Studies on the Outflow Tracts of the Liver *

I. On a Method for the Functional Demonstration of the Outflow Tracts of the Liver and its Application to the Study of Hepatic Hemodynamics in Normal and Cirrhotic Rats

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BLOOD entering the liver through the portal vein and hepatic artery normally finds its way out through a single common outlet system—the hepatic veins. This venous system has been shown, in many species, to be unique in anatomic characteristics and physiological behavior. It is conceivable that it may play a role as a regulatory mechanism controlling the blood reservoir function of the liver. The study of these hepatic outflow tracts has remained, for the most part, in the realm of physiological and anatomical investigators.[1, 2, 10, 13] The discovery that disease processes may distort the normal function of this system directed the attention of clinicians and surgeons to its study. A considerable part of the interest in hepatic vein occlusive diseases has been devoted to the diffuse partial intrahepatic obstruction generally accepted to be present in the cirrhotic liver.[9, 12, 15] It has been suggested that under these conditions of diffuse partial obstruction of the normal outflow system, the portal vein could assume the role of an accessory outflow tract.[26, 27] That a surgically constructed outlet for such an accessory outflow tract might be used in the treatment of ascites was of particular interest to surgeons[14, 22, 26, 27] (Fig. 1). Working under conditions less controllable than those of physiological experiments, surgical investigators have endeavored to provide supporting evidence for these assumptions.[6, 11, 16, 25, 27, 28]

The present investigation was designed to study the hemodynamic behavior of the outflow tracts of the liver in different species under varying experimental conditions. Corresponding studies in humans were planned within the limitations inherent in clinical research.

The method used to demonstrate the functional activity of the outflow tracts of the liver evolved from the findings that followed the accidental injection of radiopaque medium into the substance of the liver of a patient undergoing splenoportography.[19] Although the true significance of the findings observed was not realized at the time, further evaluation suggested that the hepatic vein outflow tracts had been delineated by this procedure. Subsequent experimental studies designed to evaluate the possibilities of this method in-

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dicated that, contrary to the anatomical demonstration that follows the intrahepatic injection of vascular and ductal structures, the intraparenchymal deposition of contrast medium permitted the hemodynamic delineation of the hepatic outflow tracts (Fig. 2). It became apparent that when the dye was deposited into the parenchyma of the liver, the contrast medium was carried away by the capillaries draining the area, thus providing visualization of the hepatic outgoing pathways.

Results of serial histological studies of the sites of injection, as well as lack of morbidity and mortality in a considerable number of experimental animals, permitted cautious extension of the use of this investigative tool to a series of human subjects.

The purpose of this paper is to discuss the possible merits of the method of intrahepatic parenchymal injection of radiopaque medium as used in rats, dogs, and humans for the hemodynamic demonstration of the outflow tracts of the liver. This

