A STUDY OF THE CIRCULATION IN THE NORMAL AND PATHOLOGIC KIDNEY WITH ROENTGENOGRAPHIC VISUALIZATION OF THE ARTERIAL TREE, INCLUDING THE GLOMERULI *

RALPH S. GRAHAM, M.D.

(From the Ayer Clinical Laboratory of the Pennsylvania Hospital, Philadelphia, Pa.)

INTRODUCTION

Our knowledge of the structure and physiology of the kidney has steadily progressed in recent years, but the methods employed by the workers in these fields have not been adopted quite so vigorously by the student of general pathologic conditions of the kidney.

Oertel [1] in 1910 maintained that in order to establish a pathologic physiology of the kidney it would be necessary to "construe the plan of the whole pathological organ." Not until the recent work of Traut,[2] however, has it been possible to interpret accurately the plan of the kidney from an anatomic standpoint, and this investigator is convinced that the unit structure of the kidney is largely explainable on the basis of a unit blood supply. It would seem therefore that a study of a series of kidneys from necropsy material by some method which clearly, accurately and completely visualizes the arterial tree, might offer a valuable contribution toward our conception of renal pathology and its relationship to functional capacity.

HISTORICAL

Studies of the renal vascular tree have been made by numerous workers using celloidin and corrosion methods, but with such a procedure one is handicapped from a pathologic standpoint by the unavoidable destruction of the kidney tissue.

The use of a radiopaque injection mass for the study of the circulation dates back almost as far as the use of the Roentgen rays for diagnostic purposes. The earliest investigations are credited to V. Dutto, an Italian, who in 1896 employed in his studies a suspension of calcium sulphate in water. Since that time a large number of substances have been tried by different investigators for this purpose, a concise résumé of which is given by Gough.[3]

* Received for publication August 15, 1927.

In the study of the circulation of the kidney by these methods the earliest comprehensive work appears in 1913 by Hauch [4] who used a suspension of red lead oxide in paraffin oil. By this means he obtained beautiful and accurate radiographic reproductions of the arterial tree. He mentions the fact that glomeruli were injected, but these are lost in the reproductions accompanying his article, the injection not extending beyond the interlobular arteries. Although he demonstrated moderate and severe degrees of renal arteriosclerosis, yet his study was preliminary in character as he gave particular attention to the method and no conclusions were drawn from a pathologic standpoint.

In 1917 and 1918 Gross,[5] using gelatin preparations of Prussian blue and carmin, made a roentgenographic study of normal and arteriosclerotic kidneys with a gelatin barium sulphate injection mass. This preparation gave a clear-cut reproduction of the arterial tree extending through but not beyond the interlobular branches. More recently Hinman, Morison and Lee-Brown [6,7] used a thin suspension of barium sulphate in a 50 per cent aqueous solution of sodium bromide to demonstrate this portion of the vascular tree, but found the particles in the mass too large to go beyond the interlobular arteries. For demonstration of the afferent and efferent glomerular circulation they substituted a celloidin corrosion method with excellent results. This latter method while admirably adapted to an anatomic study is less adaptable to pathologic work, not only because of the delicate, time-consuming procedure, but also in that it destroys the tissue and precludes histologic examination.

Method

For our purpose a radiopaque mass developed by Hill [8,9] in 1921, published by him in 1924 and completed in 1927, appeared most suitable. As prepared by him, the preparation for general use consists of a 17 per cent suspension of bismuth oxychloride (a special brand) in water containing 10 per cent acacia. A number of preliminary tests with this material indicated that a preparation of 25 per cent bismuth with 12 per cent acacia visualized both the large vessels and glomeruli more satisfactorily. A microscopic study of the individual particles in the suspension as prepared in this manner showed them to be quite uniform in size and shape, measuring

from 0.5 to 3 microns; however, these particles tend to become loosely held together, appearing as irregular masses varying from 6 to 60 microns. The larger of these apparent clumps might well be expected to obstruct branches of relatively large vessels causing artefacts, but neither microscopic kidney sections (Figs. 2, 3, 4) nor magnification of the roentgenograms indicated any such condition.

A more detailed report as to the preparation and technic is deemed unnecessary and undesirable because of the simultaneous publication by Hill of the entire method [9]; particularly as the percentages of bismuth oxychloride and acacia given above apply to renal studies and would occasion difficulties if applied to other circulatory research.

Pathologic Material: The study was made on a series of forty-eight kidneys obtained from the routine necropsies performed at the Pennsylvania Hospital during the winter and spring of 1927. As a rule the right kidney was chosen and after injection was preserved for further gross or histologic examination.

Technic: It seemed desirable that the procedure should be as simple as possible and without elaborate apparatus, so as to be applicable to the exigencies of the necropsy room. After a few trial injections with the organ *in situ*, this method was abandoned and the following procedure was adopted. The renal artery was cut at the aortic junction and the kidney was then removed in each case with the surrounding perirenal fat and the adjacent suprarenal gland. The organ was immediately placed in the ice-box in physiologic saline solution until an opportunity for injection was afforded. In this way kidneys were injected for the most part a few hours after death, but in some cases a longer time elapsed. In one instance a kidney was kept in this manner for about eight days and to our surprise the prolonged delay did not seem to affect the subsequent study. When ready to inject, the organ was brought to room temperature and the renal artery was ligated under saline, any air thus being excluded from the vessels. The injection mass was introduced into the renal artery with a 20 cc. syringe and hypodermic needle, using gentle digital pressure. Leaking vessels were caught with hemostats when necessary. By placing the tissue immediately in saline, the air is not only excluded from the vessels but injection into the saline-filled system dilutes the first part of the suspension, so that the same effect is produced as if a thin suspension was fol-

lowed by a heavier one. It is felt that the cold saline also probably prevents the formation of clots and possibly helps to dissolve them.

The injection was carried out carefully and slowly, requiring from five to twenty minutes. It was considered complete when there was an even distribution of tiny white points visible through the kidney capsule. In several injections just as the procedure was completed the return venous flow of blood showed a white tinge of the injection mass, but in no instance was a sufficient quantity of the mass passed through the capillaries to visualize the veins. Where infarcts or cortical scars were present these areas refused to fill out either with prolonged gentle pressure or greater pressure. The fatty renal fascia was then stripped off, any leaking points clamped and tied if necessary, and any injection material on the surface washed off carefully in cold water and the organ dried with a towel. Stereoscopic roentgenograms were taken as soon as convenient using a low milliamperage and low spark gap technic. In a few instances where the injected specimen was not roentgenographed for eight to fifteen hours after injection, the settling out in the larger vessels produced artefacts.

The amount of material injected proved to be fairly constant (where leakage was negligible) ranging from 7 to 18 cc., and averaging from 12 to 15 cc.; kidneys of children and contracted kidneys taking a smaller amount, and large kidneys, especially those with passive congestion, taking a larger quantity.

Results

General: Roentgenograms of the injected kidneys gave a clear-cut reproduction of the arterial tree including the glomeruli, coinciding accurately with the present conception of its anatomy so clearly presented by Lee-Brown.[7] In a single instance, which will be discussed later, the pyramidal vessels were injected (Fig. 10). In each instance the films were studied both stereoscopically and separately with a hand lens. Stereoscopic examination proved to be of particular value in the study of the coarser vascular tree, the pyramids appearing as well defined hollows, between which the interlobar branches could be easily traced with the arcuate arteries arching over their bases. The relationship of areas of infarction, scars, metastatic nodules, tubercles, and artefacts was also best under-

stood by stereoscopic examination. The finer vessels were studied to best advantage with a hand lens although even with the naked eye the straight, almost parallel interlobular arteries could be readily seen surrounded by compact areas consisting of many tiny points representing the glomeruli (Fig. 8).

For further description of the findings, the cases are divided into the following groups: I. *Normal arterial tree;* II. *Arteriosclerosis* (those two groups have been based primarily on the roentgenographic appearance); III. *Thrombosis, infarction and metastatic tumors;* IV. *Syphilis;* V. *Tuberculosis;* and VI. *Hydro- or pyonephrosis.* Group I includes eighteen cases in which no pathologic change was demonstrable in the arterial tree. Group II is composed of seventeen cases in which there was some degree of generalized arteriosclerosis. Group III consists of six cases showing thrombi or infarcts in the kidney and one case in which there were multiple metastatic tumor nodules. Group IV includes six cases of syphilis, which are considered separately because of the often discussed question as to whether changes in the small vessels in such cases are of syphilitic origin or merely represent simple arteriosclerosis. Group V includes four cases of generalized miliary tuberculosis. Group IV is composed of four cases of hydro- or pyonephrosis which were encountered in the series.

