SYNOVIAL FLUID PRESSURE DETERMINATION IN THE TEMPOROMANDIBULAR JOINT

by

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Abstract

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The synovial fluid hydrostatic pressure within the joint cavity of the TMJ has received little, if any, attention in the literature. Previous investigations into the nature of synovial fluid pressure within other synovial joints such as the knee, however, have significantly added to the understanding of the biology of these joints. Most findings from these studies indicate that the fluid pressure within other synovial joint cavities is subatmospheric.

The present study was performed to examine the nature of synovial fluid hydrostatic pressure within the TMJ of the pig, Sus scrofa domesticus Utilizing the "wick method" for determination of joint fluid pressure, fluid pressures within seven surgically exposed TMJ capsules of five animals were monitored, measuring the hydrostatic pressure levels with the jaw in the resting position and during various operator-manipulated jaw movements. In addition, an attempt was made to study the nature of fluid pressure within the TMJ cavity of a functioning

experimental model by surgical implantation of a wick catheter into the joint space. This was accomplished in two animals, measuring fluid pressures in the left joint of each. Fluid pressure behavior was monitored at 10 and 14 day intervals, post-operatively, in the two TMJ cavities where successful wick catheter implantation was accomplished.

The findings are summarized as follows:

1. The synovial fluid hydrostatic pressure was subatmospheric in 6 out of 7 surgically exposed TMJ capsules with the jaw in the resting position. The mean value of the 6 animals showing negative values was -3.8 mm Hg.

2. Similar, but slightly less negative "resting" values were obtained post-surgically where successful wick catheter implantation was accomplished. The less negative values were attributed to in vivo compression of contiguous tissues upon the TMJ capsule.

3. Experiments verified that the subatmospheric values were not artifactual.

4. Pressure increased as a response to operator-manipulated jaw positioning, returning to original levels when the jaw was replaced to its initial resting position.

5. Increased synovial fluid pressure, concomitant with operator-held jaw positions, declined with time. The delay in pressure was attributed to both an absorption of fluid by extra synovial tissue and to compliance of the capsular tissue.

6. Operator-manipulated "balancing side" shifts of mandibular position, created higher synovial pressures than did operator manipulated "working side" shifts.

7. Mandibular movement in conjunction with mastication by the experimental animals themselves produced a marked pressure increase. Hard-textured foods exhibited a greater pressure response in comparison to soft-textured items.

8. To maintain negative pressure levels within the capsule of the TMJ, it is likely a constant force acts to remove fluid from the joint space. The pressure behavior in the present study supports the view that a pressure gradient across capillary walls sustained a negative pressure level by net absorption of synovial fluid.

9. Possible relations between fluid pressure and TMJ pathology were discussed. For example, sustained elevated pressures as a consequence of prolonged joint use provide a theoretical basis for long-term joint damage.

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DEDICATED

TO

Karen, my lovely wife, whose devotion, patience and unselfish love have guided me through these years and made all this possible.

Kristin and Kelly, my beautiful daughters, who have brought unending joy and enrichment to my life.

AND

IN MEMORY OF

My mother, whose dreams for her son have finally come true. . . .

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INTRODUCTION

Until fairly recent years, the dental profession has not been generally aware of its responsibility for understanding temporomandibular joint (TMJ) function physiology and pathology. Shafer (1974) points out that initially the otolaryngologist contributed greatly to our knowledge of the anatomy and physiology of this joint. Undoubtedly, this was due to its unique anatomic position and association with contiguous structures. Recent efforts by dental researchers have clarified some of the mystery surrounding this important structure. Dawson (1978) indicates there have been more changes in concepts and the rationale for diagnosing problems in the past 25 years than in the previous 2,500. However, there still exists a great amount of confusion related to TMJ function and physiology. Indeed, the biology of the TMJ is complex, but as the role of each functional component is defined, the intricacies of the whole system become more clear.

A component of the TMJ that has been neglected is synovial fluid hydrostatic pressure and its relation to the function, physiology and pathology of the TMJ. Little, if any, information is available in the literature regarding this aspect. This is unfortunate, for the importance of synovial fluid in proper joint function is well recognized. However, the relation of intraarticular pressure to the function and physiology of other

joints such as the knee has been investigated widely. Knowledge gained from these investigations has significantly increased the understanding of both normal and pathologic conditions within the capsule of those particular joints. Similarly, measuring the synovial fluid hydrostatic pressure of the TMJ, under a variety of conditions, may provide some insight into not only the unique biology of this joint but to an understanding of TMJ disease as well.

The objectives of this study are to: (1) record synovial fluid pressure at rest and during various manipulated jaw movements of a surgically exposed TMJ capsule in a laboratory animal, and (2) to develop a technique for surgical placement of a small catheter into the joint space to allow post-operative recordings of synovial fluid hydrostatic pressure in a functioning experimental model.

LITERATURE REVIEW

Joints Other than the TMJ

As previously stated, the relation of synovial fluid and its hydrostatic pressure to the biology of other articulations has been studied by a number of investigators. Bauer (1940) performed a protracted investigation on the embryological, morphological and physiological significance of the synovial joint cavity. His findings suggested that the synovial cavity is simply an enlarged interstitial space. This comparison leads to the important inference that factors regulating the properties of joint pressure include those which also regulate interstitial fluid pressure. Chemical and pressure analysis of synovial fluid (Gardner, 1950) indicate that the synovial fluid is essentially a form of interstitial fluid to which hyaluronic acid has been added. Gardner held that hydrostatic and colloid osmotic pressure of extravascular fluid and plasma govern synovial fluid pressure, as they do in other tissues. Other factors involved in synovial fluid pressure, however, have also been considered. Smith and Campbell (1928) indicated that lymphatic drainage of the synovial joints affects intraarticular pressure, as do contributions from hyaluronic acid and protein found in the synovial fluid (Jensen and Zachariae, 1959).

Reeves (1966) measured the hydrostatic pressure in the human knee joint and found that it was slightly subatmospheric. This is compatible with Bauer's theory of joint space simply being an enlarged interstitial space (fluid pressure of interstitial space is also negative). On the other hand, Caughey and Bywaters (1963) suggested that subatmospheric pressure recordings of the synovial fluid were artifactual, created by a blockage of the hollow needle place in the joint cavity. However, the experiments of Guyton (1963) and Levick (1978) agree with the findings of Reeves. They maintain that the negative pressures in the knee joints were normal and that the "synovial fluid is separated from the interstitial fluid merely by a loose layer of connective tissue permeable to fluid."

Investigations dealing with pathology associated with an abnormal fluid pressure in synovial joints have been widely reported. For example, Ekholm and Norback (1951) studied the effect of severe exercise on pressure-volume relationships within the knee joint. They held that pressures are generated which are high enough to interrupt the flow of blood to the joint possibly ischematizing the synovium for short periods of time. Similarly, Edlund (1949) and Levick (1979) describe a "breaking point phenomenon" within the rabbit knee joint. Accordingly, excessive intracapsular pressure may "break" the pulsatile (capil-

lary) flow to the joint, providing a means for potential damage to the synovium.

The relationship of joint fluid pressure to chronic joint conditions such as arthritis has been investigated extensively as well. Caughey (1963) determined that intraarticular pressure was elevated in patients suffering with chronic knee troubles. Likewise, Jayson (1970) conducted a series of investigations on patients afflicted with rheumatoid arthritis of the knee and determined that: (1) intraarticular pressures of rheumatoid knees were significantly higher than controls, (2) increased intra-articular pressure could interfere with circulation to the synovium, (3) knee distension leads to quadriceps inhibition in some subjects. Maurodes (1975) studied the effect of chronic knee effusions on the articular cartilage of the rabbit knee, and he indicated that an increase of synovial fluid pressure may inhibit fluid transport in the articular cartilage. Finally, while monitoring intracapsular pressure of patients with chronic hip problems Geiberger (1980) established that pressure is significantly above normal.

Measurement of Other Forces Associated with the TMJ

Studies of fluid pressure measurements in the TMJ have not been previously attempted. However, reports of measuring

other types of forces associated with temporomandibular joint function are numerous. For example, biting force during mastication was measured by Anderson (1956). More recently, Graf (1975) and Hylander (1978) did preliminary work on the direction or magnitude of reaction forces that act upon the human TMJ. Investigating mandibular biomechanics and joint function in primates, Smith (1978) demonstrated that during unilateral molar biting both condyles are under compressive stress and that the balancing side condyle probably bears 70 to 80% of total condylar forces in man. Hylander (1979) analyzed the TMJ reaction forces in macaques and found that the direction of force is compressive on the TMJ during the power stroke of mastication and incision, and during isometric molar and incisor biting. In addition, he demonstrated that the compressive force is larger on the contralateral side during both mastication and isometric molar biting. Force reaction on the ipsilateral side varied with location of masticatory force on the dentition. Along the bicuspids and first two molars the force on the ipsilateral TMJ was compressive. However, when the point of biting shifted to the third molar the ipsilateral TMJ demonstrated little compressive stress, no stress, or a tensile stress. Similarly, in an investigation of condylar movements, Gibbs (1971) suggested that the ipsilateral condyle may not bear any masticatory stress.

