A METHOD FOR RAPID MEASUREMENT OF INTRARENAL AND OTHER TISSUE PRESSURES*

By H. G. SWANN, Ph.D., A. V. MONTGOMERY, JOHN C. DAVIS, Jr.,
and E. R. MICKLE

(*From the Carter Physiology Laboratory, University of Texas Medical Branch, Galveston*)

In a previous report (2) from this laboratory, a method for measuring intrarenal pressure was described which utilized some of the technics described by McMaster (3) in measuring intracutaneous pressures. This method was thought to be excellent for determining intrarenal pressures (to be abbreviated IRP), but it was criticized for being too time-consuming. Still earlier estimates of IRP (4), although now known to be faulty (2), indicated that the IRP may change markedly in a short interval of time; therefore, in order to analyze the dynamic changes in IRP, a method which rapidly determines the pressure is desirable. In the present paper, a new method for the rapid measurement of intrarenal and other tissue pressures is described and critically evaluated.

Methods

A diagram of the apparatus is shown in Fig. 1. It is composed of four parts: reservoir R, stop-cock S, manometer B, and syringe needle N. These four parts are connected by tubing; the entire system is completely gas-free and leak-proof for pressures up to 250 mm. Hg. The system is filled with isotonic saline encept for the reservoir; the reservoir is filled in part with saline and in part with mercury. The pressure in the reservoir can be varied at will by varying the distance H. In operation, the pressure in the reservoir is first imposed on the manometer, a Bourdon tube, by turning the stop-cock. Then by turning the stop-cock, the pressure on the Bourdon tube is suddenly transferred to the needle in the kidney. A small volume of fluid is forced into the kidney by the elasticity of the Bourdon tube and other distensible parts of the system, but when no more fluid is forced in, the pressure has fallen to the IRP. This pressure is optically recorded on moving film F. The manometer employed was a glass Bourdon tube (5, 6). To the end of the tube was fastened the mirror M, which reflected a beam of light on the moving film, thus recording the changing pressures.

It was difficult to keep this apparatus leak-proof, but after many trials and errors, the following precautions have been found satisfactory: the stop-cock which was found to hold pressures well is a T-bore, pressure stop-cock of "pyrex" glass, especially lapped and ground, 4 mm. bore. It is built with a spring to hold the stop-cock firmly in place. Rubberbase stop-cock grease, as used in the Van Slyke-Neill manometric apparatus, is employed.

Four different types of syringe needles were used in the analysis of intrarenal pressures.

Three were 20 gauge needles, with the pointed ends closed with solder. In one type of needle, one hole was filed in the shaft; in another, there were five holes, and in a third there were ten. The most distal hole in each case was about 2 mm. from the pointed end. The five holes spread over 6 mm. of the shaft, and the ten holes spread over 9 mm. of the needle shaft. The five-hole needle was used in most of these experiments, the exceptions being Experiments 7 and 10 described below.

In order to keep the elasticity of the connecting tubing at a minimum, "Saran" tubing was used wherever possible. "Tygon" tubing was found convenient for the joints between the intractable Saran tubing and glass or metal adapters. To obtain a leak-proof connection to the special syringe needles, a small adapter was soldered into the needle and then this was connected through Tygon tubing to the Saran tubing. It is apparent that there are several
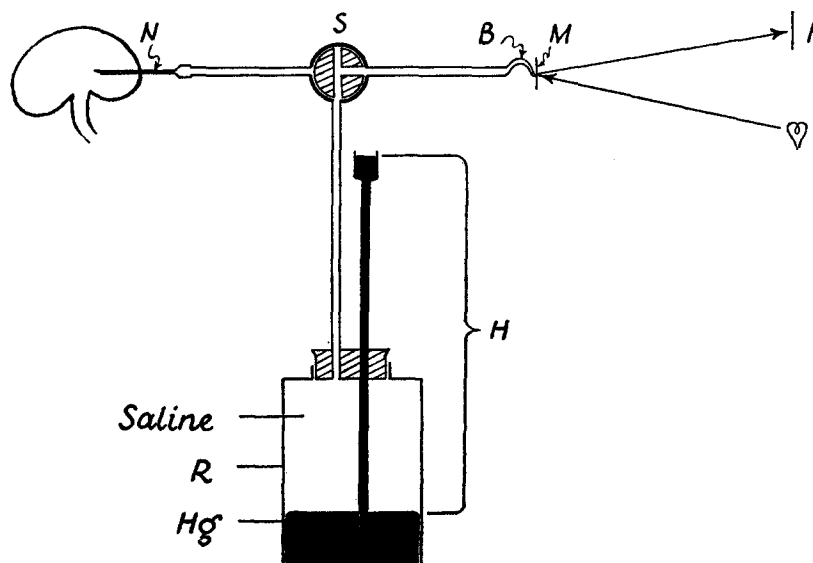