GROUP I. *Normal Arterial Tree.* In the normal arterial tree the primary division of the renal artery appears on the film either just within or lying closely outside the edge of the cortex at the hilum. The vessels show a uniform gradual diminution in the size of their lumina as they progress from the hilum toward the cortex. Except for the primary branches arising from the renal artery the branches come off at an acute angle. The interlobar and arcuate branches, passing up between the pyramids, spread out in graceful curves and arches over the bases of the pyramids not unlike the architecture of a great elm tree (Figs. 5, 6, 7 and 8). The interlobular arteries are slender, delicate, of uniform size, very straight, almost parallel and give rise to a picture of a uniformly thick vascular cortex. The glomeruli are very fine, numerous and uniform in size. They are grouped closely around the interlobular arteries giving the effect stereoscopically of slightly cone-shaped columns with the interlobular artery in the center and their bases toward the periphery of the cortex (Fig. 13).

It is of interest to note the variety of pathologic conditions in which injection showed a normal arterial tree. To establish our conception of the normal, particular attention was given to cases in which the age of the individual was within the first three decades of life. Of two in the third decade, one, age 24, died of generalized melanomatosis (Fig. 13); the other age 27, died of vegetative endocarditis (Fig. 8) and will be referred to again in a later group. Two cases of rheumatic fever are representative of the second decade, one in the acute (Fig. 5) and one in the chronic stage. The patients in both of these cases were 14 years of age. A single case of a patient 8 years of age, who died of extensive burns of the body, represents the first decade (Fig. 7). Cases showing infarcts, thrombi, or metastatic tumor nodules are included in Groups I or II depending on the appearance of the arterial tree on the films.

With kidneys from individuals in mid-life the incidence of demonstrable vascular disease is so high that selection of cases is more difficult. Five cases were listed as normal in which the ages vary from 40 to 51 years, and in which there were no appreciable arterial or arteriolar changes microscopically. On the roentgenograms the arterial tree appears somewhat less delicate than in the series of younger individuals. The glomeruli appear to be of approximately the same size and number, and the cortex of the same width, but the arcuate and interlobar branches show more abrupt changes in size of the lumina while the curves and arches lose some of their gracile, slender form (Fig. 6).

Among the conditions in which a normal vascular tree was visualized were three cases of malignant tumor, a variety of infectious conditions and one case of subacute nephritis (Fig. 9). In this series we are confronted with various degrees of passive congestion and cloudy swelling in the kidney, with one case presenting an active nephritis. To our surprise none of these factors appeared to influence or to limit the completeness of the injection. Figure 5 shows a kidney with marked passive congestion from a case of cardiac failure in active rheumatic fever. The injection is heavy, uniform, and the injection mass is beginning to enter the pyramidal vessels. Figures 9 and 14 show a roentgenogram of a kidney which histologically showed not only swelling of the tubular epithelium but also an active nephritis. Grossly this kidney was a typical example of subacute nephritis or so-called "large white kidney," yet the injection

visualizes a beautifully delicate vascular tree and from the roentgenogram it would be impossible to say that a lesion existed in this kidney.

Figure 10 is the roentgenogram of the one case in the entire series in which an injection of the pyramidal vessels is obtained which approximates completeness although some degree of pyramidal injection was obtained in several instances. The reason for this is somewhat obscure since the same technic was used. The case was one of gangrenous endometritis following an abortion, in a woman 33 years of age, who presented a profound anemia together with evidences of severe toxemia. At necropsy there was a severe toxic hepatitis and the kidneys showed marked cloudy swelling and passive congestion. The blood urea nitrogen (postmortem) was not, however, increased. The possibility presents itself that the vessels were unusually deficient in tone due to the toxic phenomena and therefore permitted a more complete penetration of the injection mass into the finer vascular tree. The pyramidal arterioles are very straight, but wide and feathery converging toward the tip of the pyramid. From the base of each pyramid delicate vessels can be distinguished running up into the cortico-medullary zone which are very tiny but not as straight as the interlobular arteries among which they lie (Fig. 15).

GROUP II. *Arteriosclerosis.* The changes in the coarser portion of the vascular tree have been visualized by Hauch and later by Gross, the latter tabulating them in detail. In the advanced stages of arteriosclerosis of the kidney associated with a generalized contraction of the entire organ the changes are most striking. The lumina, especially those of the larger vessels, are of very uneven caliber presenting many constrictions and irregularities due either to plaques in the intima or thickening of the walls, while adjacent areas show either real or apparent dilatation. The branches tend to arise more nearly at a right angle. The interlobar and arcuate arteries are wider, and instead of tapering gradually toward the cortex maintain a rather large caliber and end abruptly in smaller branches. The normal curves have become angular, and the vessels tortuous in their course. The interlobular arteries are fewer, shorter, and run less directly to the cortex, and in severe cases even exhibit a tortuous course (Fig. 11). The glomeruli are fewer in number, considerably enlarged and are seen clumped around areas of the richest

surviving vascular supply (Figs. 11 and 16). The entire picture of the arterial tree is that of a gnarled, dead oak, rather than the graceful architecture of the spreading elm tree. As the kidney contracts it shrinks uniformly but the coarser arterial tree maintains the same size and position, so that there is the appearance of a drawing out of the renal artery and its larger branches from the hilum.

In the milder degrees of nephrosclerosis the earliest change seen in the roentgenograms appears in the arcuate and peripheral portions of the interlobar arteries. These appear coarser and run a tortuous course (Fig. 12). In this stage the glomeruli may show no demonstrable change (Fig. 17) although in several instances small cortical defects appeared in the roentgenograms. On microscopic examination these were found to consist of scarred areas lying beneath the capsule. Histologically the vessels showed arteriolar sclerosis.

Between this and the contracted kidney first described there are varying degrees of arterial change. In all, however, the degree of change in the interlobar and arcuate arteries is a striking feature. Changes in the size and number of functioning glomeruli bear a close relationship to the condition of these vessels as seen in the picture of the arterial tree.

This series includes kidneys from sixteen cases ranging in age from 33 to 77 years. Only one case, however, was under 40 years, and half were over 50 years of age. In all except two cases, generalized arteriosclerosis was an important factor in the anatomic diagnosis and these two cases showed only mild arteriolar and arterial change in the kidneys.

Differentiation between nephritis of arteriosclerotic origin and other types of nephritis. In connection with the studies on kidneys showing advanced degrees of arteriosclerosis, it has seemed particularly interesting to determine whether this method of visualization of the vascular tree would prove of value in the differentiation between the contracted kidneys of arteriosclerotic origin (nephrosclerosis) and the contracted kidneys of essentially toxic or bacterial origin (chronic glomerulonephritis). A single specimen representing the latter type of lesion was available for this comparative study. No attempt has been made to define the picture of chronic glomerulonephritis on the basis of this isolated case but the findings are sufficiently striking to warrant their presentation. The case was that of a male negro,

44 years of age, who gave a history of failing renal function for a period of at least nine years. At necropsy the kidneys presented the picture of chronic glomerulonephritis associated with a relatively mild degree of vascular sclerosis. The roentgenogram (Fig. 18) is in contrast to that of the arteriosclerotic kidney (*cf.* Figs. 11, 16).

It will be noted that sclerotic changes in the arterial tree are of moderate degree and occur largely in the arcuate arteries. The cortex, although twice as wide as in the case of nephrosclerosis, shows only a very few, large and fairly evenly distributed, glomeruli. Interlobular vessels where distinguishable are thick and tortuous, and an almost complete injection of the pyramidal vessels is evident. This last feature appears especially remarkable in view of the apparent distortion of the normal circulation.

GROUP III. *Thrombosis, Infarction and Metastases.* This group includes seven cases; one with metastatic tumor nodules, two with thrombi, and four with infarcts. On the roentgenograms of kidneys with the arterial tree injected, infarcts and thrombosed vessels cause a ragged, irregular defect, extending down from the cortex corresponding quite accurately in size to that of the gross lesion. Metastatic tumor nodules are frequently well rounded, sometimes raised above the surface, and appear also as defects in the injection of the arterial tree. It must be remembered that scars, tubercles, and artefacts may give the appearance of thrombosis or infarction, whereas retention cysts and abscesses simulate the picture of metastatic nodules, so that a careful check by gross and microscopic study of the kidney is essential. However, the injection method appears to be of very definite value for the detection of certain lesions of this type and in our hands has, in two instances, enabled us to demonstrate recent infarction where it was impossible on gross examination of the organ to distinguish any change in the tissue in the thrombosed area and hence there was no indication for histologic study of the particular area except the defect in the roentgenograms. In three cases white infarcts were readily seen on gross examination, and the appearance of these on the roentgenograms was essentially the same as those in the cases showing earlier lesions except that the areas of infarction were somewhat less extensive (Figs. 7 and 8).

