Knots with many throws to prevent slipping)*

Diameter of tube or balloon	Pressure required to break thread	π (the Greek letter "pi," i.e., 3.1416) x pressure
2.77 cm.	250 mm. Hg.	1505
3.44	204	1897
4.71	82	1426
8.81	22	1344
17.4	6.5	1355
24.0	3.5	1580

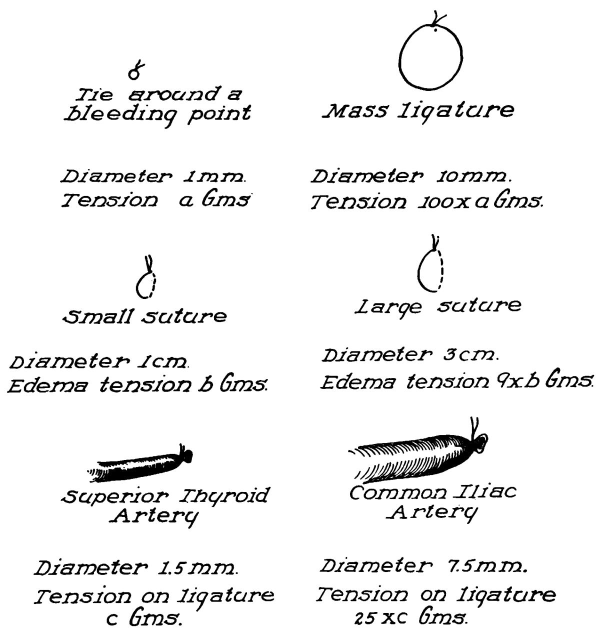

FIG. 8.—Other factors being equal, tensions on ligatures and sutures vary with the cross-section area enclosed by them.

can be studied in models and in freshly killed experimental animals, in which all the mechanical forces concerned are reproduced; and there can be little doubt that the effects observed in such experiments are similar to those which obtain in the living body. When sutures are uniformly spaced, the total tension felt by the suture line is found to be distributed equally

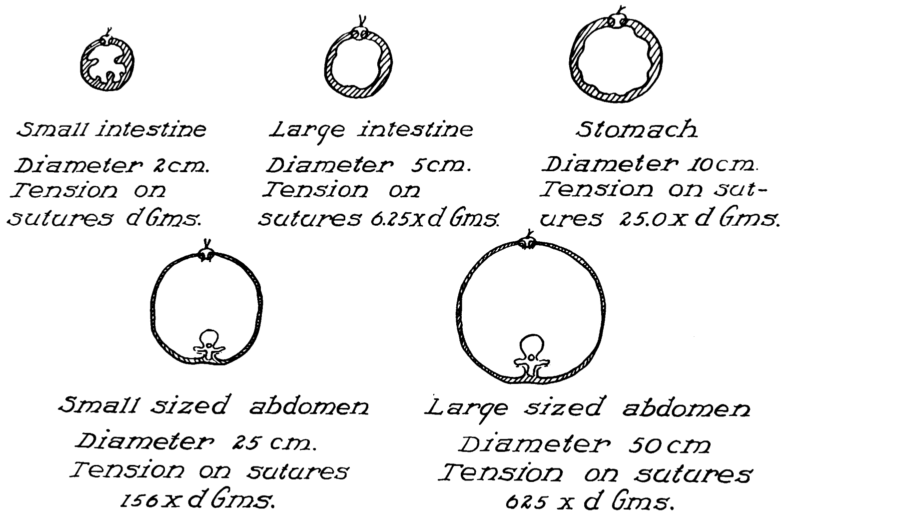

FIG. 9.—Effect of size of an organ or cavity upon the tension of sutured incisions. The values indicated in this diagram are used simply to illustrate the principle under discussion; actually, the total tension of sutured incisions is a complex matter with many variable factors involved.