FIG. 1. Diagram of apparatus employed for measuring tissue pressures. See text for ex planation.

points in the system that have considerable elasticity: the Saran tubing, the Tygon tubing joints, and the Bourdon tube. In fact, in order for pressure in the system (from the Bourdon tube to the needle) to fall to zero from an imposed pressure of 250 mm. Hg, 12 c.mm. of fluid had to be discharged from the needle; for 175 mm. pressure, the volume was 8 c.mm. and for 90 mm. pressure, the volume was 5 c. mm. Various technical improvements could be made in the apparatus, such as using lead tubing for connections, a more nearly isometric manometer, etc. However, these were found to produce a considerable sacrifice in flexibility, this being needed because of the movement of the kidney with respiration. Such improvements would presumably increase the speed of measurement but not its accuracy.

When a measurement of IRP is taken, saline, to each ml. of which 1 mg. of heparin is added, is first drawn into the needle. Then the needle is inserted into the exposed kidney. The camera is turned on and 250 mm. Hg of pressure is imposed on the Bourdon tube. To do this, the stop-cock is turned to the position shown in the diagram. This causes the spoon

of the Bourdon tube to uncoil and the pressure in the reservoir is recorded on the camera film. The stop-cock is then turned 90°, cutting the reservoir out of the system and transmitting the pressure in the Bourdon tube to the fluid in the needle. Since the pressure in the needle is greater than the pressure inside the kidney, there is a flow of fluid from the needle into the kidney. When the pressure inside the kidney equalizes the pressure in the needle-Bourdon tube system, flow of fluid ceases and no further change in pressure occurs. The pressure recorded by the Bourdon tube at this time is the tissue pressure.

Fig. 2 is an example of the records obtained by this procedure. During a routine experiment the recording camera was left on for 30 seconds after discharging the pressure then turned off for 15 seconds, and finally turned on again for 15 seconds to make certain that the pressures were equalized. This procedure was altered somewhat for the experiments in this report in order to remove the slightest chance that the Bourdon tube pressure was slowly decreasing: the recording camera was left on for 1 minute after the stop-cock was turned. Then it was turned off for 30 seconds, on for 10 seconds, off for 30 seconds, on for 10 seconds, and so on until an observer could detect no movement in the beam of light for three successive records.

Dogs were used in all experiments. With the exception of Experiment 9, in which pentobarbital sodium anesthesia was maintained, the dogs were anesthetized with ether and de-
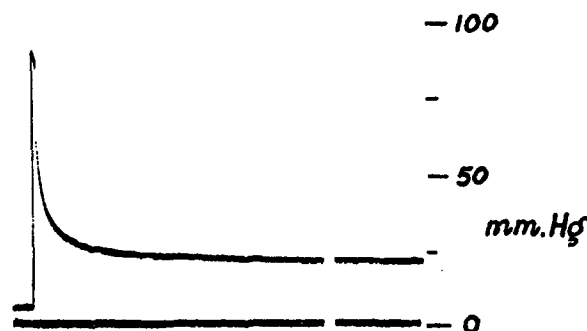

FIG. 2. Record of measurement of intrarenal pressure.

cerebrated by the technic described by Fee (7). No morphine was used. After decerebration, the dogs were allowed about 30 minutes to breathe off the ether. Then the needle was thrust deep into the parenchyma of the kidney and measurements were begun.