One case in which there was a small aneurysm of the abdominal aorta at the level of the renal arteries is of special interest. The right kidney was very large while the left was about one third the

size of the right and had a peculiar bulb-like enlargement of the lower pole which was supplied by a separate anomalous artery arising from the aorta. The left main renal artery was occluded by a laminated thrombus for a distance of two and a half cm. from the aorta, distal to which it was collapsed and flabby. Both kidneys were injected for roentgenography (Fig. 19). The right showed slight sclerosis of the interlobar and arcuate arteries. In the left, the lower pole was similar in appearance to the right kidney, but the upper two thirds of shrunken kidney showed small vessels, the branches tending to be drawn out at the hilum and more parallel than normal. The arcuate vessels were tortuous, almost spiral, yet without the marked clubbing of severe arteriosclerosis. The cortex was but 1 to 2 mm. in width and the glomeruli were not injected. During the injection it was noticed that a small amount of the suspension came through into the renal pelvis, which would suggest tiny breaks in the severely damaged tissue and this is further borne out by the fact that the patient had had hematuria before death. The perforating capsular arteries were remarkably large and the possibility of a very deficient anastomotic blood supply by this route is to be considered (Belt and Joelson [15]). The picture is evidently the result of a relatively slow occlusion of the blood supply rather than a sudden blocking of the renal artery, and stands in sharp contrast to the cases of sudden blocking of a vessel with subsequent death of the tissue in the area supplied by it.

GROUP IV. *Vascular Syphilis.* This series includes six cases, all of which exhibited syphilitic aortitis and four of which presented aortic aneurysms. Two cases, which showed aneurysms of the aorta, displayed a normal arterial tree both on roentgenograms of the injected specimens and upon gross and histologic examination. The ages of these cases were 31 and 50 years. Three cases exhibited sclerotic changes in the interlobar and arcuate arteries and their branches. The ages here ranged from 52 to 64 years. In the remaining case cerebrospinal syphilis was a prominent feature. The kidney of this patient showed marked hydronephrosis and pyelonephritis. The changes in the roentgenograms here, consisting chiefly of an elongation of the primary branches of the renal artery and the interlobar arteries with slight enlargement of the arcuate branches, were essentially those produced by hydronephrosis which have been described by Lim [10] and again by Hinman and Morison.[11]

It is impossible to draw conclusions from so small a series as to whether the high incidence of arteriosclerotic change in the renal vessels in this group is due to the common association of syphilis with simple arteriosclerosis of the medium-sized and small arteries as emphasized by Warthin,[12] or whether the fact may be accounted for by the advanced age of these patients. It is worthy of note, however, that the roentgenographic appearance of the changes in the arterial tree is similar in all respects to those noted in the series of arteriosclerotic cases. Histologically the picture is also essentially that of arteriosclerosis although in one case moderate obliterative endarteritis was present.

GROUP V. *Tuberculosis.* Out of the four cases of generalized miliary tuberculosis in the series, tuberculous lesions were found in the kidneys in only three instances. The striking feature here was the resemblance between the defects produced by tuberculous lesions and those produced by thrombi and infarcts. We were unable to distinguish the presence of tubercles in roentgenograms of injected kidneys until they reached a size of about 1 to 2 mm. in diameter and the picture then was that of tiny or small defects, apparently the result of encroachment of the spreading tubercle on surrounding capillaries, glomeruli, and arterioles. The appearance was characteristic only in respect to the widespread distribution of tiny defects, all of which were of approximately the same size. Later, when the tubercles became confluent, they appeared more as small infarcts or scars, although possibly more superficial and less likely to involve small arteries.

GROUP VI. *Hydronephrosis.* There were also four cases of hydro- or pyonephrosis encountered in the series, only one of which was of marked degree. Subsequent to injection of the arterial tree, a pyelogram was made in each of these cases, but the changes noted were constantly proximal to the interlobular arteries and the findings add nothing to the work already done on this subject (Lim,[10] and Hinman and Morison [11]).

RELATIONSHIP OF DEMONSTRABLE VASCULAR CHANGES TO KIDNEY FUNCTION

An estimate of the functional impairment of the kidneys in this series is available in thirty-one cases in which terminal urea nitrogen and creatinine determinations were made on the blood. Except in

three instances these determinations were done postmortem on blood obtained at necropsy, as it has been shown that such data are reasonably accurate within a small percentage of error when the blood specimen has been taken within twenty-four hours after death (Paul [13]).

The cases in which blood urea nitrogen determinations are available are fairly evenly distributed throughout the groups (Table I).

TABLE I

Showing the Percentage of Cases with High and Low Blood Nitrogen Figures in each Group

Group	Total cases	Number of cases with urea nitrogen and creatinine determination on blood	Cases with normal blood urea nitrogen		Cases with high blood urea nitrogen	
			Number	Per cent	Number	Per cent
I. Normal	18	9	3	33	6	66
II. Arteriosclerosis....	17	14	4	28	10	71
III. Infarcts	7	4	0	0	4	100
IV. Syphilis	8	5	1	20	4	80
V. Tuberculosis	4	4	2	50	2	50

In the two larger groups (I and II) it is surprising to find that the percentage of cases showing a high blood urea nitrogen is almost as great in the group of so-called normals as in the arteriosclerotic series. Moreover, if we exclude from the later group one case of severely contracted kidney in which there was an active nephritis at death, and from Group I the case of subacute nephritis, it is found that the limits of the blood urea nitrogen are only slightly higher in the arteriosclerotic group. Furthermore, there does not appear to be any appreciable difference in terminal kidney function between the cases of fairly marked arteriosclerosis and those of moderate degree. This might appear to be unusual, yet it is recognized that in kidneys with moderate diffuse or focal scarring there is compensatory hypertrophy of secretory tissue and consequently the functional capacity may be relatively unchanged; and, as MacCallum [14] has suggested, "Perhaps the majority of the cases in which the pathologist at autopsy writes down 'slight chronic nephritis' are only instances of such obsolete scars in the kidney whose cause is now impossible to tell." Consequently in the present series of cases it is apparent that the functional impairment present in the moderately arteriosclerotic group and also in the normal group, is, in all probability, largely due

to toxic influences associated with systemic disease rather than to demonstrable vascular changes. It has already been pointed out that most of the acute parenchymatous changes in the kidney do not appreciably affect either the injection method or the appearance of the arterial tree.

In the infarction group it is noteworthy that the blood showed some degree of urea nitrogen retention in every case. Although this suggests that infarction is responsible for lowering the functional efficiency, the series is too small to warrant such a conclusion.

In the syphilis group the percentage of normal blood urea nitrogen cases is somewhat lower than in Groups I and II, but, with the exception of one case associated with pyonephrosis, the blood urea nitrogen does not reach as high a figure as in either of the former groups.

A study of the urinalysis records on the entire series contributed nothing of further significance.

Summary

1. The injection of the renal vessels with a radiopaque suspension, and subsequent roentgenography of the kidney have proved a simple, easily accomplished procedure readily adaptable to the necropsy room as a means of reconstruction of the arterial tree including the glomeruli. This method does not interfere with the usual methods of gross and microscopic examination.

2. Roentgenographic results check accurately with the accepted anatomic conception of the arterial tree; and in the normal kidney the vessels show:

(*a*) A slender, gradually decreasing caliber of the lumen.

(*b*) Branching at an acute angle except at the primary division of the renal artery.

(*c*) Interlobar and arcuate arteries with gradual curves and arches like a spreading elm tree.

(*d*) Interlobular arteries which are slender, delicate, closely set and almost parallel, giving a thick uniform cortex.

(*e*) Glomeruli that are very fine and numerous, grouped evenly around the interlobular arteries, giving an appearance stereoscopically of slightly cone-shaped columns with the interlobular artery in the center and their bases toward the periphery of the cortex.

3. Severe arteriosclerosis is marked by:

(*a*) An uneven caliber of vessels with dilatations and constrictions.

(*b*) A branching angle which approaches a right angle.

(*c*) Interlobar and arcuate arteries which are wider, club-like and do not taper gradually. Their curves are abrupt and angular.

(*d*) Interlobular arteries which are fewer, shorter, tortuous, and do not run so perpendicularly to the cortex.

(*e*) Glomeruli that are larger, decreased in number, and clumped around areas of best vascular supply.