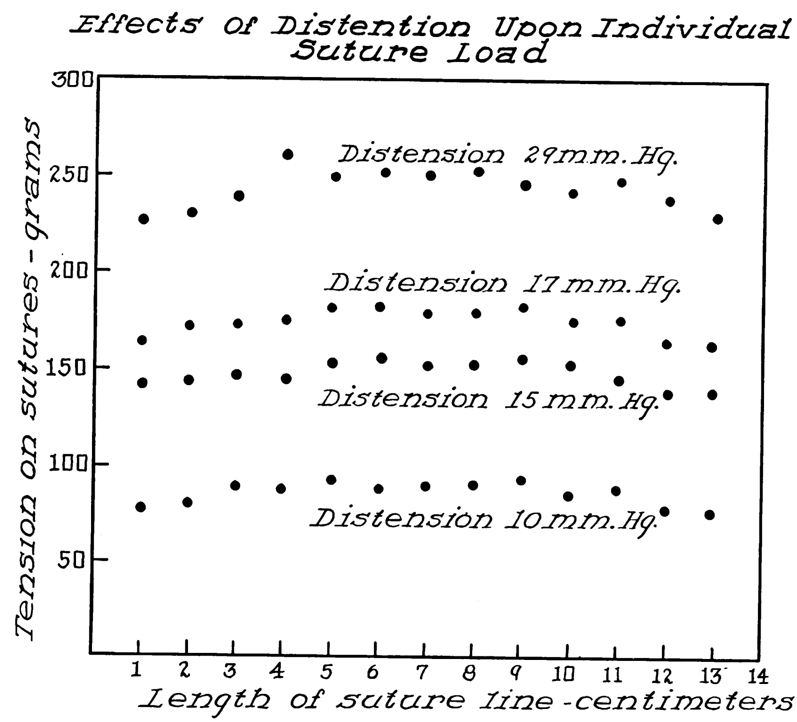

FIG. 10.—Distribution of tension between sutures in an incision, and effects of distension upon the suture load.

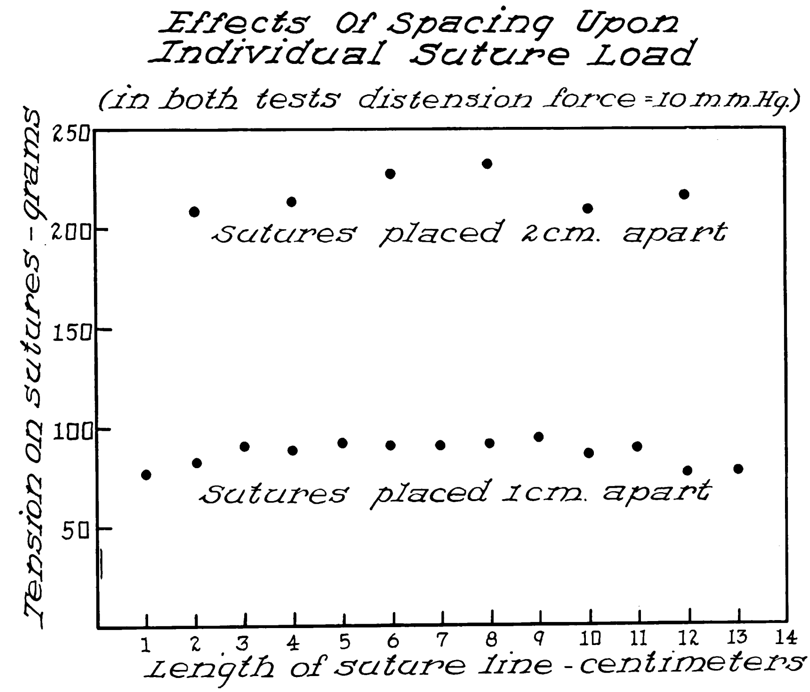

FIG. 11.—Effect of spacing of sutures upon suture load.