Interestingly, a cinefluorographic analysis of human mandibular movements conducted by Koivumaa (1961), indicated that the mandible in some subjects rotated in a counterclockwise direction while biting on hard caramel candy. It was apparent that the mandible shifted upward, while the ipsilateral TMJ moved a few millimeters off the slope of the articular eminence.

Reporting on a method for determining the physiologic equilibrium point of the mandible, Tradowsky (1981) found that depending upon the position of support (an adjustable central bearing support) the force on the TMJ is either positive (compressive), negative (tensile) or at equilibrium (no stress). For example, with a subject clenching maximally on a support placed in the anterior region of the mouth, the condyle would be pushed superiorly and the pressure on the TMJ would be positive. Tradowsky maintains that in this situation the mandible is acting as a Cl III lever. In other words, the jaw pivots around the anterior support in a clockwise direction because the resultant force passes distal to the force and anterior to the TMJ (fulcrum). On the other hand, a subject biting on a support placed posteriorly would cause an inferior displacement of the condyle and a negative pressure on the TMJ. Accordingly, the mandible now acts as a Cl II lever because the resultant force passes anterior to both the support and the TMJ with the mandible pivoting around the support in a clockwise direction. If the sup-

port were placed at a point where the resultant force of the closing muscles intersected it, Tradowsky maintains that neither positive nor negative TMJ pressure would be produced because pivoting of the mandible would not occur during muscle contractions. He believes this would be the physiologic equilibrium point of the mandible.

Technique

Understanding the role of fluid pressure in various body structures of both man and different animal species has long been a goal of many investigators. Accordingly, a number of techniques to measure fluid pressure have been devised. The method utilized in this investigation was developed by Scholander (1968) who determined that tissue fluid pressure can be measured easily and rapidly by means of a capillary tube fitted with a cotton wick (wick technique). Recording the interstitial fluid in various tissues in a number of species, Scholander established that these pressures were slightly subatmospheric. Later, Snashall (1971) utilized the wick method to measure subcutaneous interstitial fluid pressure of the arm in voluntary human subjects. Monitoring human muscle compartment pressure as a means for early diagnosis of "compartment syndrome", Hargens (1978) used a modified wick technique. Compartment syndrome is a condition in which fluid pressure within muscle compartments becomes elevated to

levels which may cause pain and/or induce pathology. Subsequently, emergency rooms in many hospitals instituted this technique to determine the need for muscle fasciotomy after crush injuries In addition, Fronek and Zweifach (1975) utilized the wick technique to determine the effect of vasodilation on microvascular pressure distribution in skeletal muscle. Also, during surgical procedures such as high tibial osteotomies, the wick method has been employed to monitor changes in muscle pressure (Hargens, 1981).

Recently, some investigators have utilized the wick method to measure the intraarticular pressure in various joints. For example, Levick (1979) used this method to measure the synovial fluid hydrostatic pressure of the rabbit knee in an attempt to determine certain physiological aspects of the knee. In addition, Geiberger (1980) instituted a modified method to monitor intraarticular pressure of the hip joint during osteotomies.

It is noted that other techniques have also been developed to measure fluid pressure and which have been widely used. Perhaps the most utilized of all methods, employs a cannula (21 gauge needle or smaller) inserted into either the interstitial fluid or synovial fluid to be measured (Levick, 1978, 1979; Reeves, 1966; Guyton, 1971; and Jayson, 1970). This technique offers the same advantages as the wick method in that

it is simple, accurate, reproducible and responds rapidly to tissue fluid pressure dynamics. However, the wick procedure may permit long term post-surgical recording of fluid pressure since it neither utilizes a metal hollow needle, causing possible trauma to surrounding tissue under prolonged usage, nor will it become as readily clogged due to the exposed dexon fibers.

MATERIALS AND METHODS

Animal Model

In choosing an experimental animal for this investigation of the TMJ, certain basic anatomical and functional criteria had to be met. For example, the structure/function relationships of the experimental model's TMJ must allow for mandibular movements analogous to the human counterpart, i.e., protrusive, lateral, opening and closing jaw movements. In addition, the anatomy of the animal's TMJ must be relatively similar to that of the human's, and most importantly, the potential volume within the capsule of the experimental animal's TMJ must be large enough to allow insertion of the wick catheter without causing unnecessary trauma to surrounding tissue. Carnivorous animals such as dogs were rejected on the basis that the masticatory system of these animals allows for primarily opening and closing jaw movements. Rodents such as rabbits and rats, although meeting the basic anatomical and functional requirements, were excluded because it was felt that the relatively small joint space prohibited the use of the wick catheter Large herbivores (pigs, cattle and sheep) satisfy all of the above criteria. The pig, Sus scrofa domesticus, was selected as the experimental model because it was felt that of the large herbivores, it would be the easiest to work with due to its relatively smaller size.

Although herbivores such as the pig meet the basic requirements to conduct this investigation, it should be noted that a number of important anatomical features exist that are unique to the pig. For example, it jaws are relatively longer and greatly deepened to contain the long posterior teeth. In addition, vestigial canines are present sometimes, but no canine buttress exist. Allowing for a greater area for insertion of the relatively larger masseter muscle, the mandible has a high vertical ramus which is very wide at its base. Consequently, the masseter tends to be the most powerful closing muscle. Both the area of the temporal fossa and the size of the coronoid process is small relative to the human or primate counterpart. Accordingly, the temporalis muscle is small, functioning slightly in mastication. Providing for wide horizontal movements during lateral grinding, the TMJ of the pig is both loosely bound and has a well developed articular disc.

General Procedure

Pigs, Sus scrofa domesticus, of either sex weighing 15-40 kg were premedicated with Ketamine intramuscularly (20 mg/kg). The anesthetic, three percent Serrital plus saline, was then administered through the auricular vein, utilizing a threaded 20 gauge 1¼ intracath to facilitate an IV drip. The pigs were intubated with a 32 Fr endotracheal tube. On occasion, 0.5 mg atropine was administered intramuscularly to dry oral secretions.

Wick Catheter

The wick catheter contains one four centimeter cord length of No. 1 Dexon absorbable suture tied centrally to 40 cm of No. 6-0 nylon monofilament. The monofilament's free end is passed through either PE-40 or PE-30 tubing (36 cm length) fitted with a 21 gauge Luer stub adapter. The Dexon fibers are pulled one centimeter into the catheter leaving approximately two millimeters of Dexon exposed on the catheter's free end. This allows only fluid pressure to be monitored because the exposed Dexon prevents the recording of unnecessary mechanical forces by tissue impedance against the catheter's opening.

Insertion of Wick Catheter into the TMJ

The skin overlying the TMJ was incised and reflected until the capsule of the joint was exposed. Wick placement was facilitated by prior insertion of a 20 gauge, 1.5 inch intravenous catheter into the superolateral aspect of the joint cavity. For this procedure, an additional dose of anesthetic was usually administered as the periarticular tissues appeared to be quite sensitive to mechanical stimulation. The metal portion of the intravenous catheter was then retracted, leaving the plastic outer catheter in place. Next, the wick was zeroed with the transducer and recorder, removing excess fluid from the wick fibers and any air bubbles inside the wick catheter. The wick was then intro-

duced through the plastic outer catheter and the latter was retracted, leaving the wick in place. Lastly, a silk purse-string suture was placed around the insertion site to eliminate leakages.

Measurement of Synovial Fluid Hydrostatic Pressure

The wick catheter was connected to a P23Db Statham pressure transducer positioned level with the animal's TMJ. Transducer output was fed into a Gould-Statham amplifier and recorded on a Gould-Statham 220 two-channel chart recorder.

Equilibrium of synovial fluid pressures were attained immediately. Wick response to fluid pressure was checked by digital pressure to the capsule of the TMJ. A slight but immediate rise in pressure recording resulted.

Because of the relatively small bore of the intravenous catheter, insertion of the wick was usually possible without resultant hemorrhage: a rapidly rising pressure and development of a bloody effusion indicated significant intraarticular bleeding. If this occurred, that particular trial was abandoned.

Measurement and Changes of Jaw Position

Measurements of TMJ synovial fluid pressure were initially recorded in the resting jaw position. The relationship between joint hydrostatic pressure and lateral, protrusive, and open jaw movements/positions were also recorded. Fluid pressure was continuously recorded for two to three minutes after the mandible

had been placed in a new position, allowing sufficient time for pressure recordings to stabilize.