(*f*) With contraction of the kidney the cortex thins and the entire vascular tree appears drawn out from the hilum, and the picture of the arterial tree as a whole suggests a gnarled oak rather than a graceful elm.

(*g*) Milder degrees of sclerosis are found first in the periphery, *i. e.*, in the arcuate and interlobar arteries, and extend farther toward the hilum as the changes become more marked.

4. The vascular changes in syphilis, when present, were of the same appearance as those of arteriosclerosis in this series.

5. Examination by the injection method is of definite value in the study of thrombosis of vessels and infarcts.

6. A comparison of the roentgenographic appearance of the arterial tree with the urea nitrogen retention in the blood has failed to show a direct relationship between moderate arteriosclerosis *per se* and impaired renal function.

7. Acute nephritis, acute degenerative parenchymatous changes in the kidney tissue, and passive congestion have neither interfered with the injection procedure nor have they given a distinctive picture on the roentgenograms.

I wish to thank Dr. Eben C. Hill of the Department of Anatomy of Johns Hopkins Medical School for his kind assistance in the adaptation of his injection mass to this special work, without which the study would not have been possible.

I am also greatly indebted to Dr. J. R. Paul, Director of the Ayer Clinical Laboratory for his encouragement and constructive criticism throughout this work and to Drs. D. R. Bowen and P. A. Bishop of the Department of Roentgenology of the Pennsylvania Hospital for their kindness and coöperation in doing the roentgenography.

REFERENCES

1. Oertel, H. The Anatomic Histologic Processes of Bright's Disease, Philadelphia, 1910, 44.
2. Traut, H. F. The structural unit of the human kidney, *Carnegie Institution of Washington, Contributions to Embryology*, No. 332 (1923), xv.
3. Gough, J. A. A method of injecting the blood vessels for roentgenological studies and simultaneous embalming, *Anat. Record*, 1920, xviii, 193.
4. Hauch. Die Arterien der gesunden und kranken Niere im Roentgenbilde, *Fortschr. a. d. Geb. d. Röntgenstrahlen*, 1913, xx, 172.
5. Gross, L. Studies on the circulation of the kidney in relation to architecture and function of the organ in health and disease, *J. Med. Res.*, 1917, xxxvi, (new series xxxi), 327; 1918, xxxviii (new series xxxiii), 379.
6. Hinman, F., Morison, D. M., and Lee-Brown, R. K. Methods of demonstrating the circulation in general, as applied to a study of the renal circulation in particular, *J. A. M. A.*, 1923, lxxxi, 177.
7. Lee-Brown, R. K. The renal circulation. *Arch. Surg.*, 1924, viii, 83.
8. Hill, E. C. Notes on an opaque X-ray mass, *Bull. Johns Hopkins Hosp.*, 1924, xxxv, 218.
9. Hill, E. C. A reliable radiopaque bismuth suspension for anatomical and pathological research. *Bull. Johns Hopkins Hosp.*, 1928, xvii. (March, No. 3, in press.)
10. Lim, W. K. Roentgenological studies of injected kidneys. *Am. J. Roentgenol.*, 1921, viii, 704.
11. Hinman, F., and Morison, D. M. An experimental study of the circulatory changes in hydronephrosis: A preliminary report relating to the unilobed kidney as instanced in the rabbit. *Tr. Am. A. Genito-Urin. Surg.*, 1923, xvi, 7.

    Experimental hydronephrosis: Arterial changes in the progressive hydronephrosis of rabbits with complete ureteral obstruction. *Surg. Gynec. Obst.*, 1926, xlii, 209.

    Comparative study of circulatory changes in hydronephrosis, caseocavernous tuberculosis and polycystic kidney. *J. Urol.*, 1924, xi, 131.
12. Warthin, A. S. Syphilis of the medium and smaller arteries. *New York M. J.*, 1922, lxv, 69.
13. Paul, J. R. Postmortem blood chemical determinations, *Bull. of the Ayer Clin. Lab.*, 1925, No. 9, 51.
14. MacCallum, W. G. Textbook of Pathology, Philadelphia, 1924, Ed. 3, 269.
15. Belt, A. E., and Joelson, J. J. The effect of ligation of branches of the renal artery, *Arch. Surg.*, 1925, x, 117.

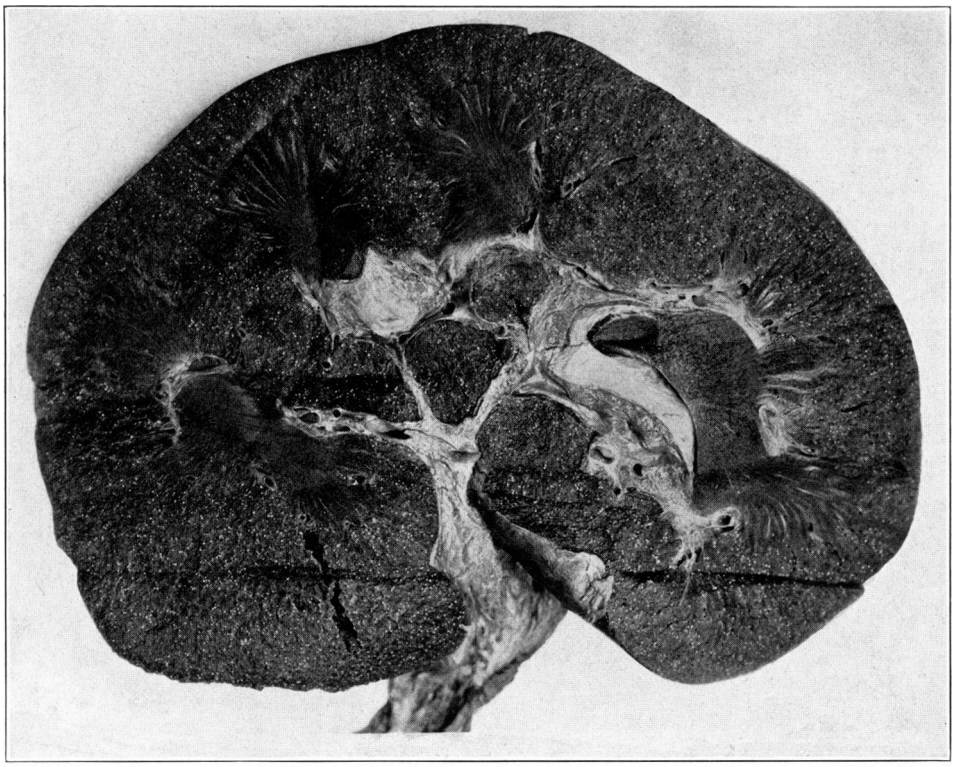
DESCRIPTION OF PLATES

PLATE 7

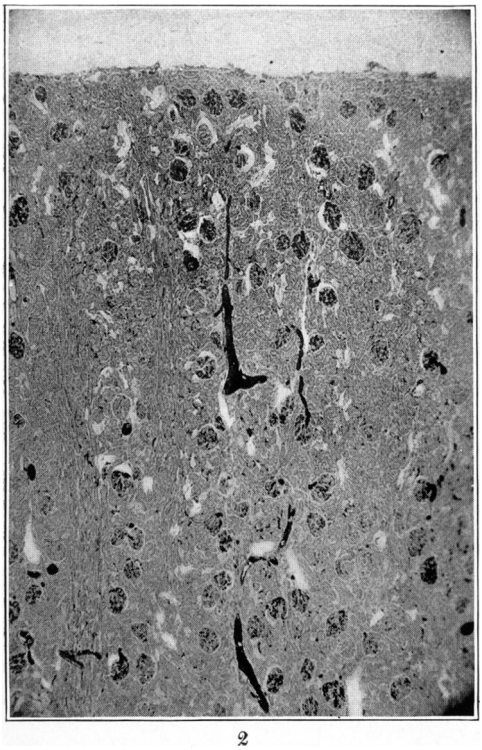
FIG. 1. Photograph of section of kidney showing appearance after injection. The specimen was cut, washed, and fixed in Klotz' solution so that the injected mass has been washed out of the larger vessels; but tiny vessels in the cortex and pyramids are well seen as fine lines, and the glomeruli appear as punctate points. See Fig. 6 for roentgenogram.

FIG. 2. Photomicrograph (very low power) of injected renal cortex showing the injection mass in interlobular arteries, in glomerular arteries and in glomeruli as dense black material. Note the anatomic arrangement of glomeruli around the interlobular artery.

FIG. 3. Photomicrograph (low power). Portion of an interlobular artery showing glomerular arteries arising from it and glomeruli filled with the injection mass.