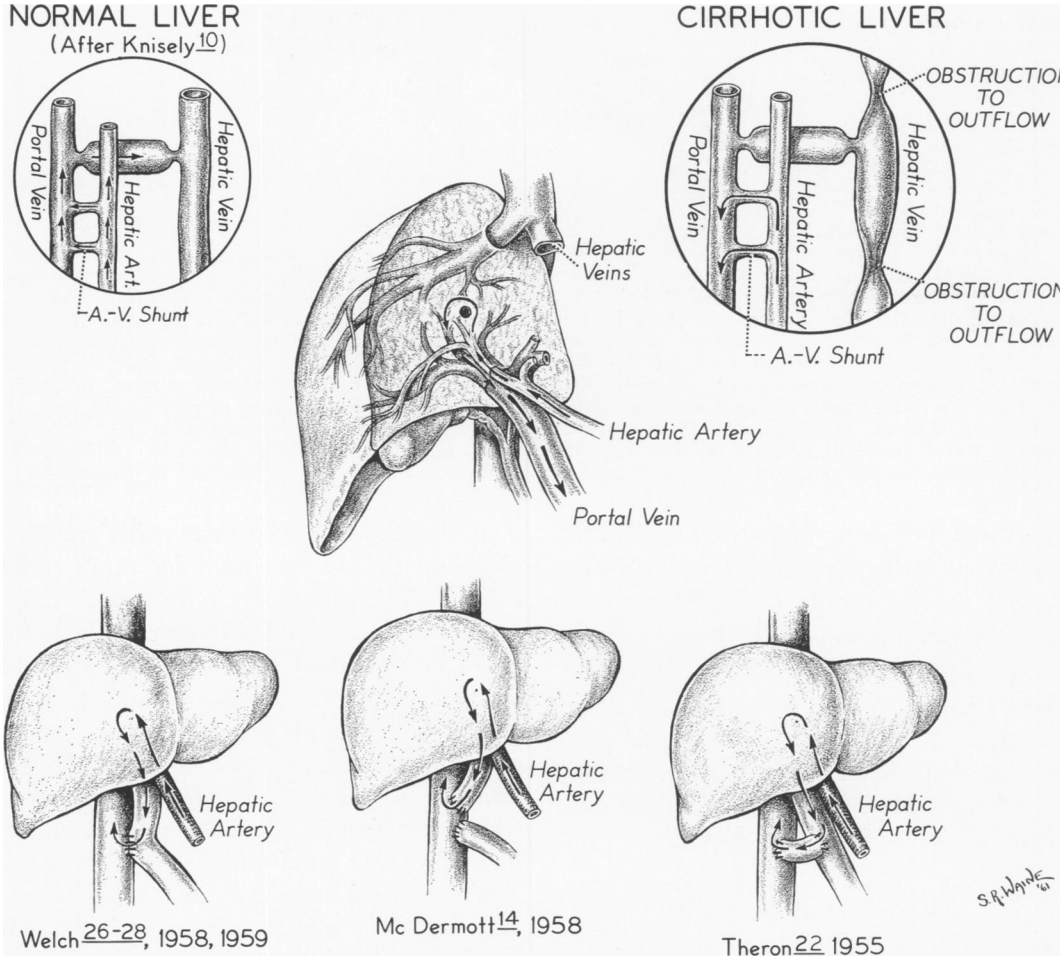

FIG. 1. Diagrammatic representation of the role of the portal vein as an accessory hepatic outflow tract as suggested by several investigators. In the presence of pathologic obstruction to the normal outflow tracts(hepatic vein system), it has been assumed that hepatic artery blood reverses its course through multiple arteriovenous communications to find its way out of the liver through the portal vein. In the lower part of the illustration variations of side-to-side portacaval shunts are depicted which have been intended to provide an outlet for the accessory outflow tract. Decompression of the congested liver has been expected to follow these procedures.