RESULTS

Experiment 1. Measure of Water Pressure.—The needles of two apparatuses were submerged under water to a depth of 367 mm. and the pressures taken just as if the needles were inserted in the kidney. The record revealed that in every case both apparatuses recorded the same pressure and that the pressure recorded was equal to the pressure exerted by the column of water above the needles. From these results the conclusion was drawn that the method does record fluid pressures with accuracy.

Experiment 2. Duplication of Measurements in Time.—In 6 dogs the IRP was determined repeatedly over a period of about an hour. The needle was

inserted in the kidney and left in place for all determinations. Table I presents the data. It shows that over periods of 35 to 68 minutes, the IRP stays fairly constant. The extreme of variation in any single experiment was 10 mm. Hg; the average was about 6 mm.; the standard deviation of measurements on a single dog was about 1.7 mm. It is apparent that results are readily duplicated in time. It is also apparent that a series of measurements can be taken with the apparatus without the technic itself causing an increase or decrease in IRP. The IRP changes which are noted here are not in one direc-

TABLE I

Repeated Measurements of IRP

Dog No.	C-170	C-171	C-173	C-179	C-182	C-183
Duration of measurement, *min*.	35	40	68	50	47	58
	mm. Hg	*mm. Hg*	*mm. Hg*	*mm. Hg*	*mm. Hg*	*mm. Hg*
	27	26	16	15	36	25
	27	23	20	24	35	25
	28	21	16	22	35	24
	29	22	17	18	32	25
	30	21	16	18	31	27
IRPs measured in consecutive de-	28	22	16	18	36	26
terminations	30	21	17	15	35	27
		21	17	15	37	28
		23	17	14	36	27
		23	17	15	36	27
		23	17			27
			17			27
			18			30
			18			
Range of variation	3	5	4	10	6	6
Standard deviation	1.2	1.5	1.1	3.3	1.8	1.6

tion only, but either increase or decrease over a period of time. Dog C-179 shows the extreme variation of 10 mm. Hg over a 50 minute interval. It is interesting to note, however, that even with a variation in IRP of this magnitude, the initial and final IRPs of this dog are the same.

Experiment 3. Reproducibility of IRP of Dead Kidney.—In 12 dogs, three or more IRP determinations were made during the 10 to 30 minute interval after the animal had been killed with intravenously injected ether. The initial IRP of each of the twelve dead dogs was 20, 10, 10, 10, 15, 11, 4, 13, 6, 11, 5, and 15 mm. Hg, respectively. There were only three instances in which the observed IRP changed in subsequent measurements. Of these three instances, in two cases the change indicated was 1 mm. Hg and in the other the

change was 2 mm. From this experiment, it is concluded that the fluctuations in IRP found in the previous experiments are not due to instrumental error, but to functional changes in IRP.

TABLE II

Effect of Reinsertion of Needle on IRP

Dog	Intrarenal pressure		Difference: before—after
	Before reinsertion	After reinsertion	
No.	*mm. Hg*	*mm. Hg*	
C-170	24	27	−3
C-171	25	23	+2
C-179	18	20	−2
C-183	28	27	+1
C-188	10	15	−5
	14	16	−2
	17	21	−4
C-189	22	22	0
	22	25	−3
	21	23	−2
	23	31	−8
	29	22	+7
C-190	29	23	+6
	23	25	−2
	25	28	−3
	27	31	−4
C-191	19	20	−1
	20	24	−4
	23	21	+2
Mean variation due to reinsertion...............................			3

Experiment 4. Effect of Changing Needle Position on the Measurement.—In 8 dogs, three IRP measurements were taken; then the needle was removed, reinserted in another site, and three more measurements were taken. (This procedure was carried out several times on some dogs.) The results of the experiments are presented in Table II. Each value given for IRP is the mean of three measurements taken immediately before reinserting or after reinserting the needle. The mean variation due to reinsertion was found to be 3 mm. Hg.

From this table it can be seen that a reinsertion of the needle may give a slightly different IRP, but since it does not give a consistently higher or lower IRP, as indicated by the scattered pluses and minuses in the right hand column of the table, the reinsertion itself does not alter the IRP.