1



2

3

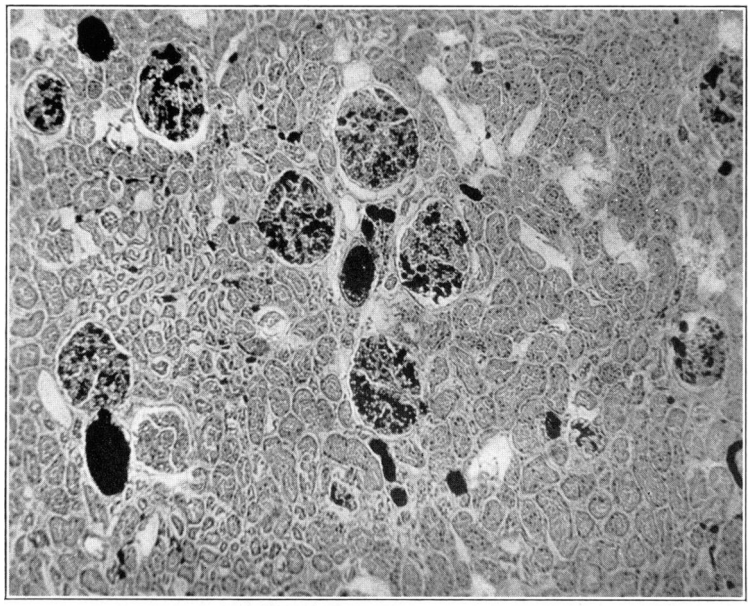
Graham

Circulation in Normal and Pathologic Kidney

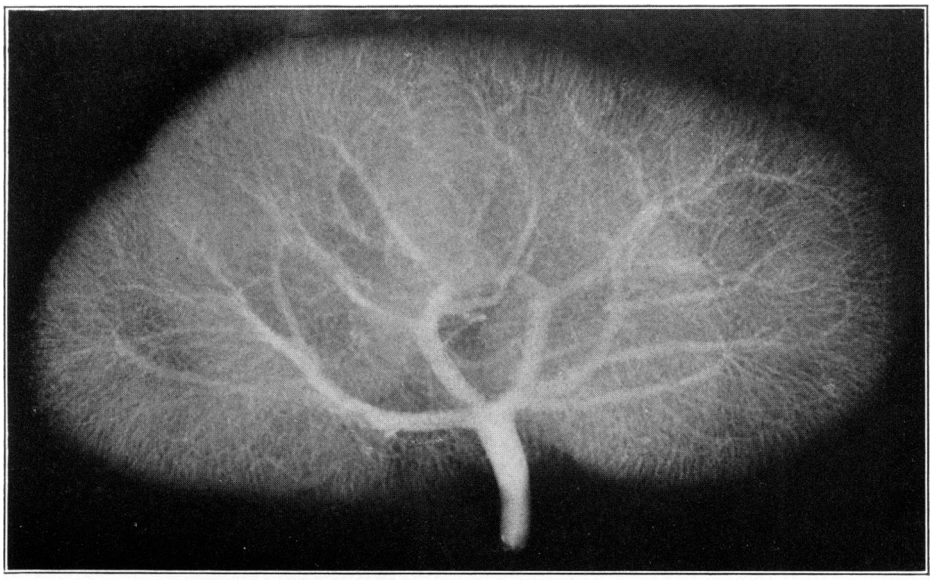
PLATE 8

FIG. 4. Photomicrograph (low power). A tangential section of the cortex showing the injection mass in interlobular arteries and glomeruli. Note the grouping of glomeruli around the interlobular vessels. The histologic study is not interfered with by the injected material.

FIG. 5. Roentgenogram of a normal arterial tree. Kidney from a boy, 14 years of age, dying of cardiac decompensation in active rheumatic fever.



4

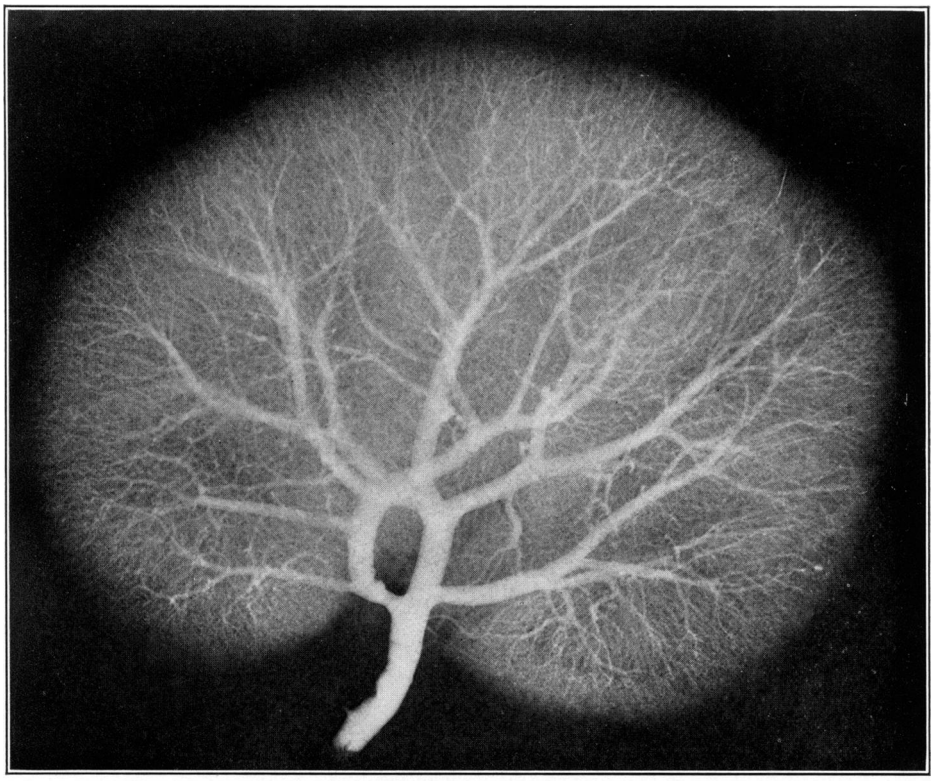


5

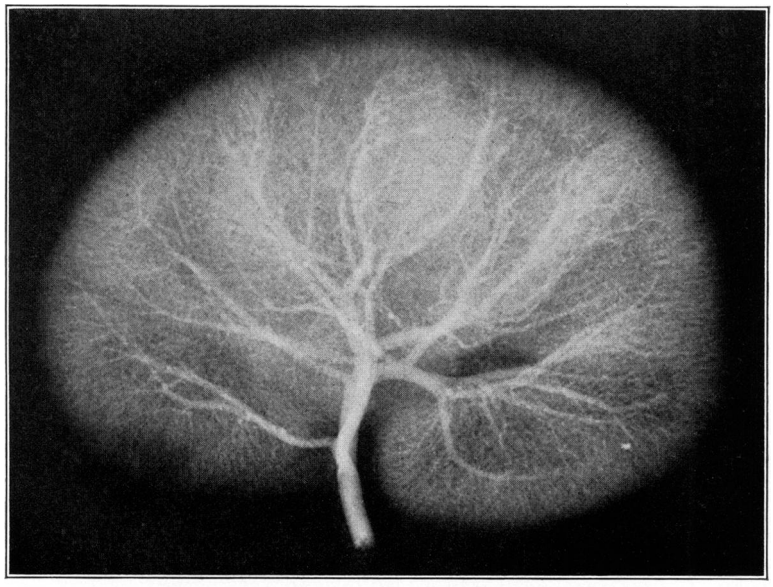
PLATE 9

FIG. 6. Roentgenogram of a normal arterial tree. Kidney from a man, 40 years of age, dying of carcinoma of the liver. The apparent constriction of the origin of one of the large primary divisions of the renal artery is found stereoscopically to be due to an optical phenomenon on the flat view.

FIG. 7. Roentgenogram of a normal arterial tree with infarcts. One infarct is seen at the periphery of the cortex near the hilum as an irregular defect and another as a dark area in the middle of the opposite pole. The hollows of the pyramids are well seen. Kidney from an 8-year-old girl dying twenty-eight days following extensive third degree burns of the body and extremities.