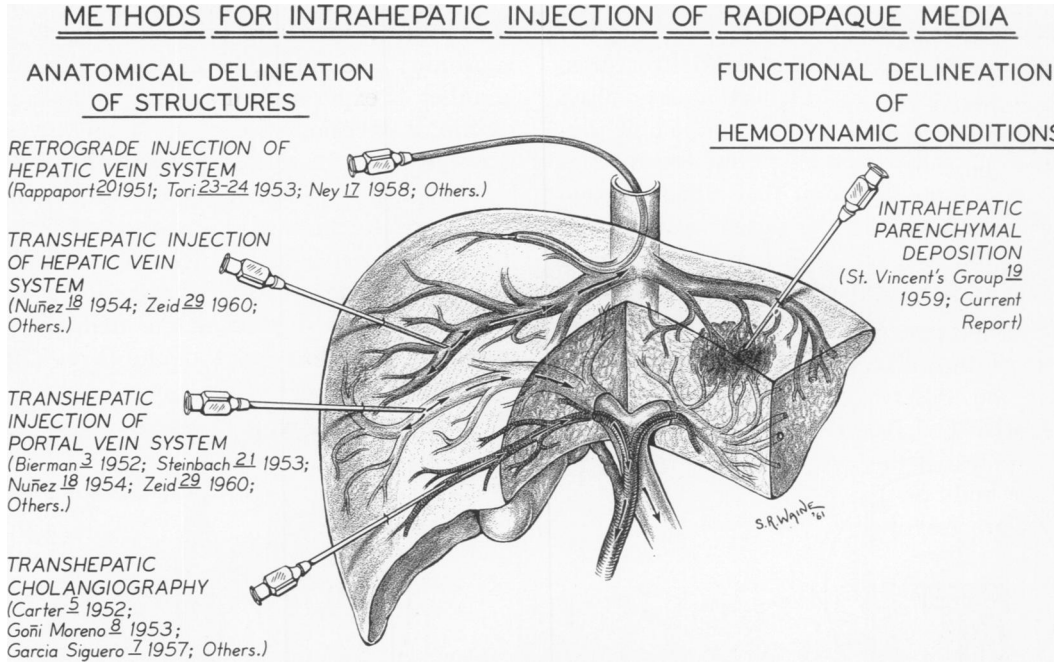

FIG. 2. Diagrammatic representation of various methods for the radiological visualization of intrahepatic structures, including the method being reported in this paper. Intravsacular injection of both the portal and hepatic vein systems, retrograde injection of hepatic veins by means of "wedged" cardiac catheters, and injection of the biliary tract system, as reported in the literature, are depicted on the left side of the illustration. Because of the direct intraluminal injection of the opaque medium, these procedures may provide only an anatomical demonstration of the system being studied. For convenience, the intrahepatic parenchymal injection is depicted on the right side of the illustration. It is believed that the dye deposited in the area of disrupted parenchyma and capillaries has an equal opportunity of entering vessels of any vascular system depending on the direction of flow. A hemodynamic demonstration of the outflow tracts of the liver is thought to be obtained by this method.

report will include a comparison of hepatic hemodynamics in normal and cirrhotic rats as well as the results of an attempt to assay the possible role of the portal vein as an accessory hepatic outflow tract. The hemodynamics of the canine liver as demonstrated by the use of this method and the situations influencing hepatic outflow in patients with cirrhosis of the liver will be the subjects of separate reports.

Materials and Methods

Normal and cirrhotic albino rats of the Wistar strain and normal mongrel dogs were used in the experimental phase of this investigation. Normal human subjects who volunteered constituted material for the clinical phase.

A Fairchild x-ray camera with an F280 roll film casette was used for rapid serial radiological exposures in rats and dogs. A standard x-ray unit with a manual casette changer was used for the examination of human subjects. Eastman Kodak Blue Brand film was used in all cases.

Contrast medium was a 50 per cent solution of sodium diatrizoate (Hypaque®). Intraparenchymal deposition of contrast medium was performed at laparotomy under general anesthesia in rats and dogs, and by the percutaneous route in human subjects, using 1.0 per cent procaine hydrochloride as local anesthesia. A needle of suitable size for the particular subject studied was introduced well into the substance of the liver and negative pressure applied to ascertain that the tip of the

needle was neither in the lumen of a vessel, nor in a biliary duct. Dye was injected in amounts and at rates of speed previously determined for each species and a rapid sequence of radiological exposures was obtained.

Although examples of the demonstration of the hepatic outflow tracts in dogs and humans will be included in this report as part of a general presentation of the method of intraparenchymal injection, the particulars of the technic used in these instances will be described in the corresponding reports. For the study of hepatic hemodynamics in the rat, which comprises the main body of this report, the following details are pertinent.

One hundred and thirty-two male albino rats, weighing an average of 350 Gm. were used. Sixty-three were normal animals, and 21 had experimentally-induced cirrhosis of the liver. To test the validity of the method as a functional demonstration of the hepatic circulation, 48 animals were sacrificed prior to the injection to observe the fate of the injected dye in the absence of active flow of blood. In the latter group, 26 were normal animals and 22 had experimentally-induced cirrhosis of the liver.

In addition to the intrahepatic parenchymal injection performed to visualize the outflow tracts of the liver, the cirrhotic animals were submitted to splenoportographic

FIG. 3. Extreme low power view of a section of liver tissue obtained from a rat one hour after the intraparenchymal injection of radiopaque medium. A moderate degree of parenchymal disruption and hemorrhage produced by the injection of the material can be observed. Daily histological sections obtained over a period of 10 days in a series of animals sacrificed for this purpose showed the area of hemorrhage to be rapidly reabsorbed.