Experiment 5. Two Simultaneous Measurements on the Same Kidney.—In 5 animals two measurements were made simultaneously with two apparatuses. The needles were inserted at different positions in the same kidney. As shown in Table III, essentially the same results were obtained in this series of experiments as were obtained in the previous experiment. Each of the measurements is a mean of three readings. The mean difference between the IRP of apparatus 1 as compared with apparatus 2 in these measurements was 5

TABLE III

Two Simultaneous Measurements of IRP

| Dog | Mean IRP | | Difference, No. 1 — No. 2 |
	Apparatus 1	Apparatus 2	
No.	*mm. Hg*	*mm. Hg*	
C-170	27	27	0
	29	23	6
C-171	23	18	5
C-173	17	25	−8
C-178 -	16	13	3
C-183	17	27	−10
	25	27	−2
Mean difference..			5

mm. Hg. The greatest difference observed was 10 mm. Hg. On numerous occasions when a series of IRPs were taken with two instruments simultaneously, a small rise in pressure took place in one apparatus while there was a fall in the other. It is apparent that even though there are small fluctuations in IRP throughout the kidney, the pressure of the kidney as a whole is fairly uniform.

Experiment 6. Effect of Reservoir Pressure and Volume of Fluid Injected.— The IRP was recorded over a period of about 1 hour in 6 dogs. Only one insertion of the needle was used for the entire period. During the course of each experiment the reservoir pressure was varied, IRP measurements being taken at reservoir pressures of 250, 175, and 90 mm. Hg. Since the reservoir pressure of the apparatus controls both the volume injected into the kidney (see Methods) and the pressure with which the fluid is injected, this exper-

iment measures two effects: first, introducing large or small volumes of fluid into the kidney and second, starting with high or low pressures in the manometer.

The data from these experiments are presented in Table IV. In this table, the value given for the IRP at each reservoir pressure is the mean of three readings. In the right hand column, the "average of the three means" is the average of the mean IRPs taken at each of the three reservoir pressures. The deviation between this average and the mean IRP at each reservoir pressure is also shown. It is evident that in most cases the three different reservoir pressures gave results that were within a few millimeters of Hg of each other. The extreme difference was 5 mm. (Dog C-185). There is not

TABLE IV

Effects on IRP of Reservoir Pressures and Amount of Fluid Injected

Reservoir pressure, mm. Hg	250		175		90		
Approximate volume of fluid injected, c. mm....	12		8		5		Average of the 3 means
Dog	Mean IRP	(Observed IRP) minus (average of 3 means)	Mean IRP	(Observed IRP) minus (average of 3 means)	Mean IRP	(Observed IRP) minus (average of 3 means)	
No.	mm. Hg		mm. Hg		mm. Hg		mm. Hg
C-171	23	0	25	+2	21	−2	23
C-173	25	0	25	0	26	+1	25
C-178	13	+1	12	0			12
C-184	30	+2	24	−4	31	+3	28
C-185	24	−5	30	+1	33	+4	29
C-186	21	−1	22	0	22	0	22

a constant direction of the deviation of the mean IRPs from the average, as shown by the scattered pluses and minuses in the table.

These data show that the magnitude of the measured pressure is not related to either the volume of fluid injected into the kidney or the initial pressure with which the fluid is injected. The variations seen in the individual dogs are no greater than the variations observed when the reservoir pressure is kept constant and measurements repeatedly taken over a period of time.

Experiment 7. Effect of the Number of Holes in the Needle.—In 5 dogs two records of IRP were made simultaneously with two apparatuses. The reservoir pressure was kept constant at 250 mm. Hg. In one apparatus there were five holes in the shaft of the needle and in the other there were ten. The needles were inserted at different sites in the same kidney. The needles were reinserted several times so that the means of several different series of simultaneous readings could be compared.

The results of these experiments are shown in Table V. Each single value is actually the average of two or three readings. The data show that the IRP is not consistently related to the number of holes in the needle when multiple-hole needles are used. The mean difference between the two needles was 4 mm. Hg. By referring to Table II the mean variation due to reinsertion

TABLE V

IRPs with Different Cannulas

Dog	Intrarenal pressure		
	10-hole needle	5-hole needle	10-hole minus 5-hole needle
No.	*mm. Hg*	*mm. Hg*	*mm. Hg*
C-187	30	27	+3
	33	23	+10
	45	38	+7
C-188	10	17	−7
	15	16	−1
	14	23	−9
	17	22	−5
C-189	29	22	+7
	21	22	−1
	23	25	−2
	31	25	+6
C-190	29	31	−2
	24	26	−2
	25	30	−5
	29	32	−3
C-191	19	17	+2
	20	20	0
	21	18	−3
Mean................	24	24	4

is 3 mm. Hg; therefore the variations observed between the two conditions in Table V are probably due to changes in position of the needle in the kidney and not to the number of holes.