Surgical Placement of Catheter

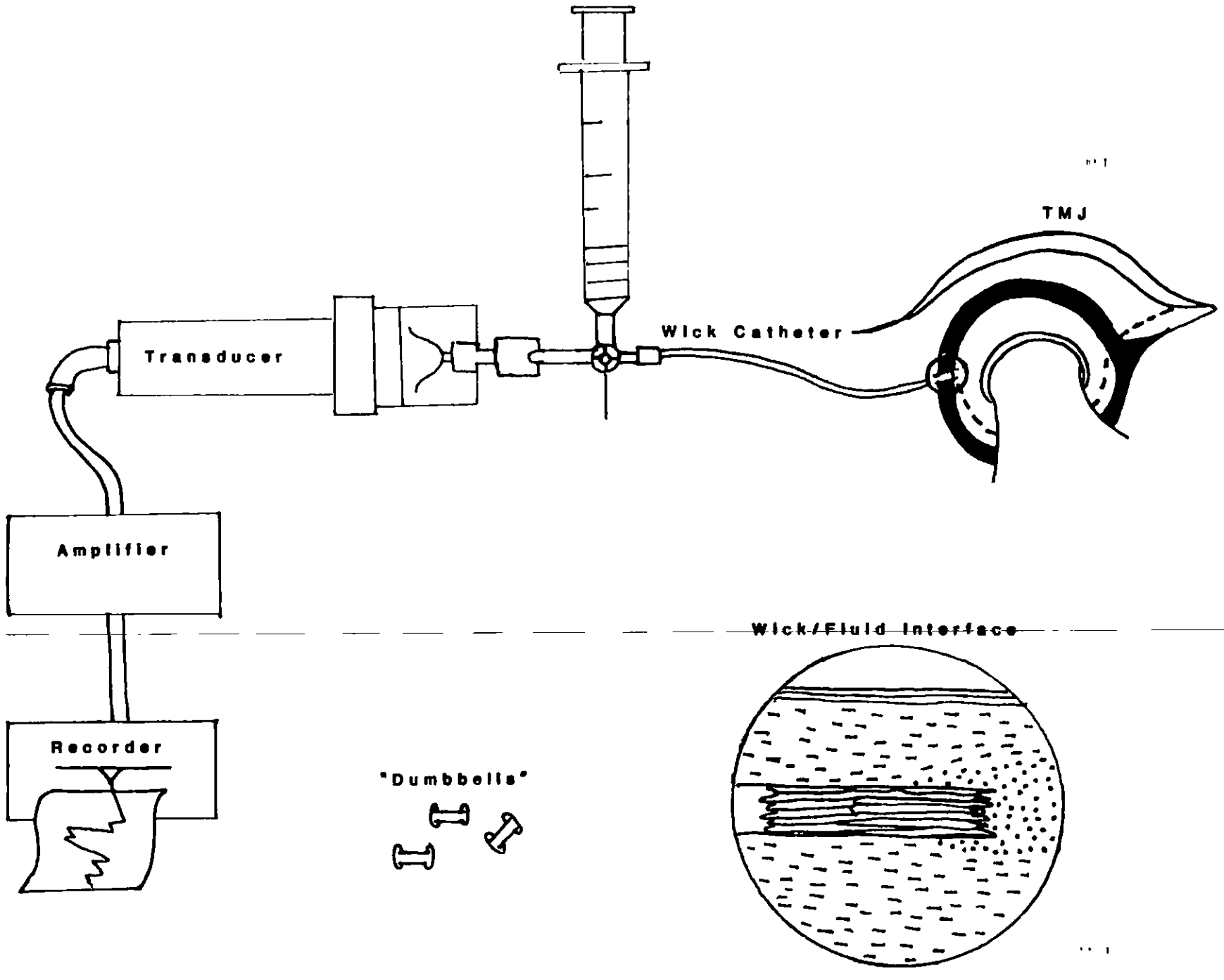
To facilitate placement of the catheter for post-operative measurements of fluid pressure, the wick catheter was detached from the pressure transducer. As a means of anchoring the catheter to surrounding tissue, thereby preventing slippage of the wick from its desired position within the TMJ, four or five sterile polyethylene "dumbbells" were slipped over the catheter into various positions. These dumbbells were fashioned from either PE90 or PE100 tubing, cut into portions of five to six millimeters in length and then flamed at both ends, to produce the dumbbell shape. In addition, the dumbbells fit snug around the catheter to prevent the latter from sliding through the former. The silk purse-string suture was removed from the insertion site and one small dumbbell was placed just inside the capsule and sutured in place. Next, a second dumbbell was positioned approximately 1.5 cm from the capsule and sutured to the surrounding tissue. Then, a tunnel was made by blunt dissection between the skin and underlying connective tissue, permitting passage of the catheter, beginning at the original incision and ending at the posterior aspect of the ear. After the remaining dumbbells were slipped into place, the catheter was

pushed through the tunnel until exposed behind the ear The remaining portion of the catheter was pulled through the opening and the dumbbells were then sutured along the tunnel. Tunneling the skin in the above manner created both additional anchorage for the catheter and prevented the animal from scratching the exposed portion of the catheter after the surgery was completed. Next, excess tubing was cut leaving four to six centimeters exposed behind the ear. Heparinized saline was then introduced into the wick unit to prevent clotting around the fibers. Lastly, the exposed section of the wick catheter was stopped with an 0.030 inch portion of wire to prevent possible contamination.

Measurement of Fluid Pressure Post-Surgically

After periods of ten and fourteen days fluid pressures were monitored. It was felt that, following the surgical procedure, 10 days was sufficient time to allow for any acute or chronic inflammatory response, resulting from the surgical implantation of the wick catheter, to manifest itself. Fluid pressure was monitored at the 14 day interval to determine if any significant changes in fluid pressure would occur with time. Measurements at later intervals were not recorded because it became increasingly difficult to "stabilize" the experimental animal for pressure monitoring.

Figure 1.--Assembly of apparatus to measure TMJ synovial fluid pressure.


TMJ
Wick Catheter
Transducer
Amplifier
Recorder
"Dumbbells"
Wick/Fluid Interface

To record synovial fluid pressures post-surgically, the animal was placed in a "chute" which stabilized the head, but allowed the animal to masticate without hindrance of function. Next, the 0.030 inch stop was removed and was replaced with a 21 gauge Luer stub adapter. A fluid filled connector tube was then joined to both the wick catheter and the pressure transducer. Digital pressure was then applied to the area of the joint to ensure that the wick unit was recording properly. Measurements were recorded with the jaw at rest and during mastication of foods with various textures and consistencies.

RESULTS

Synovial Fluid Hydrostatic Pressure with Jaw in Resting Position

Pressures were measured in seven joint cavities in five pigs (Table I). Attempts were made to measure fluid pressures in both right and left joint cavities. The pressures in the left joint were recorded initially, while measurements were recorded in the right joints in a second surgical procedure. The wick catheter was inserted into the superiolateral aspect of the joint capsule. Initial attempts were made to locate the catheter in either the upper or lower joint cavity in an effort to determine possible pressure variations in different parts of the TMJ cavity. However, the exact location of the catheter within the joint space was difficult to ascertain. A significant intraarticular hemorrhage occurred in a right joint during one surgery, therefore the trial was abandoned A second procedure was discontinued because the animal died when the premedication (Ketamine) was administered.

Synovial fluid hydrostatic pressures were subatmospheric in six out of seven joint cavities. In the right TMJ of animal A, the pressure was slightly positive 0.2 mm Hg. The average hydrostatic pressure with the jaw in the rest position, four to five minutes after wick insertion, was -3.8 mm Hg (n = 6) (Figure 2). The total range was between +0.2 to -5.5 mm Hg