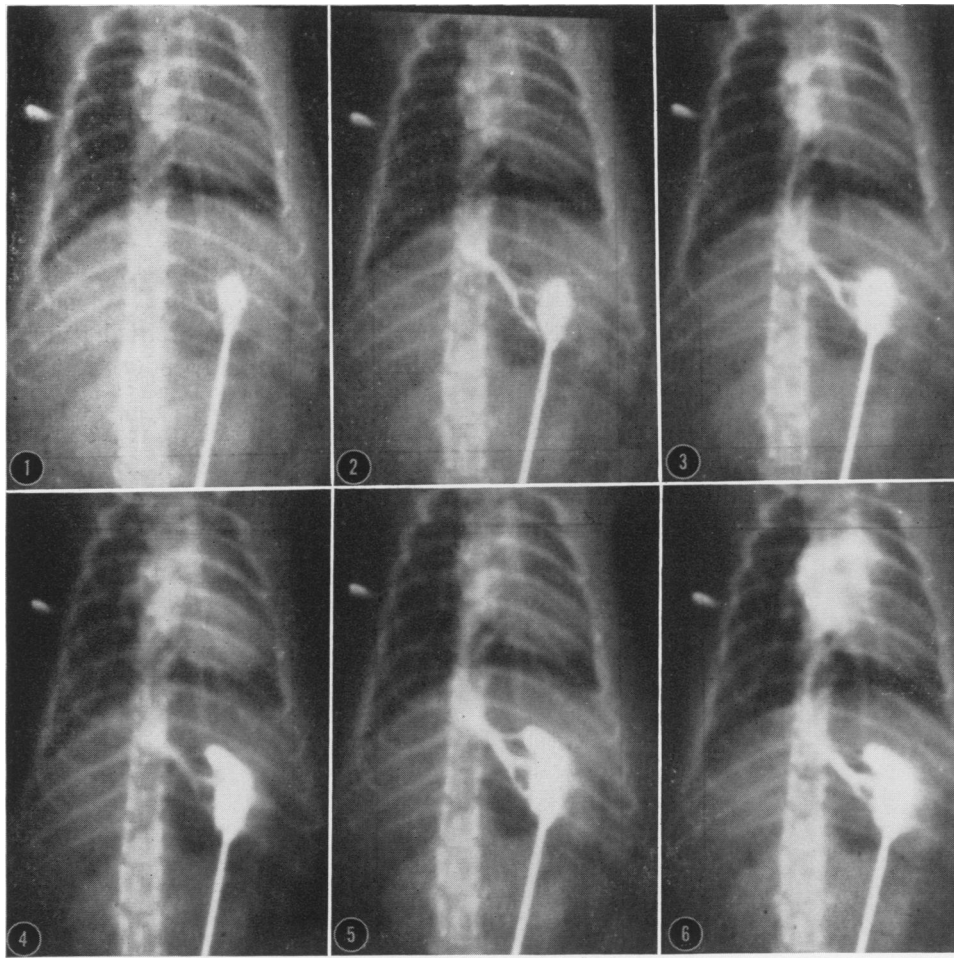

FIG. 4. Satisfactory intrahepatic parenchymal injection in the rat. Representative films from a multiple exposure radiological study. Films are separated by 1 second intervals. Frame #1 shows the beginning of the injection. The pool of dye delineates the area of parenchymal disruption produced by the injection. No vascular structures are as yet visualized. Frames #2, 3, 4 and 5 show enlargement of the pool of dye and progressive filling of vessels draining the area as they carry the dye into a hepatic vein and the vena cava. In Frame 5, three of these draining vessels can be seen. Frame #6 shows the complete process of visualization of the outflow tract including opacification of the right heart.

studies intended to delineate the vascular pattern of the portal system.