6

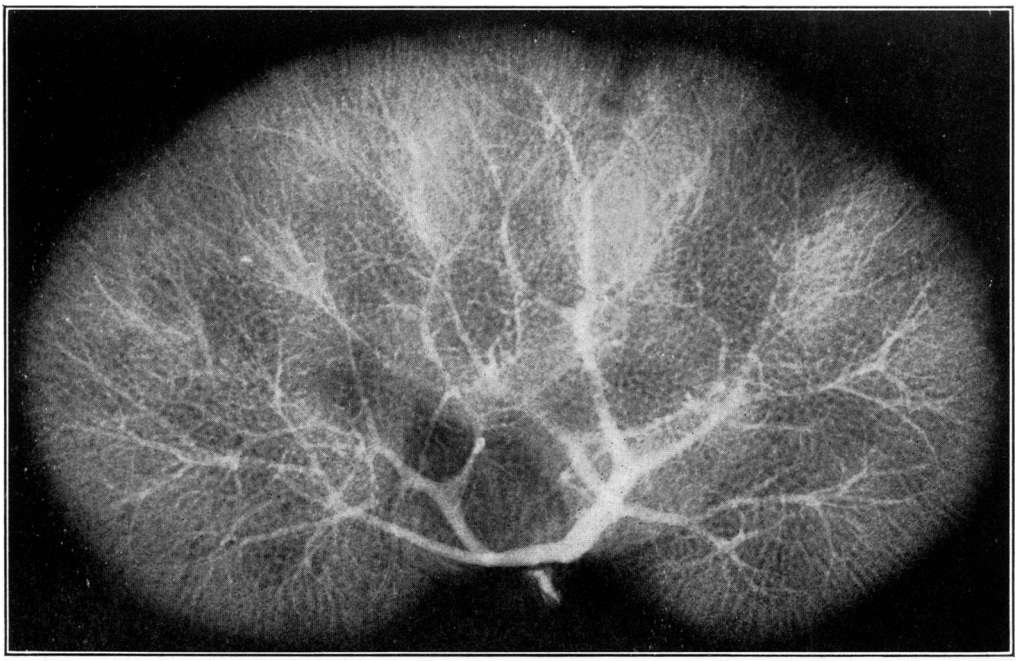


7

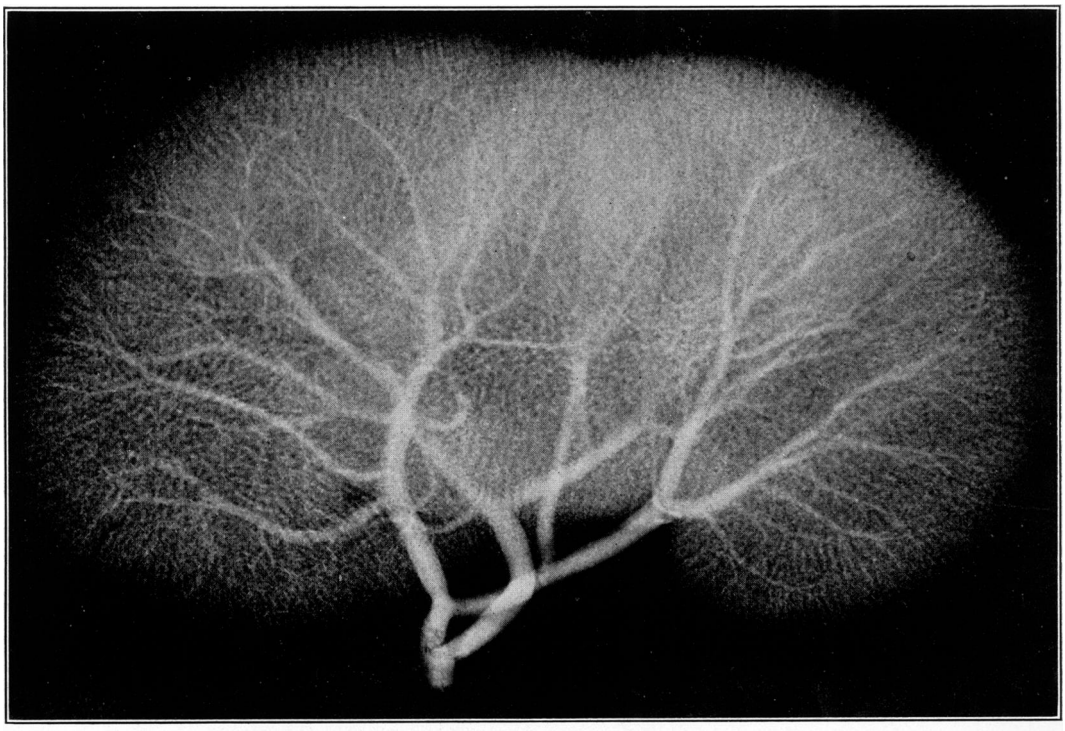
Plate 10

Fig. 8. Roentgenogram of a normal arterial tree with infarcts. Three rather large defects in the cortical injection are seen at the periphery of the upper pole, and two deep in the region of the lower calyx near the hilum. These were white infarcts grossly. Kidney from a patient 27 years of age dying of vegetative endocarditis.

Fig. 9. Roentgenogram of a kidney with subacute nephritis, "large white kidney." The arterial tree is normal and the injection complete and heavy.



8



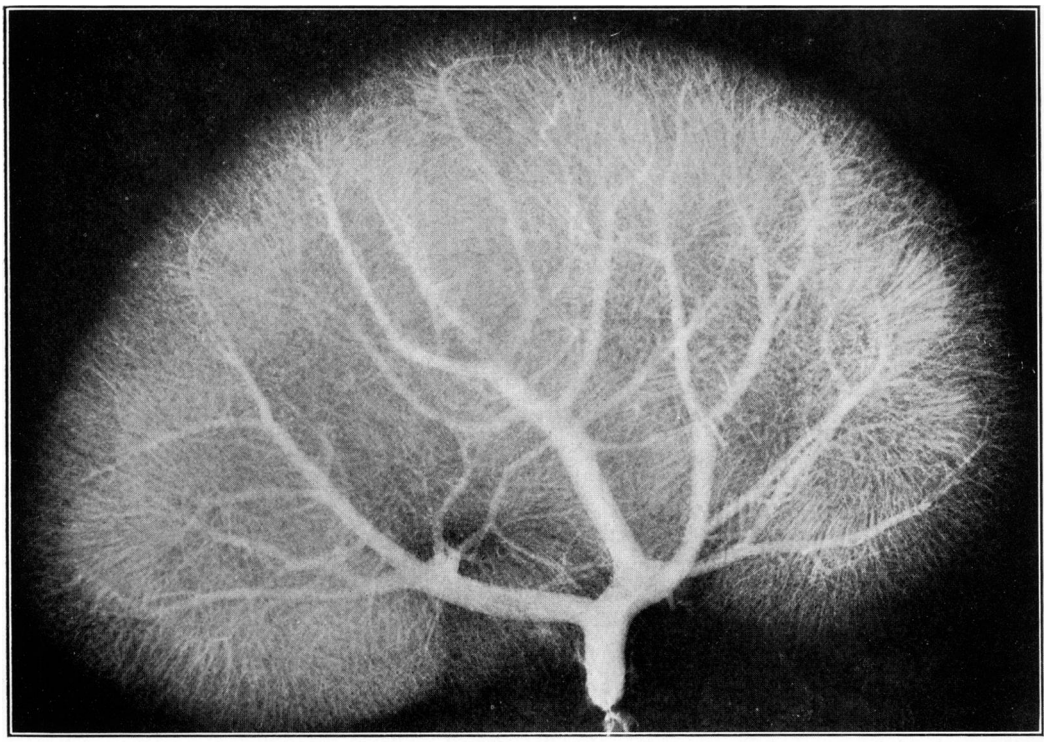
9

Graham Circulation in Normal and Pathologic Kidney

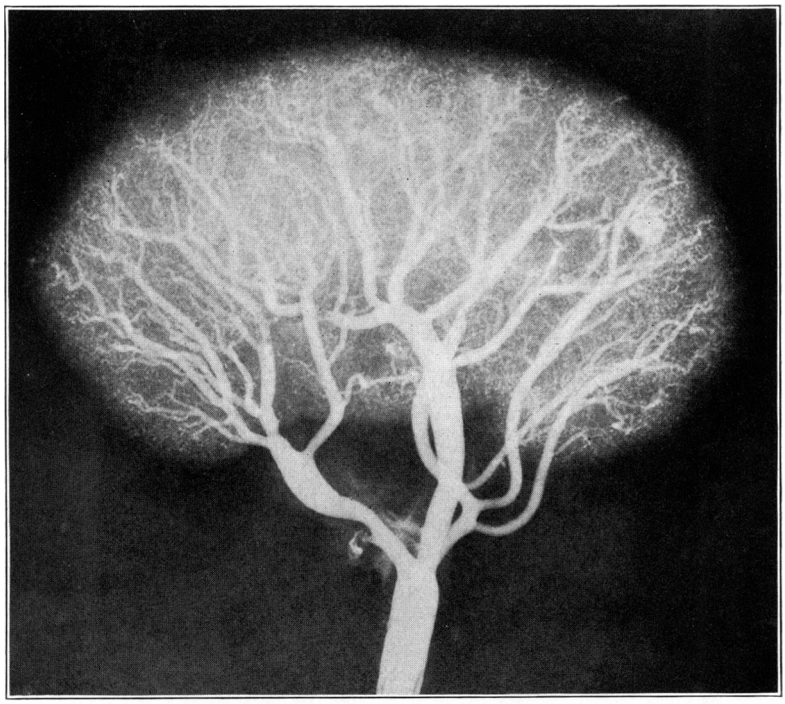
PLATE 11

FIG. 10. Roentgenogram of a kidney showing apparently complete injection of the pyramidal vessels. The arterial tree is normal. Kidney from a woman, 33 years of age, dying of gangrenous endometritis. Histologically there was marked passive congestion and cloudy swelling.