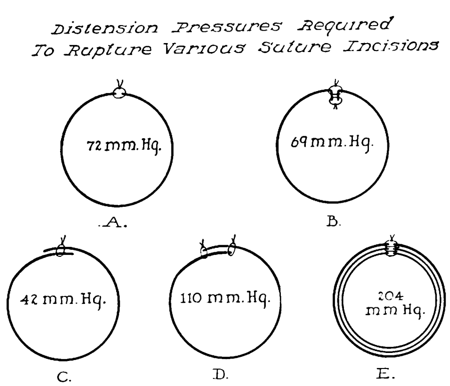

FIG. 12.—Results of tests made under comparable conditions to show the relative strengths of various sorts of closure. A, a single row of approximating sutures; B, a second, "reinforcing" row of invaginating sutures; C, imbrication with a single row of sutures; D, imbrication with two rows of sutures; E, 3 layers closed independently.

between the sutures (Fig. 10). In the case of an abdominal incision, the greater the intra-abdominal pressure, the greater the tension upon the entire suture line, and the greater the tension upon each individual suture. If there are fewer sutures more widely spaced, each suture then has to carry a larger share of the total load (Fig. 11).

Other factors being equal, the over-all tension on an incision is proportional to its length. There are usually more sutures in a long incision to share the load, however, so that the tension upon individual sutures is apt to be much the same, whether the incision is long or short. Should one suture of a row slip or break, the tension which it has borne is immediately transferred to its neighbors. If, with the sudden increase in tension, those sutures break also, even greater strain is then thrown upon the next in line. Thus a sort of "chain reaction" may be set up with disruption of the entire row of sutures.

Figure 12 shows diagrammatically the relative strengths of various closures by layers. In the so-called reinforcing row (Fig. 12B), all of the tension is concentrated on the outer row; should that give way, the full force is then thrown on the inner row. The main advantange of that sort of closure is watertightness. Imbrication does not add to strength unless both edges are sewed down A closure with three independent layers is three times as strong as a single layer closure.

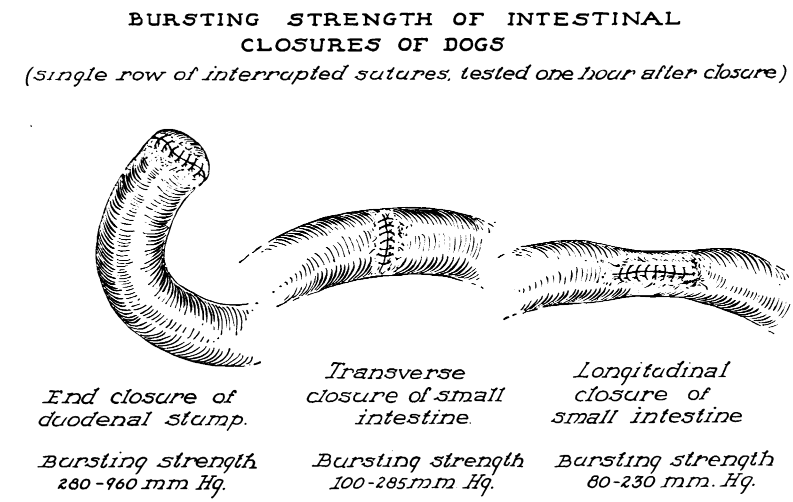

FIG. 13.—Bursting strength of intestinal incisions in dogs. Not infrequently in these tests the wall of the intestine ruptured before the suture line gave way or leaked.

Experiments in dogs show that a duodenal stump closed with a single row of well-placed, interrupted, inverting sutures of No. 60 cotton or 4-0 silk thread (Fig. 13) is able, without leakage or disruption, to withstand intraduodenal pressures of 280 to 960 mm. Hg.—pressures far in excess of anything ever encountered clinically. I am convinced that leakage of the duodenal stump is due not so much to weakness of sutures as to ischemia, necrosis, and cutting through of sutures, either because they were tied too tight, or because too much bowel wall was turned in and strangulated with multiple rows of sutures.

Since the transverse or cross section stretch of the bowel exceeds the longitudinal stretch (Fig. 13), intestinal distention puts less strain on transverse than on longitudinal incisions. For that reason end-to-end anastomoses are mechanically stronger than side-to-side anastomoses.