The method of inducing experimental cirrhosis and the technic for splenoportography in small animals are described elsewhere.[4]

A No. 22 needle was used for the intrahepatic parenchymal injection in these small laboratory animals. Since the weight of the hub of this size needle was found to dislodge it from its proper parenchymal position, the shaft was separated from the hub and directly attached to a polyethelene catheter which, in turn, was connected to a 2.0 ml. syringe. Under inhalation ether anesthesia the liver was exposed, and while the left lobe was held between the thumb and forefinger, the needle was introduced into the parenchyma to a depth of from 1.0 to 1.5 cm. After negative pressure was applied to the syringe to confirm the extravascular position of the needle, 0.5 ml. of

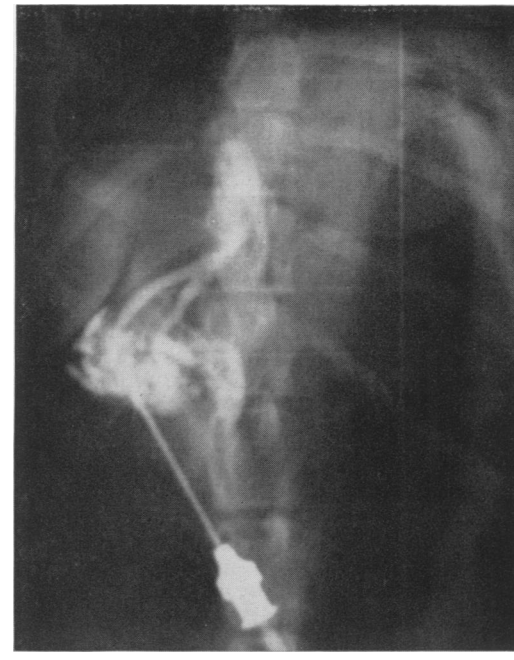

FIG. 5. Satisfactory intrahepatic parenchymal injection in the dog. Representative film from a multiple exposure radiological study. The area of disrupted parenchyma is outlined by the dye. Three vessels draining this area converge to form a hepatic vein which in turn empties into the vena cava.

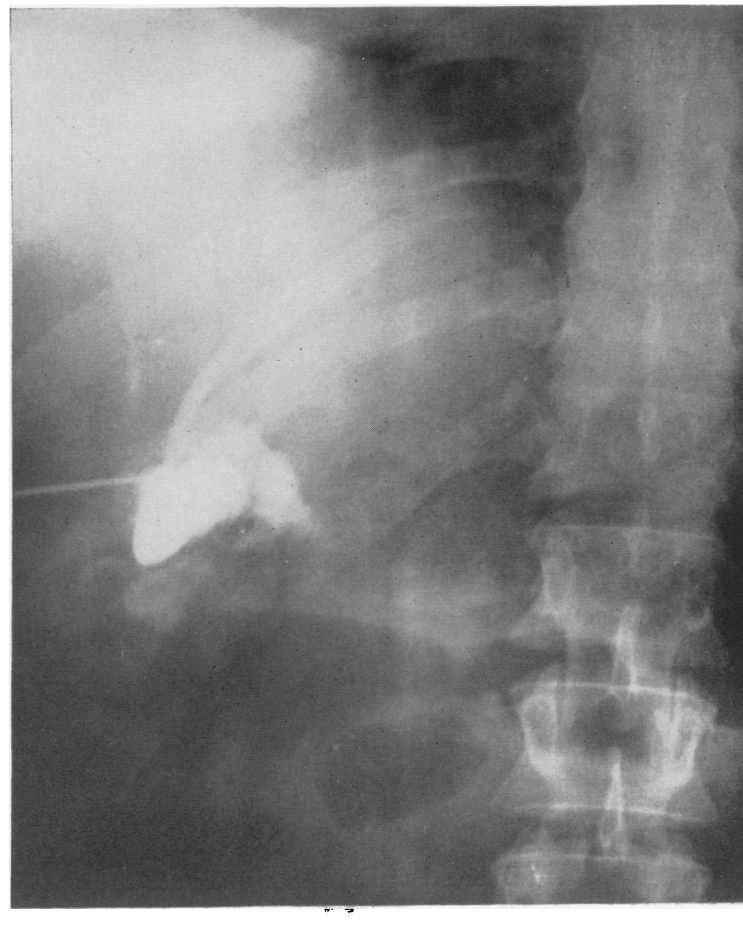

FIG. 6. Satisfactory intrahepatic parenchymal injection in man. Representative film from a multiple exposure radiological study. The site of the injection is delineated by a small collection of dye. A large branch of the hepatic vein system carries the contrast medium in the direction of the vena cava.

contrast medium were injected at the rate of 0.1 ml. per second. Excessive pressures resulting from faster rates of injection were associated with disruption of the parenchyma and failure of the examination. As a rule, an average of ten x-ray exposures were obtained at one-second intervals starting with the beginning of the injection. Exposure factors were 30 Ma, 1/20 of a second, 56 Kv, at a target field distance of 100 cm.