FIG. 11. Roentgenogram of a severely contracted kidney (nephrosclerosis). Note the uneven lumina and "dead tree" appearance of the vessels and the relatively few and very large glomeruli. A large retention cyst is seen on the periphery opposite the lower border of the hilum. Kidney from a man, 55 years of age, having generalized arteriosclerosis and dying of uremia.



10



11

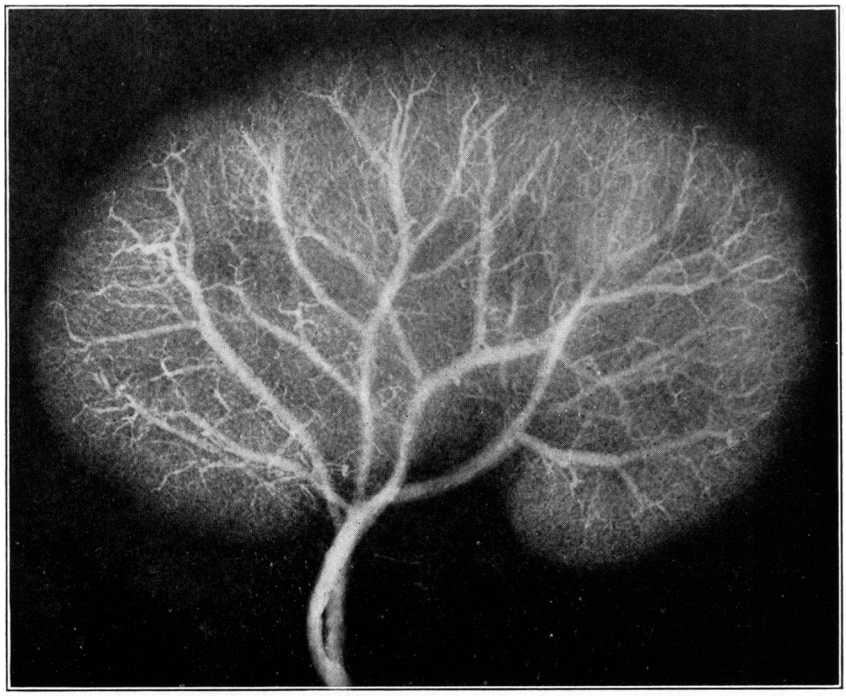
Graham Circulation in Normal and Pathologic Kidney

PLATE 12

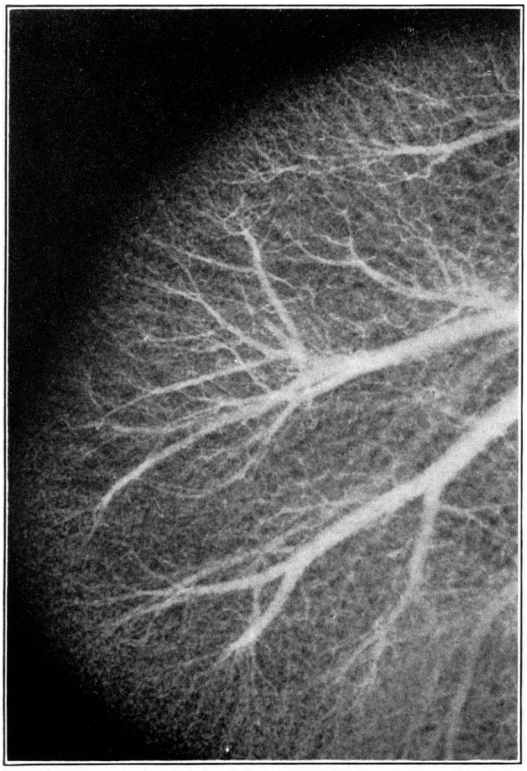
FIG. 12. Roentgenogram of a kidney, the vessels of which show moderate arteriosclerosis. Changes are most marked peripherally, the cortex is narrow, and the arcuate and interlobar vessels are tortuous with widened lumina, and end abruptly. Kidney from a woman, 70 years of age, with generalized arteriosclerosis, dying of cerebral thrombosis with infarction.

FIG. 13. Roentgenogram (small area enlarged $2\frac{1}{4}$ times) of normal arterial tree to show the details of the delicate tapering structure of the interlobar and arcuate arteries, and the small, very straight interlobular arteries almost hidden by surrounding clumps of glomeruli.

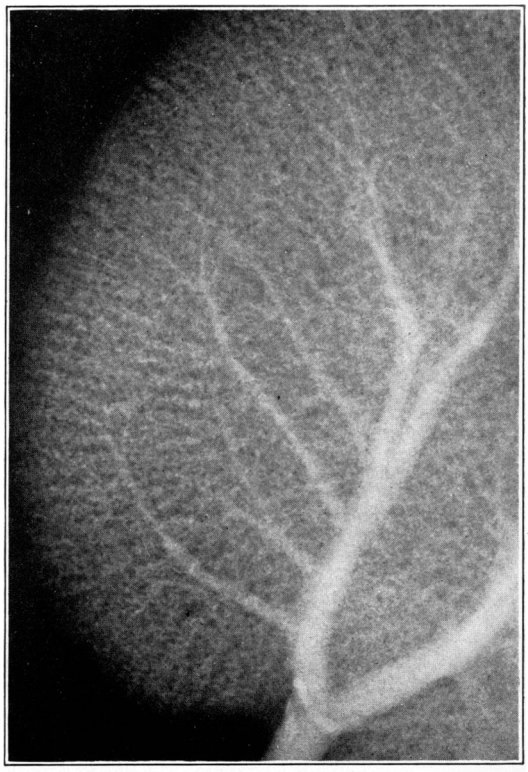
FIG. 14. Small area of roentgenogram of Fig. 9 (enlarged $2\frac{1}{4}$ times). The thick cortex shows the column-like appearance produced by glomeruli clumped around the interlobular arteries.



12



13



14

Graham

Circulation in Normal and Pathologic Kidney

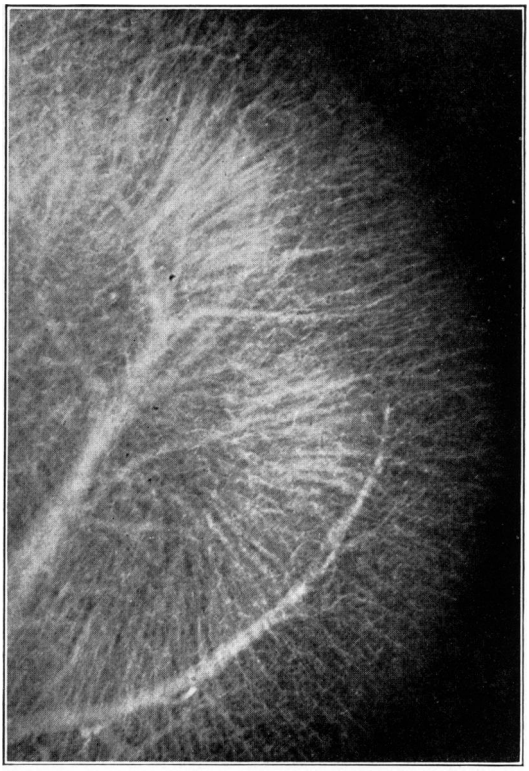
PLATE 13

FIG. 15. Small area of roentgenogram of Fig. 10 (enlarged $2\frac{1}{4}$ times). The vessels of the pyramids, broad and feathery at the base and narrowing as they converge toward the tip, are well shown.