Another aspect of the problem is strength of tissues. Unless the tissue sewed is as strong as the suture used, variations in suture strength become irrelevant. Three variable factors must be considered in this connection. First, the sort of tissue one has to deal with. Skin and fibrous tissue are the toughest of the soft tissues; indeed, the suture-holding strength of most soft tissues depends upon the amount of fibrous tissue they contain. Thus the brain and spinal cord, containing minimal amounts of fibrous tissue, will scarcely support sutures, but the sutured sheath of a peripheral nerve will hold even under considerable tension. The seromuscular coat of the

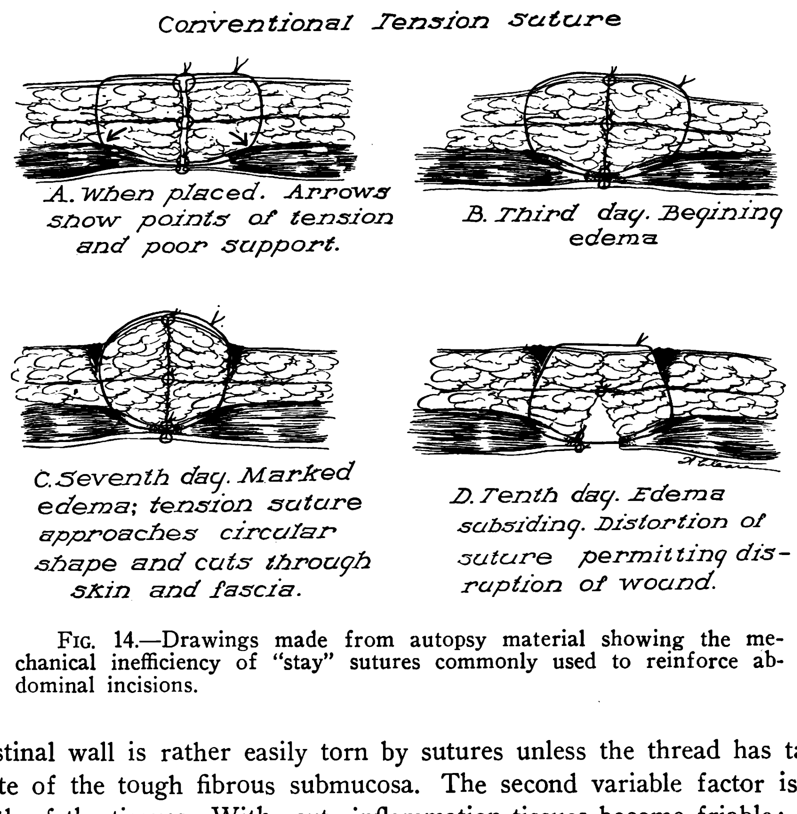

FIG. 14.—Drawings made from autopsy material showing the mechanical inefficiency of "stay" sutures commonly used to reinforce abdominal incisions.

intestinal wall is rather easily torn by sutures unless the thread has taken a bite of the tough fibrous submucosa. The second variable factor is the health of the tissues. With acute inflammation tissues become friable; with ischemia—we all tie our sutures too tightly—and with necrosis, tissues slowly give way before the advancing pressure of the thread and we say that the suture "cuts through." The third variable factor is the size of the suture material. The finer the thread, the more readily it will cut through either healthy or diseased tissue. Recently steel wire sutures have become popular; yet steel wire cuts through most soft tissues long before full advantage can be taken of its enormous tensile strength.

Technically, *strain* means distortion due to stress. An example of strain is provided by the conventional tension suture often used in closing abdominal incisions. Figure 14 shows why that suture is inefficient mechanically and often fails in its purpose because of distortion. The lateral pull of the musculofascial layer is opposed only indirectly by the suture, much as a bowstring opposes the pull of an archer's fingers. Inevitable edema plays its nefarious role.