When the examination was completed, and without changing the position of the needle, hepatic blood outflow was impaired by occlusion of the intrathoracic segment of the inferior vena cava. Then a second injection of contrast medium, identical to the first, was made and followed by the same sequence of exposures. The purpose of this additional examination was to test the reactivity of the hepatic and portal vein systems of normal and cirrhotic rats

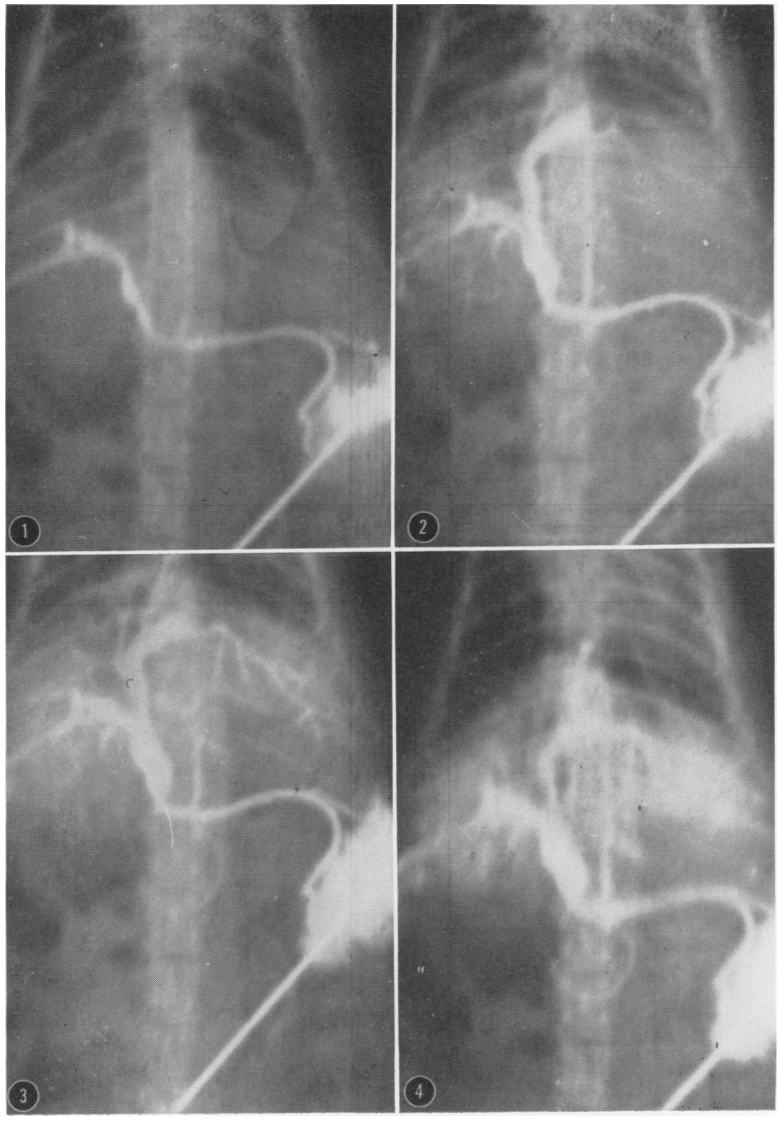

FIG. 7a. Study comparing changes in the intrahepatic portal vasculature (splenoportogram) and changes in the hepatic vein system (delineation of outflow tracts by the intraparenchymal injection of contrast medium) in a cirrhotic rat. Both studies were performed during the same radiological session. a) Splenoportogram shows distorted intrahepatic portal vasculature. A state of portal hypertension is demonstrated by the reverse flow into the coronary vein and by the presence of a perigastric-left adrenal-left renal natural shunt.

when submitted to the extremely artificial conditions of sudden complete block of the outflow tracts.