TABLE I

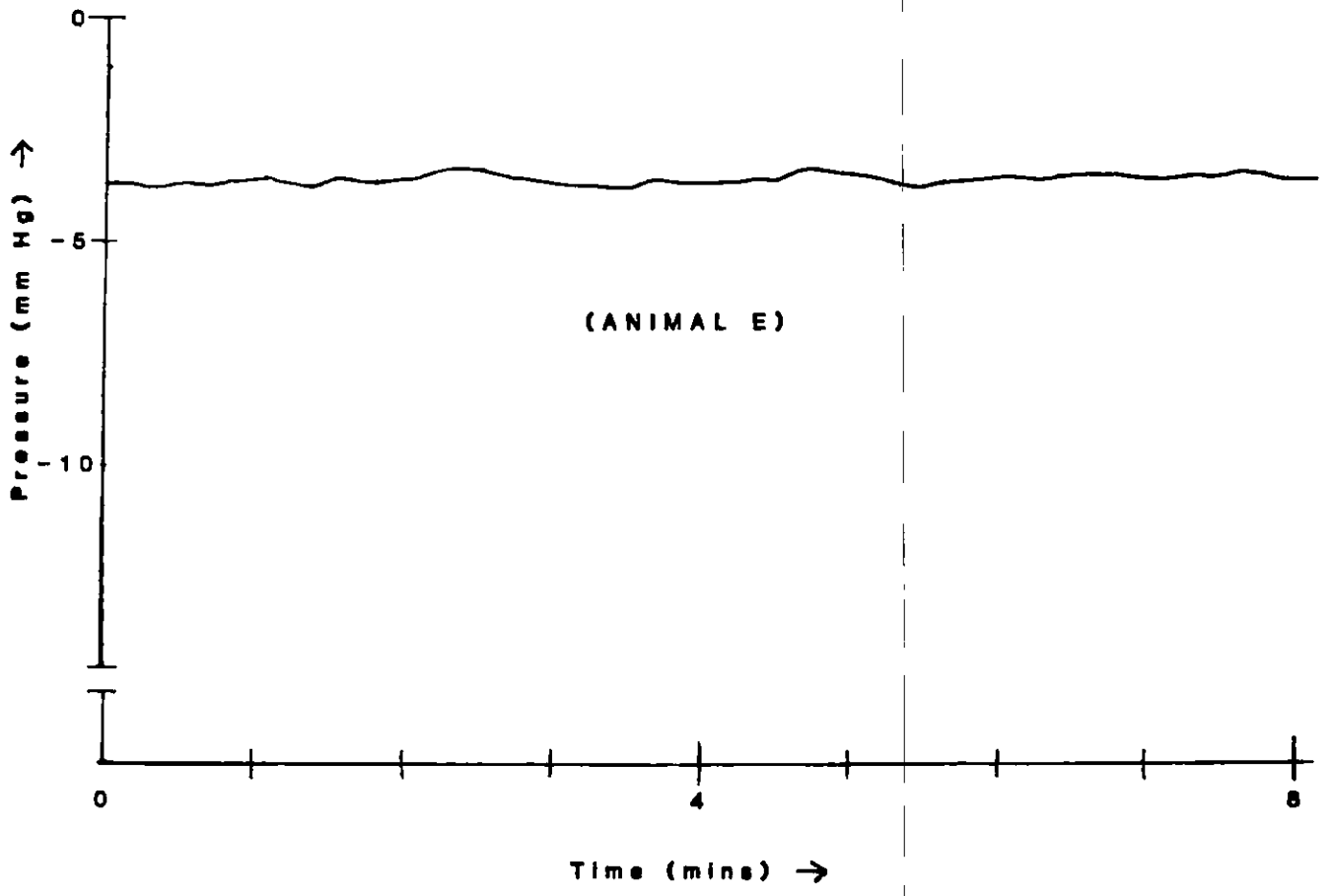
FLUID PRESSURE IN SURGICALLY EXPOSED CAPSULE WITH JAW IN RESTING POSITION

Animal	Left TMJ	Right TMJ
A	-2.8	0.2
B	-5.0	-2.8
C	-5.5	Joint Hemorrhage
D	-2.8	Animal Death
E	-3.7	No Surgery Attempted

FIGURE 2

"RESTING" SYNOVIAL FLUID PRESSURE

IN SURGICALLY EXPOSED TMJ CAPSULE



and the modal value was -2.8 mm Hg (n = 3). In two animals, pressures were recorded in both right and left joint cavities. In both animals, measurements were more negative in the left TMJ cavity. Due to the small sample size this was not considered significant.

Subatmospheric Pressure Recordings

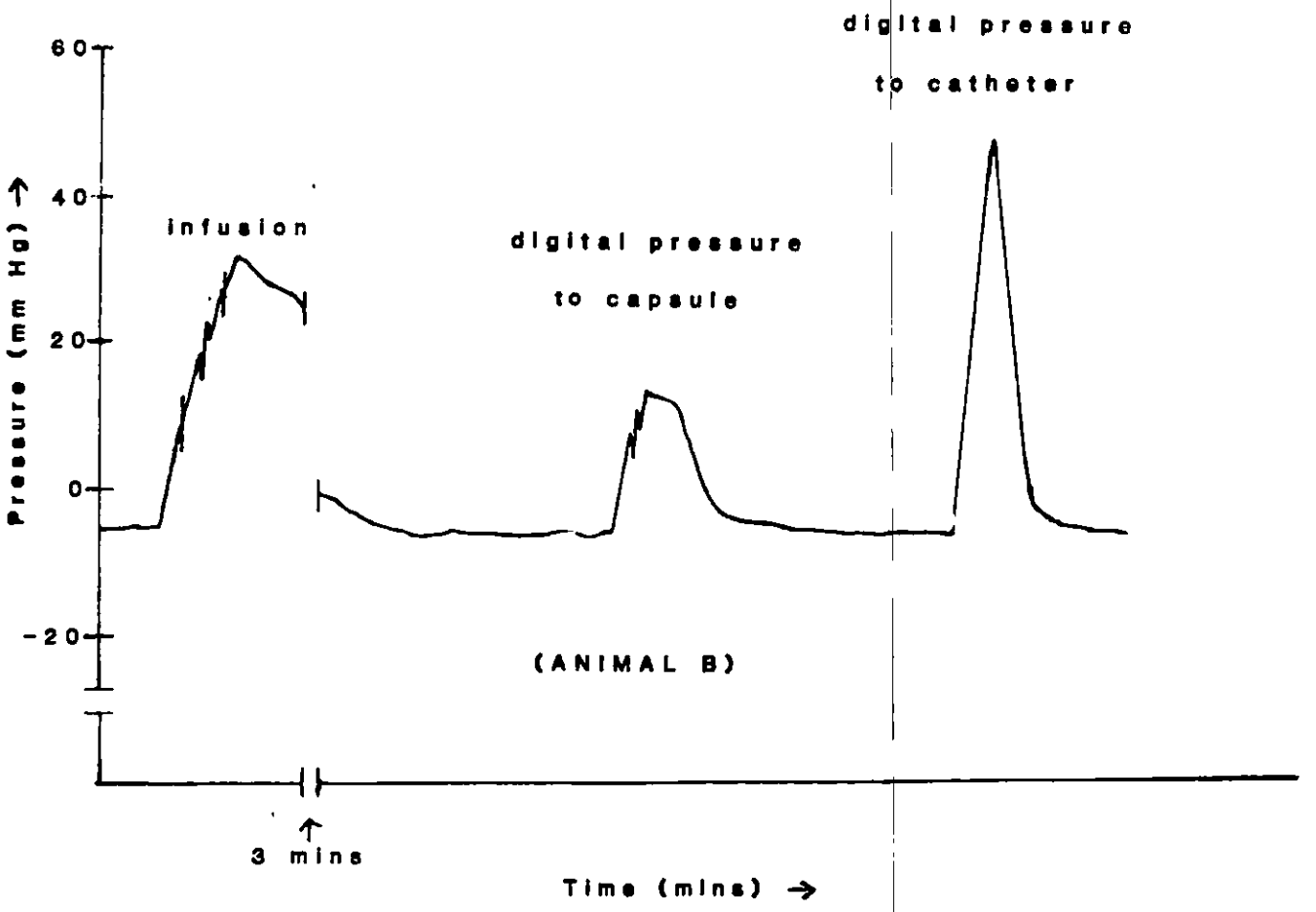
To determine the validity of negative pressure values, tests were performed during the surgical procedures (Figure 3). In one experiment, physiologic saline was injected into the joint space via the wick catheter. Subsequently, a rise in pressure to positive values was exhibited, establishing that the wick catheter was functioning properly. Within a few minutes the fluid pressure returned to original or near original levels. In four out of seven joints, the original negative reading was not completely recovered during the monitoring period.

A second test involved inserting a fluid filled, 25 gauge injection needle into the joint cavity after wick catheter placement. Presumably, if the hydrostatic pressure within the joint cavity is subatmospheric, the fluid in the injection needle should flow spontaneously in the joint space when opened to the atmosphere. In the three trials attempted (animals B, C and E) the fluid in the hub of the needle quickly disappeared into the joint space.

FIGURE 3

EXPERIMENTALLY INDUCED

FLUID PRESSURE RESPONSES



The last experiment included exerting digital pressure onto the joint capsule (animal E), which produced a small rise in fluid pressure and demonstrated that the wick catheter was again operating properly. Upon removal of the digital pressure, the values returned to the original negative level.

Relationship Between Pressure and Jaw Position

After the pressures were recorded with the jaw in the rest position, TMJ fluid pressures were monitored while manually placing the mandible into various jaw positions. All movements were initiated from the initial rest position. All manipulations produced immediate rise in pressure response which returned to original or near original levels after the mandible was returned to the initial resting position (Figure 4). When the mandible was held in a new position for a period of time, the pressure slowly returned to the original negative level in that position (Figure 5).

Rotating the mandible into an open position, evoked a sharp increase in fluid pressure. Returning the mandible to the initial position, restored the original subatmospheric pressure level. Maintaining the mandible in the open position, produced a sustained, but decreasing pressure response. After a period of two to three minutes, the pressure returned to the original or near original recording.