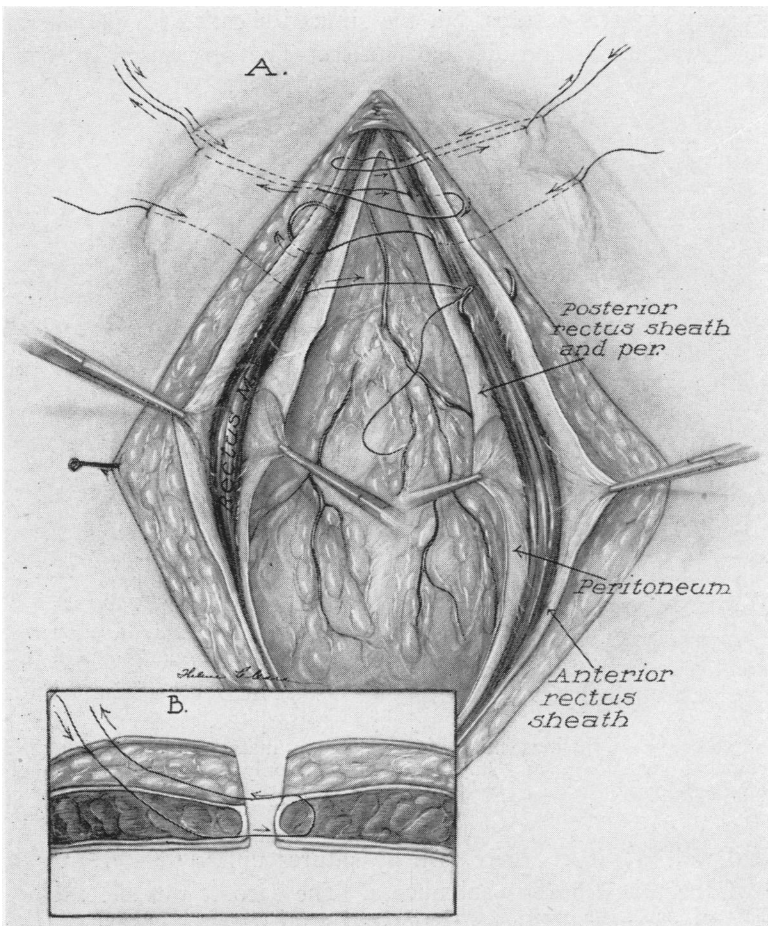

FIG. 15.—A new tension suture which enters the abdominal wall at a distance from the incision, crosses the incision to take a generous bite in the musculofascial layers of the opposite wall, and returns to emerge near the point of entry. The posterior rectus fascia should be grasped by this suture.

Figures 15, 16 and 17 illustrate a tension suture which has been used by the writer during the last two years with satisfaction. There are no closed loops to produce ischemia or to be affected by edema. These sutures, which are staggered, take generous bites of fascia and muscle so as to minimize the danger of tearing or cutting through. They should be drawn just tight enough to approximate the muscles and fascia. Inasmuch as their pull directly opposes the strong lateral pull of those structures, they cannot be distorted to any extent, unless they break, however great the tension. These sutures can be adapted to paramedian, transverse, subcostal, hockey-