In another set of experiments, a needle with a single hole in its shaft was employed in one apparatus and a 5-hole needle in the other. The two apparatuses again gave similar results for IRP. However, with only a single hole in the needle, it required a long time—up to 30 minutes—for the establishment of equilibrium.

Experiment 8. Simultaneous Measurements in Two Kidneys.—In 3 animals the IRP was determined in both kidneys simultaneously. Table VI shows the results obtained in these dogs. Each pair of IRP values represents a separate insertion of the needle in each kidney. It is obvious from the table that the IRP in the two kidneys correspond as well as two simultaneous readings in the same kidney. Over a period of time the IRP varies in each kidney; it does not vary in the same direction at the same time as indicated by the scattering of pluses and minuses.

Experiment 9. Other Tissue Pressures.—Using the same apparatus, pressures in other tissues were ascertained on 3 dogs anesthetized with sodium pentobarbital. The pressures observed for liver were −2 to 14 mm. Hg, for

TABLE VI

Simultaneous Measurements of IRP of Both Kidneys

Dog	IRP of right kidney	IRP of left kidney	Right minus left
No.	*mm. Hg*	*mm. Hg*	
C-192	15	19	−4
	24	15	9
C-193	18	14	4
	19	28	−9
C-194	24	18	6
	23	20	3
	18	24	−6
Mean difference...			6

spleen 5 to 16 mm. Hg, for cerebral cortex 0 to 5 mm. Hg, for calf muscles 1 to 10 mm. Hg, and for subcutaneous tissue 0 to 3 mm. Hg.

Experiment 10. Allowing Equilibrium to Establish Itself Passively.—While the evidence presented in the previous section suggests that the observed pressure is not a function of the apparatus, it was thought that the injection into the kidney of even a minute volume of fluid might give faulty results. Therefore, the IRP was determined in 7 dogs by inserting the cannulating needle into the renal medulla and then leaving it in place, with no further manipulations of the system, until a constant pressure was observed. After this had occurred, the IRP was determined in the usual way with the needle remaining in the same position in the kidney. The needle was then removed, reinserted in a different position, and the entire procedure repeated. In some experiments a 22 gauge needle was employed, rather than a 20 gauge needle, but this did not influence the results.

When the needle was first inserted into the kidney, the initial pressure

observed was unexpectedly variable, ranging in the first few seconds from
− 10 to 21 mm. Hg as shown in Table VII. (The reason for obtaining negative
values in some cases for the initial pressure is not apparent.) The magnitude
of this initial pressure depended to a great degree upon the velocity with
which the needle was inserted: the faster the insertion, the greater the ob-
served initial pressure. After a variable period of time, in most instances
within 1 to 10 seconds, but in some cases as long as a minute, the pressure
in the system began to rise slowly, reaching equilibrium within 10 to 20 min-

TABLE VII

IRP as Established Passively

| Dog | IRP without injecting fluid | | IRP by usual method |
	Initial pressure	Equilibrium pressure	
No.	*mm. Hg*	*mm. Hg*	*mm. Hg*
C-215	−10	40	38
	−2	29	29
C-218	21	38	23
	20	32	31
C-219	20	34	37
	−3	18	29
C-220	11	23	29
	18	29	26
C-222	7	29	36
	15	34	40
C-223	19	32	28
	−2	19	21
C-225	21	35	28
	9	33	31
Mean...................................		30	30

utes. As the table shows, the final pressure, obtained by placing the needle
within the medulla and forcing no fluid into the kidney averaged 30 mm. Hg.
This is not consistently different from the IRP obtained in the usual way,
i.e., by injecting a small volume of fluid into the renal parenchyma.