FIGURE 4

FLUID PRESSURE RESPONSE TO OPERATOR-INDUCED LATERAL JAW MOVEMENT

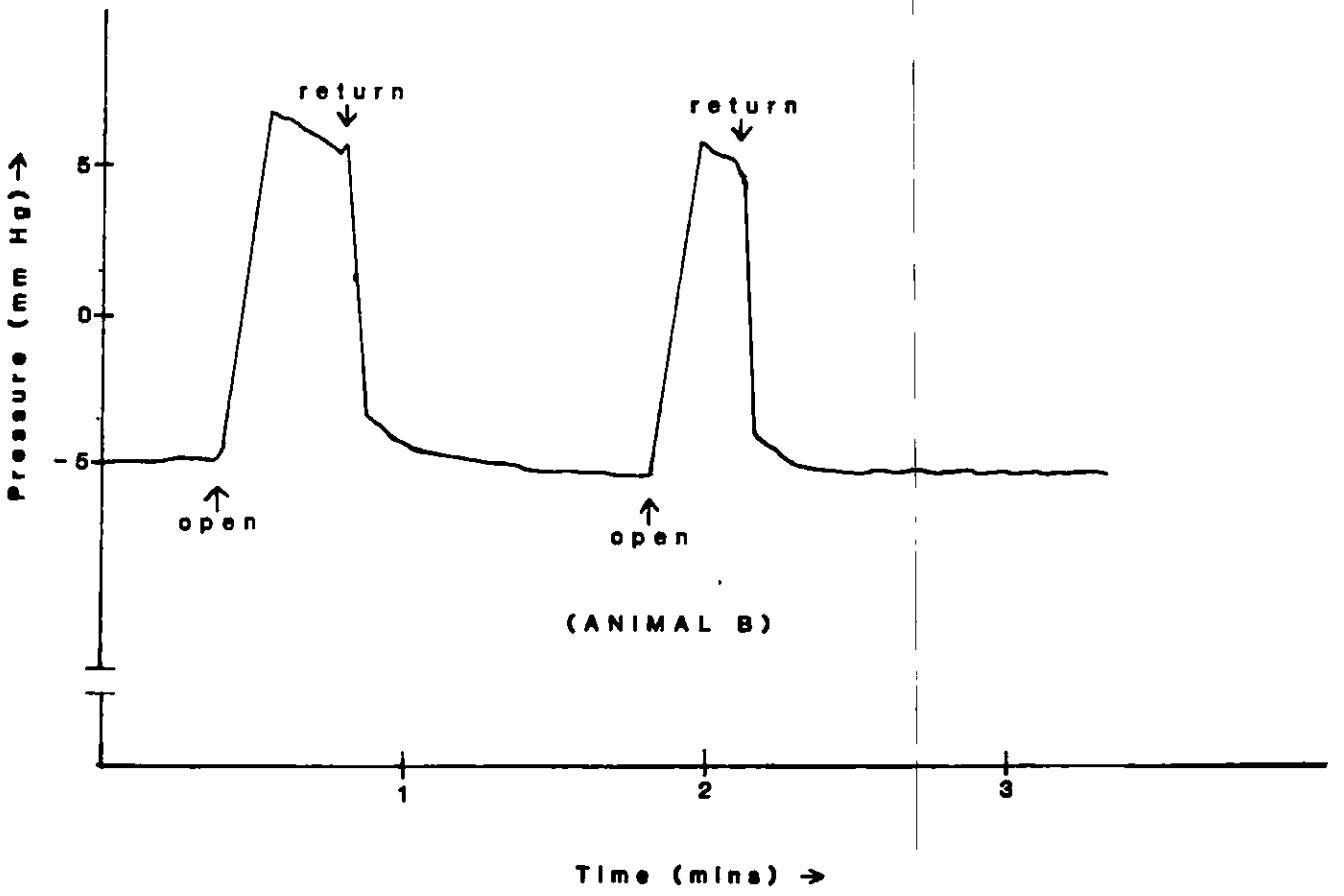
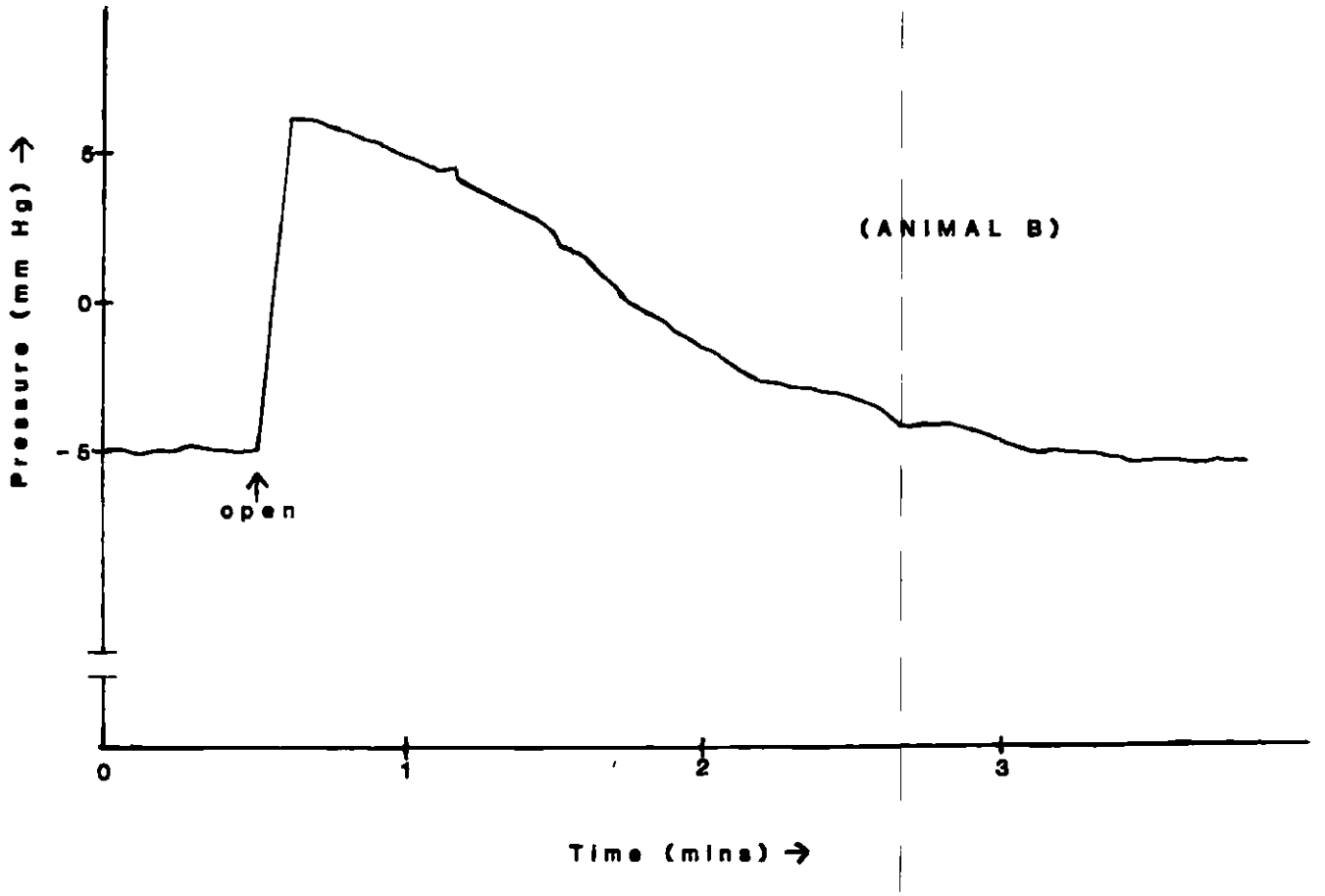


FIGURE 5

FLUID PRESSURE DECAY WITH MANDIBLE IN OPERATOR-HELD LATERAL POSITION



Protrusive and lateral jaw manipulations by the operator created pressure recordings comparable to the open jaw position. One interesting difference was noted during lateral movements. When the wick catheter was placed in the left TMJ, the pressure increase was greater when the mandible was shifted to the right as opposed to a shift toward the left. Similarly, when the wick catheter was placed in the right TMJ, the response was greater to left lateral movements as opposed to right lateral movements. In other words, the pressure response to a balancing side shift is greater than a response to a working side shift (Figure 6). Interestingly, investigations into the biomechanics and reaction forces of the TMJ have shown that the balancing side condyle bears considerably more stress than the working side condyle (Smith, 1978 and Hylander, 1979).