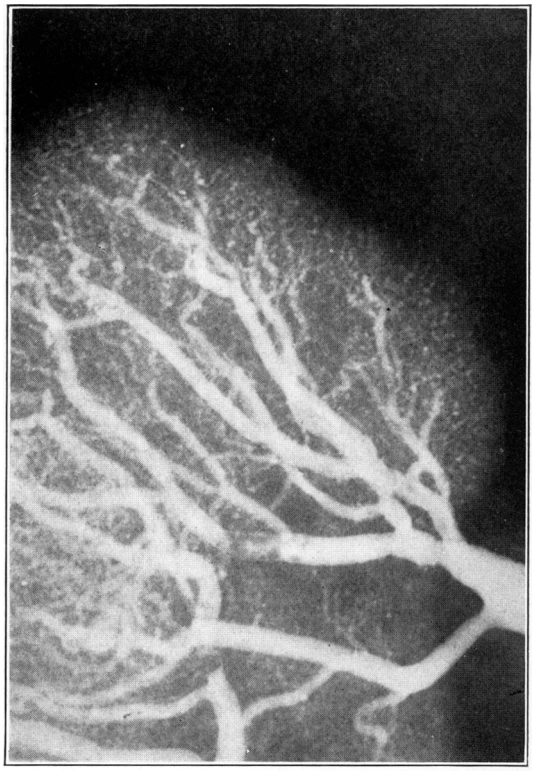
FIG. 16. Small area of roentgenogram of Fig. 11 (enlarged $2\frac{1}{4}$ times). Note the few and very large glomeruli in the narrowed cortex.

FIG. 17. Small area of roentgenogram of Fig. 12 (enlarged $2\frac{1}{4}$ times). The tortuosity and uneven dilatation of the lumina of interlobar and arcuate arteries is clearly seen. The glomeruli do not appear increased in size.

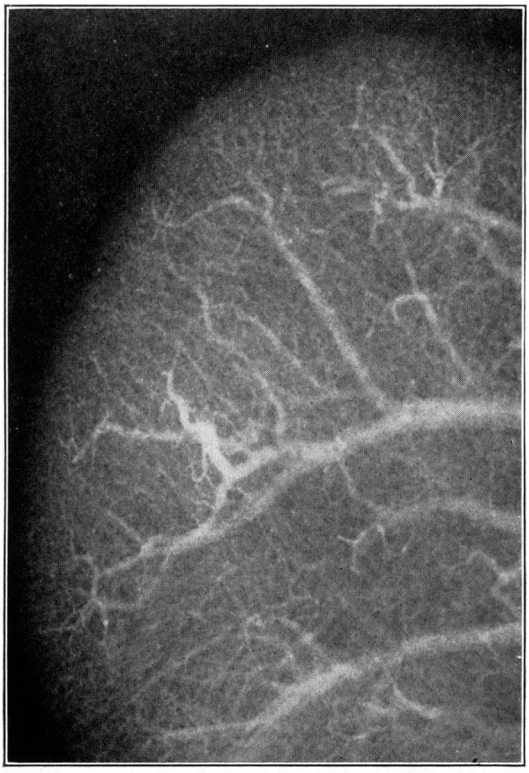
FIG. 18. Roentgenogram (small area enlarged $2\frac{1}{4}$ times) of a contracted kidney of chronic nephritis. Note the relatively mild sclerotic changes in the arterial tree, the rather wide cortex containing but few greatly enlarged glomeruli and the fairly complete injection of the pyramidal vessels. Compare the appearance here with that of a contracted nephrosclerotic kidney in Fig. 16.



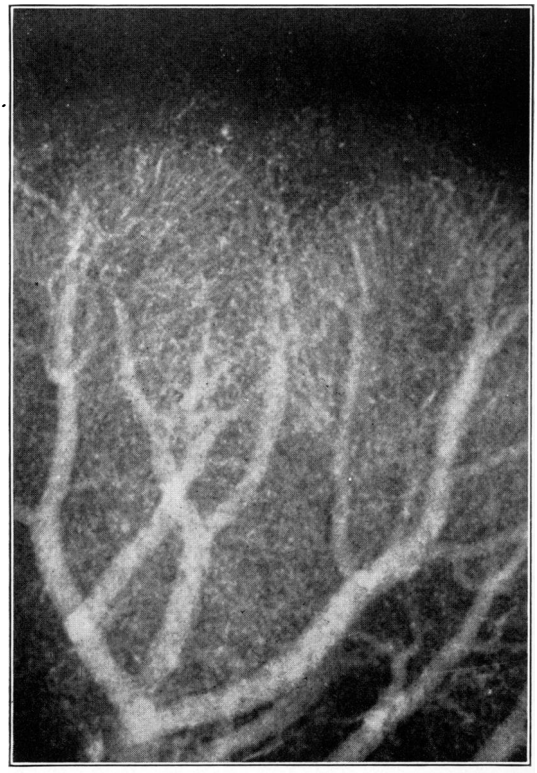
15



16



17



18

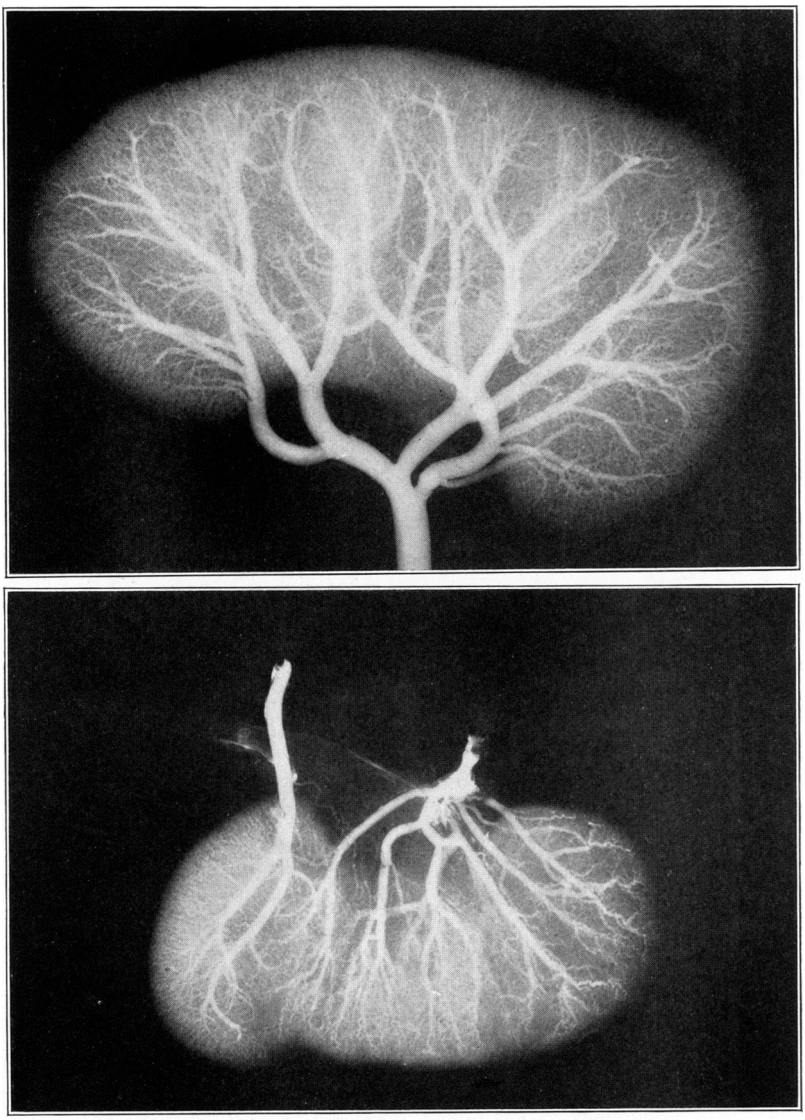
Graham

Circulation in Normal and Pathologic Kidney

PLATE 14

FIG. 19. Roentgenograms of both kidneys from a case of aneurysm of the aorta at the level of the renal arteries. The left renal artery was thrombosed and injection distal to the thrombus in the upper two thirds, shows a shrunken kidney and a shriveled arterial tree with no glomeruli injected. The lower pole supplied by an anomalous artery is larger and normal in appearance and the line of division is sharply drawn. The renal pelvis is faintly visualized by some of the injection mass which appeared in the pelvis during the arterial injection.

The right kidney is hypertrophied. Well defined hollows are seen where pyramids (uninjected) occur. There are mild sclerotic changes in the arcuate and interlobar arteries. The patient was 45 years of age.



19