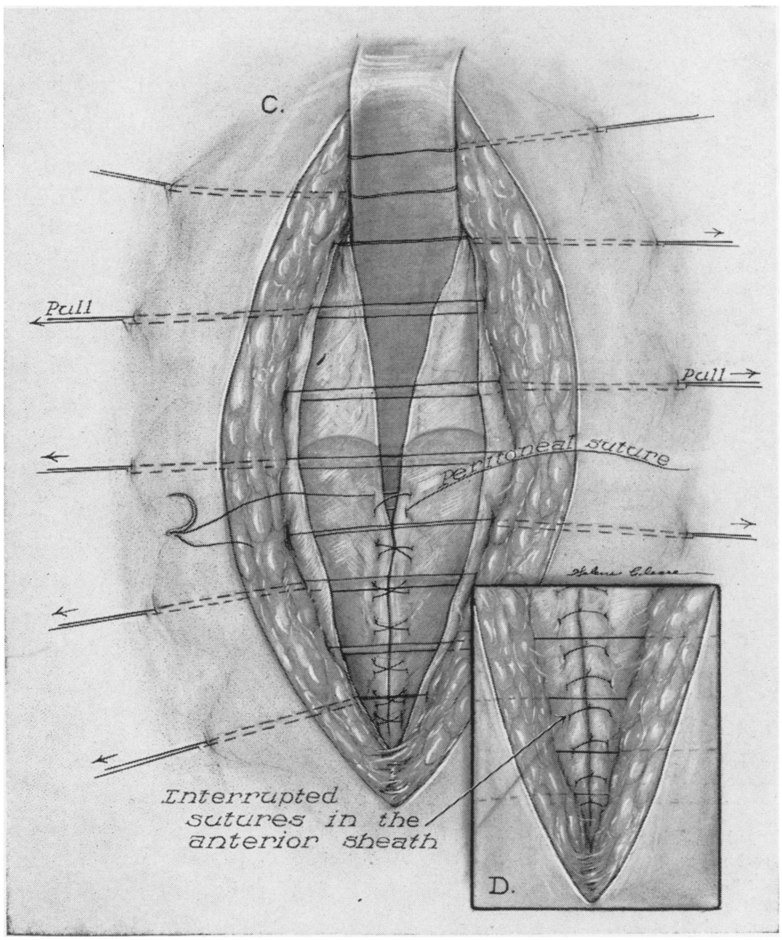

FIG. 16.—Further steps in placing the tension sutures and in closing the abdominal wall.

stick, and T-incisions. If desired, the ends may be tied over rubber tubes or rolls of gauze instead of the metal frame shown in Figure 17. The suture is readily removed after cutting one of the strands close to the skin.

If No. 2 or No. 3 silk or nylon is used, the combined holding strength of these tension sutures is very great, amounting altogether to some 200 or 300 pounds. Patients find them relatively comfortable since they do not tend to cut through or irritate the skin, since their firm support relieves much of the pain of turning, coughing, and early ambulation, and since they obviate the necessity for tight adhesive strapping and supportive binders.

SUMMARY

No reputable engineer attempts to construct a bridge without knowing first the stresses and strains to which his structure probably will be subjected, the tensile and shearing strengths of his building materials, the calculated total strength of his design, and the margins of safety to be allowed. But in surgery, where the health or life of a patient may literally "hang by a thread," the caliber and sort of suture and ligature material to be used is too often left to guess or habit; the size and spacing of sutures, the number of rows to be used, the sort of knots to be employed, are often simply matters of hand-me-down custom, with scant reference to well-established laws of mechanical forces. Indeed, most surgeons have vague ideas about the amounts of stress and strain which lines of suture are apt to feel, or how best to meet those potential disrupting forces. To play safe, suture material is often used that is unnecessarily coarse, or wire that is many times stronger than the tissues being approximated, or tension sutures that are mechanically inefficient.

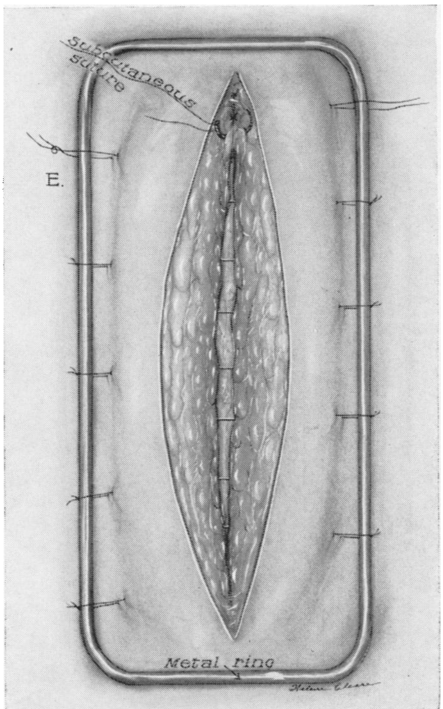

FIG. 17.—These tension sutures are staggered so as to avoid undue squeezing and ischemia of tissues. They are carefully adjusted and tied before the more superficial layers of the wound are closed.

The present paper attempts to explore that neglected but important aspect of operative surgery. Largely on the basis of some original investigations, it presents certain basic principles which should be followed, and offers some practical suggestions which (it is hoped) will give the surgeon better-founded confidence in his ligatures, anastomoses, and wound closures. A new tension suture is described, which is believed to be mechanically superior to the conventional through-and-through tension suture.