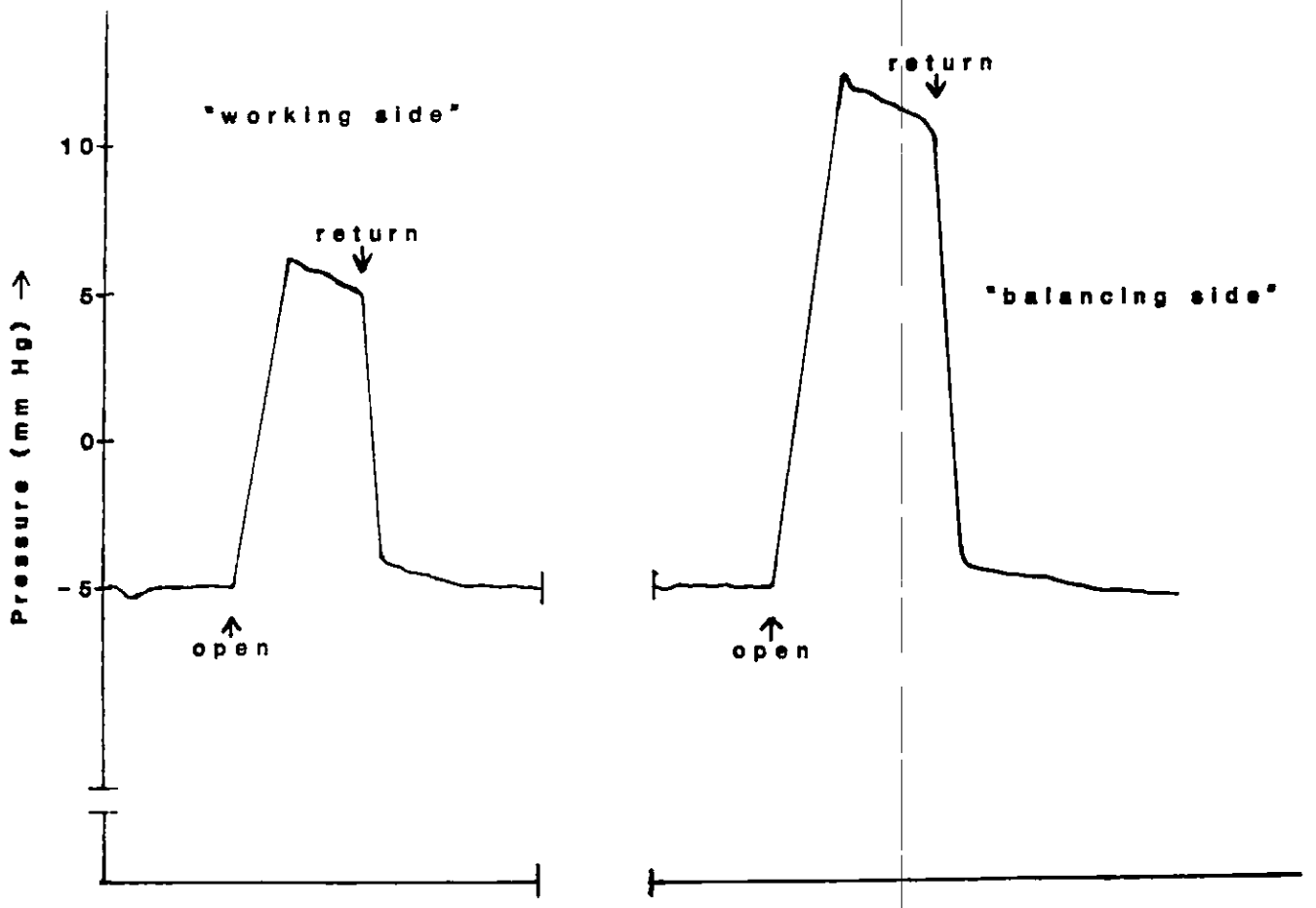
Placing the mandible into the closed position produced a pressure response that was atypical when compared to the responses of other jaw movements. Closing the mandible elicited only a small rise in pressure (0.15 mm Hg-1 mm Hg) which quickly dropped to the original value. This was the only jaw position that did not sustain an increased pressure level (Figure 7).

Post-operative Measurements

Utilizing the technique allowing post-operative recording

FIGURE 6

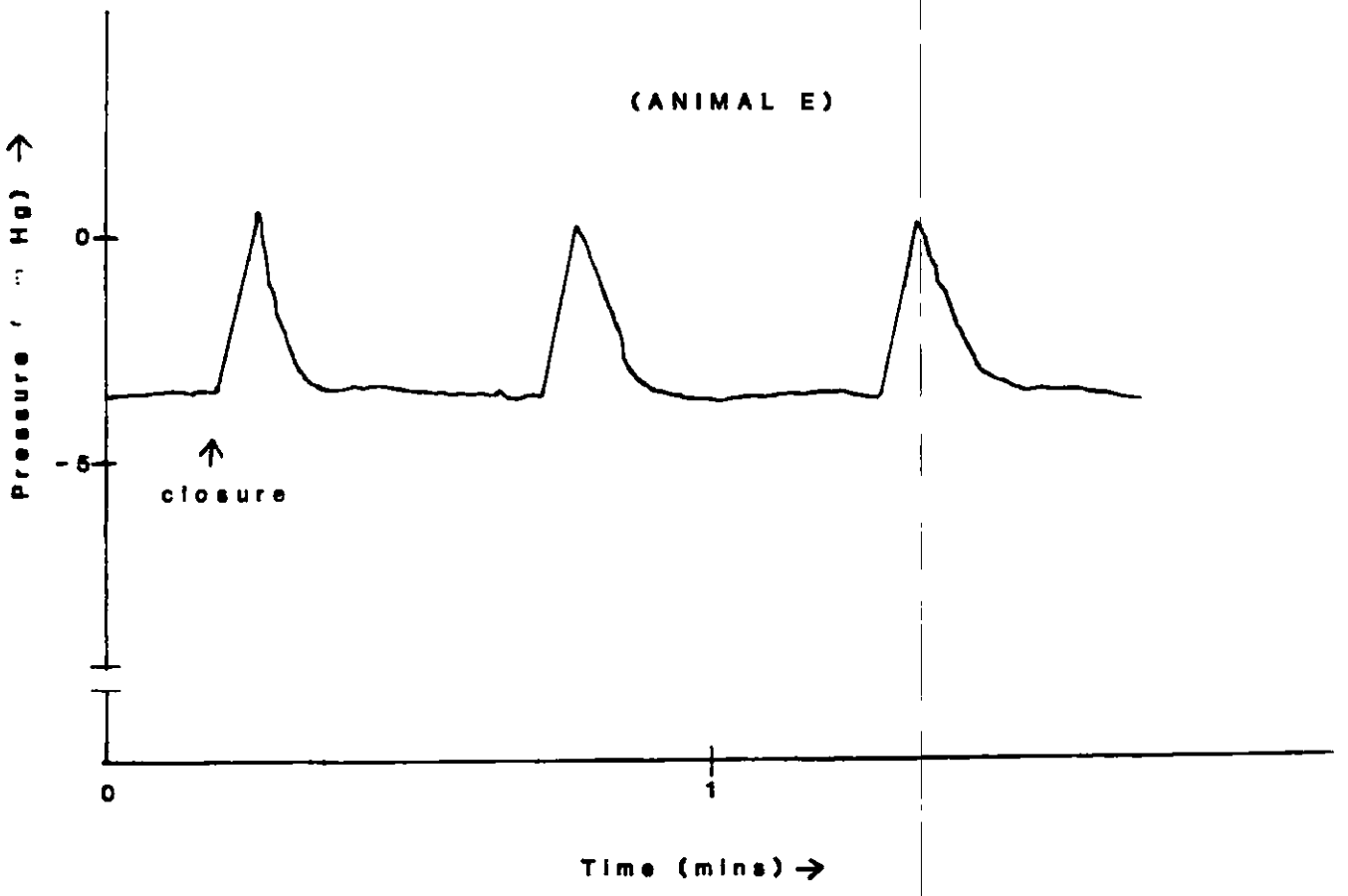
FLUID PRESSURE RESPONSE TO "WORKING SIDE" AND "BALANCING SIDE" SHIFTS



(ANIMAL B)

FIGURE 7

FLUID PRESSURE RESPONSE TO "MANUAL" JAW CLOSURE



of synovial fluid hydrostatic pressure in an experimental model, pressures were monitored in two animals. Initially, attempts were made to suture the catheter to the capsule and surrounding tissue in an effort to secure the catheter. These first attempts were unsuccessful because the catheter either slipped within a short time after surgery or it moved during attempts to monitor the pressure. An effort was then made to secure the wick catheter utilizing polyethylene "dumbbells" slipped onto various positions along the length of the catheter tubing. These modified catheters were successfully placed into two left joint cavities. To verify that these catheters were secure, the exposed segment behind the ear was measured periodically after the surgery had been completed.

Post-surgical measurements of the synovial fluid hydrostatic pressure were arbitrarily recorded at 10 and 14 days (Table II). Subatmospheric pressures were recorded at both intervals in each of the two joint cavities measured. To insure that the wick catheter was patent, a small volume of fluid was introduced into the cavity through the catheter itself. This procedure elicited a sharp rise in pressure which returned to normal after a two to three minute period.

The recording of synovial fluid pressure during mastication, in an unanesthetized animal, was carried out during feeding with one of several foods having various textures, and consistencies (Table III). Just prior to the initial power stroke

TABLE II

COMPARISON OF INITIAL FLUID PRESSURE MEASUREMENTS WITH POST-OPERATIVE VALUES

Animal	Pressure at Rest		
	Initial	10th Day	14th Day
C	-5.5	-3.1	-2.8
E	-3.7	-2.3	-2.5

TABLE III

MAXIMUM PRESSURE VALUES
DURING MASTICATION

Food Item	Maximum Pressure	
	Animal C	Animal E
Pig Chow	17.6	15.9
Hard Candy	17.2	19.8
Corn	14.7	14.0
Soft Apple	9.9	11.2
Marshmallow	-3.1	-2.3
Soft Candy	9.0	9.7
Grapes	-3.1	9.5
Caramel	9.3	9.6
Popcorn (popped)	16.5	21.2