DISCUSSION

The method described, when applied to tissues other than renal, gives
results that correspond closely to previous reports of tissue pressure. Where

Wells, Youmans, and Miller (8), employing a different technic, report intramuscular (relaxed human calf) pressure to be 1.5 to 8 mm. Hg, we have found it to be in dogs 1 to 10 mm. Hg; where they report subcutaneous tissue pressure to be 0 to 6 mm. Hg, we have found it to be about 0 to 3 mm. Hg.

The intrarenal pressure has now been measured by us by four different methods. The first (4) has been discarded because a large and unpredictable component of tissue distortion is involved (2). But each of three other methods has given intrarenal pressures of the same magnitude. With the first, the pressure required just to prevent fluid from moving out of a small cannula set in the tissue was measured (2). With the second—most of the experiments reported here—, a high pressure was imposed upon the fluid filling a cannula set in the tissue and the pressure recorded at a time when flow of fluid out of the cannula ceased. With the third—Experiment 10 in this paper—, the pressure with which fluid flows into a needle cannula set in the kidney was ascertained. But the second of the three methods is by far the easiest; objective measures of tissue pressures may be obtained within a minute by the apparatus as presently designed. In future studies, therefore, it is this method that will be used.

When applied to the kidney, the technic here described has given relatively reproducible results; the final pressure does not depend upon the position of the cannulating needle in the kidney (Experiments 4 and 5), upon the lapse of time (Experiment 2), upon the volume of fluid forced into the kidney (Experiment 6), or upon the initial pressure in the system (Experiment 6). In dead kidneys, the pressure was found to be constant; but in live kidneys, the observed mean variation was some 5 mm. Hg, other things being constant. This variability, in contrast with the constancy of the IRP of the dead kidney, suggests that functional changes are responsible for the small fluctuations here reported for the live kidney.

In order to ascertain the effect on the tissue of inserting the cannulating needle, histological sections were prepared of kidneys into which the perforated 20 gauge needle had been thrust several times. Much damage was visible microscopically; detached fragments of glomeruli, tubules, and even small blood vessels were found in the lacerated area. Now, this would almost certainly cause, adjacent to the openings in the shaft of the cannulating needle, the accumulation of a small pool of fluid. It is into this pool that the apparatus forces saline; the stretched Bourdon tube suddenly pushes into it some 10 c.mm. of saline. This must increase the volume of the kidney by some 10 c.mm. But the increase is only very transient because of the many possible effluents out of the kidney: veins, tubules, and lymphatics. Hence the added 10 c.mm. probably diffuse rapidly away from the pool around the needle, enter one of the several possible effluents, and so drain away from the kidney. As Fig. 2 shows, it takes about a minute before the added fluid comes into a pressure equilibrium with the pool of fluid initially around the needle. The

delay in reaching equilibrium is probably a measure of the rate at which the added saline, now mixed with other fluids, leaves the region of the needle shaft. When no more fluid is forced out of the region, then the pressure in the Bourdon tube mirrors the pressure of the region and this is the "intrarenal pressure."

SUMMARY

A rapid method for measuring tissue pressures has been designed. A pressure of 250 mm. Hg is imposed on a manometer. Then the system is allowed to discharge into a needle cannula inserted in the tissue. The manometer forces out fluid (about 10 c.mm.) until the pressure within it is the same as that within the tissue. Records of the pressure changes are made. Each observation takes about a minute. The method gives results that are closely comparable with other reports of tissue pressures. With this method, the pressure in the following organs of dogs was found to be: kidney, 26 mm. Hg, cerebral cortex, 0 to 5 mm., muscle, 1 to 10 mm., spleen, 5 to 16 mm., subcutaneous tissue, 0 to 3 mm., and liver −2 to 14 mm.

The reliability of the method was tested on the kidneys of decerebrate dogs. Measurements were found to be the same within narrow limits over a period of an hour; they were the same when taken simultaneously in different regions of the same kidney or in opposite kidneys. They were independent of the volume of fluid forced into the tissue. Similar pressures were observed with 1 or 5 or 10 holes bored in the shaft of the cannulating needle.

The intrarenal pressure was also measured by inserting a needle cannula into the tissue and then allowing the pressure to reach equilibrium passively with a manometer. This method gave similar results. The intrarenal pressure has now found to be the same when measured by three different technics.

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