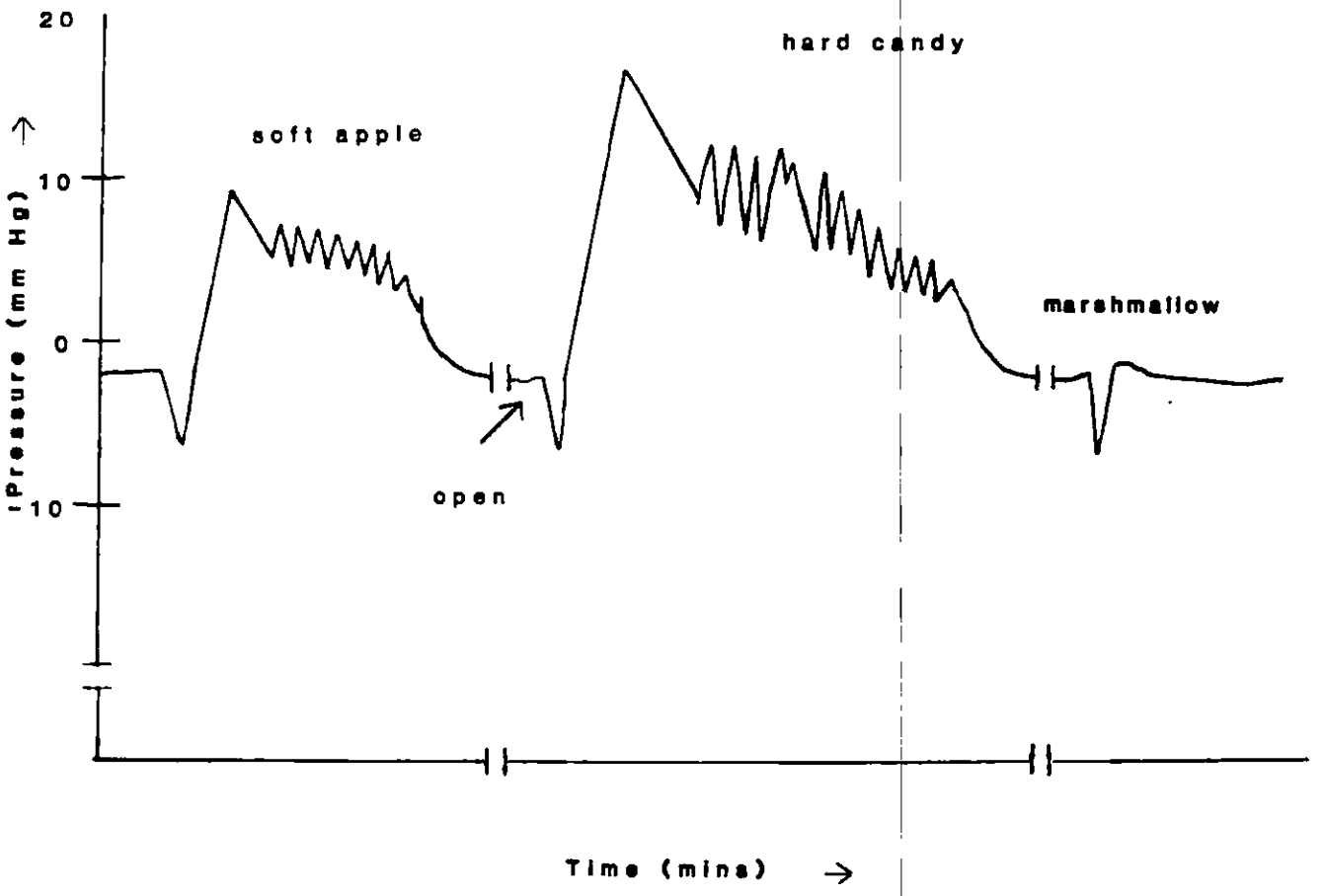
of mastication, as the mandible rotated downward to receive the food item, a decrease in pressure occurred (Figure 8). This response was consistent, occurring at the beginning of every feeding cycle. However, this decrease in pressure is inconsistent with the rise in pressure demonstrated when the mandible was manually rotated to the open position. During the initial power stroke of mastication, a sharp increase in pressure occurred which declined approximately one-third when the animal shifted to the grinding masticatory phase. According to Brul (1980), this grinding action occurs unilaterally in the pig, and after several strokes on one side, the bolus is moved to the opposite side and the process repeated. Moderate oscillations of pressure were noted during the grinding phase of mastication which presumably represent separate chewing strokes (Figure 8). After mastication had been completed and swallowing initiated, the pressure fell to its original level until chewing resumed. During the chewing cycle, it was difficult to determine on which side grinding was occurring. Consequently, pressure variations related to balancing and working side shifts were not examined.

It was evident that the harder textured food items evoked greater pressure responses (Figure 8). For example, during the initial masticatory power stroke, hard candy related to a higher pressure level, than did a soft apple. In addition, the oscillations present during grinding were of a higher amplitude when

FIGURE 8

MASTICATORY FLUID PRESSURES

ANIMAL E (14th day post-op)



the harder textured food items were chewed (Figure 8). Interestingly, very soft foods such as marshmallows were not chewed, but simply were swallowed. Accordingly, a pressure decrease was noted when the pig opened to receive the food, which returned to the original negative value as the animal swallowed (Figure 8).

DISCUSSION

The synovial fluid hydrostatic pressure measurements recorded by the wick method (with the jaw in the resting position) are comparable to measurements recorded within other joints as well. The mean values, both the initial and post-operative, reported in this investigation are consistent with the measurements obtained by Reeves (-4.0 cm H_2O; rabbit and human knee; 1966), Levick (-4.6 cm H_2O; rabbit knee; 1979), and Muller (-4.9 cm H_2O; dog and human knee; 1929). Small oscillations coincident with the arterial pulse were noted in some joints during the present investigation. However, the amplitude of such oscillation were considered small enough to permit description of the TMJ synovial fluid pressure as essentially a single value.

Validity of Subatmospheric Values

It has been suggested that subatmospheric pressure measurements obtained within joint spaces are possibly artifactual, being caused by obstruction of the catheter (Caughey and Bywaters, 1963). The construction of the wick catheter (with exposed Dexon fibers), however, effectively prevents such block-age. In addition, certain observations of pressure behavior disagree with the possibility raised by Caughey and Bywaters. A

pressure recording will not return to a subatmospheric value after a small fluid infusion if the catheter had become obstructed. Also, the rapid influx of fluid into the joint space when a fluid filled needle was opened to the atmosphere is only possible if a pressure gradient exists within the needle.

The construction of the wick catheter also circumvents a second potential error. Mechanical pressure from contact of surrounding solid tissues on the catheter's tip can introduce false recording values. However, the exposed wick fibers prevent this from occuring by preventing tissue from contacting the tip (Figure 1).

Another potential criticism of the experimental design is that insertion of the wick catheter elicits a subatmospheric pressure response by an expansive response of the TMJ cavity. This seems unlikely because the occurrence of a sustained negative pressure level demonstrates that fluid around the tip of the catheter was in equilibrium with fluid in more distant, undeformed regions of the capsule. In addition, Agostoni (1972) has shown that needles of less than 1 mm in diameter elicit reliable recordings of fluid pressure in the pleural cavity, a potential space somewhat analogous to the joint cavity.

Origin of Negative Pressures

The occurence of subatmospheric synovial fluid pressure

within the capsule of the TMJ might be explained by a pulling effect caused by capsular tension, thus tending to increase joint space volume without a corresponding increase in synovial content. This is unlikely, however, because Levick (1978) has shown that the synovial membrane of the knee is permeable to fluid. Consequently, extracapsular fluid would in time permeate into the joint cavity until the fluid pressure elevated to zero. Therefore, it seems likely that a constant force, existing within the capsule of the TMJ, acts to remove the continually manufactured synovial fluid from the joint space, maintaining a negative pressure level. Indeed, it has been suggested that the lymphatic plexus within the synovium operates as a motion-augmented pump to remove fluid from the joint space (Levick, 1979). In support of their view, Smith and Campbell (1928) demonstrated that joint motion creates removal of fluid from the joint cavity to the lymphatics by alternate compression and expansion of the lymphatic plexus in the synovium.

On the other hand, a negative fluid pressure level might be sustained by a pressure gradient across capillary walls favoring net absorption of synovial fluid (Guyton, 1971). The pressure behavior in the present investigation appear to support this view. It is unlikely that in the presence of a motion-aug-

mented lymphatic pump, sustained negative pressure levels would exist when the jaw was held motionless for a period of time (Figure 1).

Jaw Movement and Fluid Pressure

Generally speaking, rises in synovial fluid pressure were concomitant with the various jaw movements occuring both at the time of surgery (operator-manipulated) and post-operatively (mastication). One explanation for this increase in fluid pressure is that as the condyle rotates during mandibular movements, fluid is displaced within the joint cavity causing an increased, but transient, response in fluid pressure. Another explanation for the rise in pressure is that as the mandible rotates to its various positions, the TMJ capsule becomes deformed decreasing the amount of potential joint space which therefore produces an increase in synovial fluid pressure. This process would elicit a less transient pressure response, requiring either a change in fluid volume or tissue compliance to allow equilibration of fluid pressure to original levels. It is possible that the former mechanism occurs in conjunction with the latter.

It was observed that the operator-closed rotation, during the surgical procedure, gave a short-lived pressure increase. Most likely, this pressure behavior represents fluid displacement within the joint without an attendant tissue deformation. The

remaining jaw movements exhibited less transient increased pressure responses which steadily declined to the original negative level when the mandible was operator-held in its new position for a period of time (Figure 5). This pressure behavior suggests that the TMJ capsule is deformed during these movements. A possible explanation for the steady decay in fluid pressure is that the increase of pressure within the joint cavity creates a pressure gradient allowing the flow of fluid from the joint space into the extracapsular tissue until equilibration at normal pressure levels occur. On the other hand, another interpretation suggests that the capsule became more compliant over a period of time while the volume of fluid remains the same. To determine if either of these explanations may be operational, Levick (1979) removed the synovial fluid from rabbit knee joints with replacement by a light grade paraffin oil. The synovial membrane is impermeable to this oil The pressure response was compared between flexed joints containing either synovial fluid or the paraffin oil. In both instances the pressure declined with time, but the rate of decline was more than twice as fast for the synovial joint as for the oil-containing joint, thus suggesting that both of the above explanations may hold true within the joint. The faster rate of pressure decrease in the synovial fluid containing flexed joint implies that a flow of fluid across a pressure gradient into the extracapsular tissue occurs. On the other hand, the decline in

pressure demonstrated by the fluid which was impermeable to the synovial membrane suggests a compliant distension of the capsular connective tissue.

Validity of Measurements During Jaw Movements

A potential recording error arises if a portion of the catheter is compressed between articulating surfaces during joint movements, causing mechanical pressures to be monitored. Slight digital compression anywhere along the length of the wick catheter produce very significant spikes in pressure response (50 mm Hg) (Figure 3). These extreme values were neither observed during mastication in the post-oparative trials, nor at the time of surgery when the mandible was manually positioned.

A further criticism of experimental design is that following surgical implantation of the catheter, the recording tip conceivably could have slipped out of the TMJ capsule without a resulting increase in length of the exposed portion of catheter, consequently, measuring the fluid pressures in the extracapsular tissues. However, securing the catheter to capsular and surrounding tissue by suturing to snugly fitting dumbbells make any slippage unlikely.

Surgical Versus Post-Surgical Values

The synovial fluid pressures recorded with the jaw in the resting position, both at the time of surgery and at the 10 and 14

day post-operative intervals, are generally consistent with each other (Table II). The only difference observed is that the post-surgical values are slightly less negative. Considerable surrounding tissue was necessarily reflected during the surgical procedure in order to adequately expose the capsule. In vivo, this contiguous tissue may exert a reinforcing or gently compressive effect on the capsule, thus giving rise to the less negative values observed when the tissue is lacking.

The pressure response to operator-manipulated open jaw rotation (causing pressure increase) differs in the nature of response observed when the animal itself opens to receive food prior to mastication (causing pressure decrease). In the former situation, the pressure increases primarily because manual rotation of the muscle-relaxed jaw causes capsular compression. On the other hand, it is probable that active capsular tension caused by muscle fibers inserted into the TMJ capsule expand the capsule when the jaw is opened and a net pressure decrease thereby occurs. In other words, forces existing in vivo that do not exist in an anesthetized model (muscle contraction) are responsible for the apparent discrepancy described above.

A transient decrease in synovial fluid pressure within the human knee joint during locomotion was reported by Jayson and Dixon (1970). They found that contraction of muscle fibers within the joint capsule expanded the capsule, creating a momen-

tary decrease in pressure. This cause and effect relationship seems to be consistent with the decrease in pressure exhibited by the TMJ cavity of the pig.

In general, the pressure response to jaw movements were higher during mastication post-operatively than was observed during operator-manipulated movements at the time of surgery. The higher responses demonstrated during active chewing, are likely attributable to the contraction of contiguous muscle tissue, exerting a compressive effect on the TMJ capsule thereby increasing fluid pressure within the joint cavity. Such an effect could not take place during the muscle relaxed movements at the time of surgery. Presumably, the higher pressure levels demonstrated while the pig was chewing the hard-textured food items as opposed to the soft-textured ones, are derived from a greater compressive force on the TMJ capsule resulting from a stronger force of contraction of contiguous muscle tissue.

Fluid Pressure and Other TMJ Forces

It is difficult to compare the response of fluid pressure (hydrostatic) with those of reaction forces (mechanical). For example, a strong reaction force which is compressive may be coincidental with no change in fluid pressure if neither capsular deformation nor fluid displacement takes place. Moreover, tensile

reaction forces (negative stress) may be concurrent with a significant increase in synovial fluid pressure. Jayson and Dixon (1970) point out that the synovial fluid pressure within the knee joint of humans does not change under either a compressive or tensile load.

Fluid Pressure and TMJ Pathology

The relationships between jaw movement and fluid pressure likely have considerable biologic significance. Marked rises in TMJ fluid pressure were observed during mastication. Seemingly, prolonged joint use (gum chewing, bruxism) may create sustained elevated pressures, which in turn are believed to contribute to damage of the synovium (Edlund, 1949; Jayson and Dixon, 1970); Levick, 1979). Compliance of capsular tissue may reduce intraarticular pressures, circumventing potential problems. However, as an individual ages the tissues may become less compliant, providing a theoretical basis for long-term joint damage. In any advent, more extensive research into the areas of tissue compliance and increased synovial fluid pressure and their possible relation to TMJ pathology is required.

The actual biologic significance of the decreasing pressure response, observed when the experimental animal opened to receive food items prior to mastication, is not presently understood. It would be interesting to determine if an experimental

decrease in TMJ synovial fluid pressure, below the normal negative level, could be sustained in vivo. Such a procedure could provide a clinical means to "release" pressure within the capsule of the TMJ. It seems, however, that a more negative pressure within the cavity of the TMJ would promote fluid transport into the joint space, creating only a transient decrease in pressure response.

It was noted that fluid pressure response to a balancing side shift is greater than the response to a working side shift in operator-manipulated jaw movements. Interestingly, investigations into the biomechanics and reaction forces of the TMJ have shown that the balancing side condyle bears considerably more stress than the working side condyle (Smith, 1978; Hylander, 1979). Although it is difficult to compare fluid pressures with reaction forces, elevated fluid pressures and excessive or prolonged reaction forces, when combined, may have an additive or synergistic effect in terms of potential TMJ pathology.

Fluid Pressure and Facial Growth and Development

Although it is difficult to ascertain the influence TMJ synovial fluid pressure would have on facial growth and development, conceivably alterations in fluid pressure may effect facial growth indirectly by exerting influence on the condyle, an important growth site effecting facial growth and development.

For example, excessive fluid pressure within the TMJ may damage the synovium or cartilage, altering the TMJ environment and disrupting the growth potential of the condyle. Additional research is needed to determine both the long and short term effects orthodontic therapy (elastic wear, functional appliances) may have on the synovial fluid pressure of the TMJ, and to ascertain whether or not alterations in fluid pressure either positively or negatively effect the "condylar growth" mechanism.

SUMMARY AND CONCLUSIONS

The synovial fluid hydrostatic pressure within the joint cavity of the TMJ has received little, if any, attention in the literature. Previous investigations into the nature of synovial fluid pressure within other synovial joints such as the knee, however, have significantly added to the understanding of the biology of these joints. Most findings from these studies indicate that the fluid pressure within other synovial joint cavities is subatmospheric.

The present study was performed to examine the nature of synovial fluid hydrostatic pressure within the TMJ of the pig, Sus scrofa domesticus. Utilizing the "wick method" for determination of joint fluid pressure, fluid pressures within seven surgically exposed TMJ capsules of five animals were monitored, measuring the hydrostatic pressure levels with the jaw in the resting position and during various operator-manipulated jaw movements. In addition, an attempt was made to study the nature of fluid pressure within the TMJ cavity of a functioning experimental model by surgical implantation of a wick catheter into the joint space. This was accomplished in two animals, measuring fluid pressures in the left joint of each. Fluid pressure behavior was monitored at 10 and 14 day intervals, post-operatively, in the

two TMJ cavities where successful wick catheter implantation was accomplished.

The findings are summarized as follows:

1. The synovial fluid hydrostatic pressure was subatmospheric in 6 out of 7 surgically exposed TMJ capsules with the jaw in the resting position. The mean value of the 6 animals showing negative values was -3.8 mm Hg.

2. Similar, but slightly less negative "resting" values were obtained post-surgically where successful wick catheter implantation was accomplished. The less negative values were attributed to in vivo compression of contiguous tissues upon the TMJ capsule.

3. Experiments verified that the subatmospheric values were not artifactual.

4. Pressure increased as a response to operator-manipulated jaw positioning, returning to original levels when the jaw was replaced to its initial resting position.

5. Increased synovial fluid pressure, concomitant with operator-held jaw positions, declined with time. The delay in pressure was attributed to both an absorption of fluid by extra synovial tissue and to compliance of the capsular tissue.

6. Operator-manipulated "balancing side" shifts of mandibular position, created higher synovial pressures than did operator manipulated "working side" shifts.

7. Mandibular movement in conjunction with mastication by the experimental animals themselves produced a marked pressure increase. Hard-textured foods exhibited a greater pressure response in comparison to soft-textured items.

8. To maintain negative pressure levels within the capsule of the TMJ, it is likely a constant force acts to remove fluid from the joint space. The pressure behavior in the present study supports the view that a pressure gradient across capillary walls sustained a negative pressure level by net absorption of synovial fluid.

9. Possible relations between fluid pressure and TMJ pathology were discussed. For example, sustained elevated pressures as a consequence of prolonged joint use provide a theoretical basis for long-term joint damage.

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