Results

No immediate or delayed untoward reactions that could be ascribed to the intraparenchymal hepatic deposition of radiopaque dye were detected in dogs, rats, and humans submitted to this procedure. Daily histological sections obtained in a series of laboratory animals sacrificed for this purpose showed an area of localized hemorrhage at site of injection (Fig. 3). No extensive disruption of liver parenchyma or significant cellular changes were observed. The area of hemorrhage was quickly reabsorbed; after ten days, the site of injection could no longer be detected.

After the technic for intraparenchymal deposition of contrast medium was perfected, visualization of the outflow tracts of the liver was regularly obtained in rats, dogs, and humans (Figs. 4–6).

Hemodynamic delineation of the outflow tracts of the liver was considered satisfactory, for the purpose of this study, in 36 of 63 normal rats, and 20 of 21 cirrhotic rats.

In the normal animal, a complete process of delineation of the outflow tracts of the injected lobe and opacification of the intrathoracic segment of the inferior vena cava occurred at an extremely fast rate of speed. Usually in three to four seconds the head of the dye-stained column of blood had been carried by branches of the hepatic vein system to the vena cava, and by the end of five to six seconds had reached the right atrium (Fig. 4). Retrograde flow into intrahepatic branches not draining the area of injection was rarely observed in this normal group. On no occasion was the dye seen to enter the portal system.

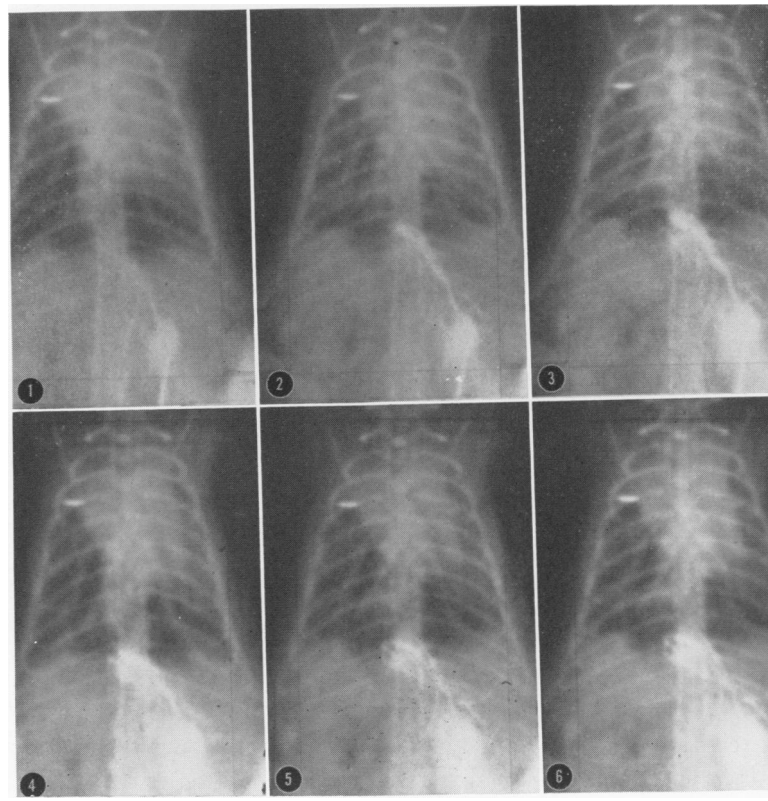

FIG. 7b. Following the intrahepatic parenchymal injection of contrast medium, branches of the hepatic vein system are outlined. No detectable amount of dye reaches the vena cava or the right heart. These findings, particularly when compared with those in the normal animal (Fig. 4), are interpreted as evidence of obstruction to the outflow tracts of the liver. Despite this apparently severe degree of obstruction to the outflow tracts, no evidence of the portal system acting as an accessory outflow tract can be seen. (Same animal as in 7a.)

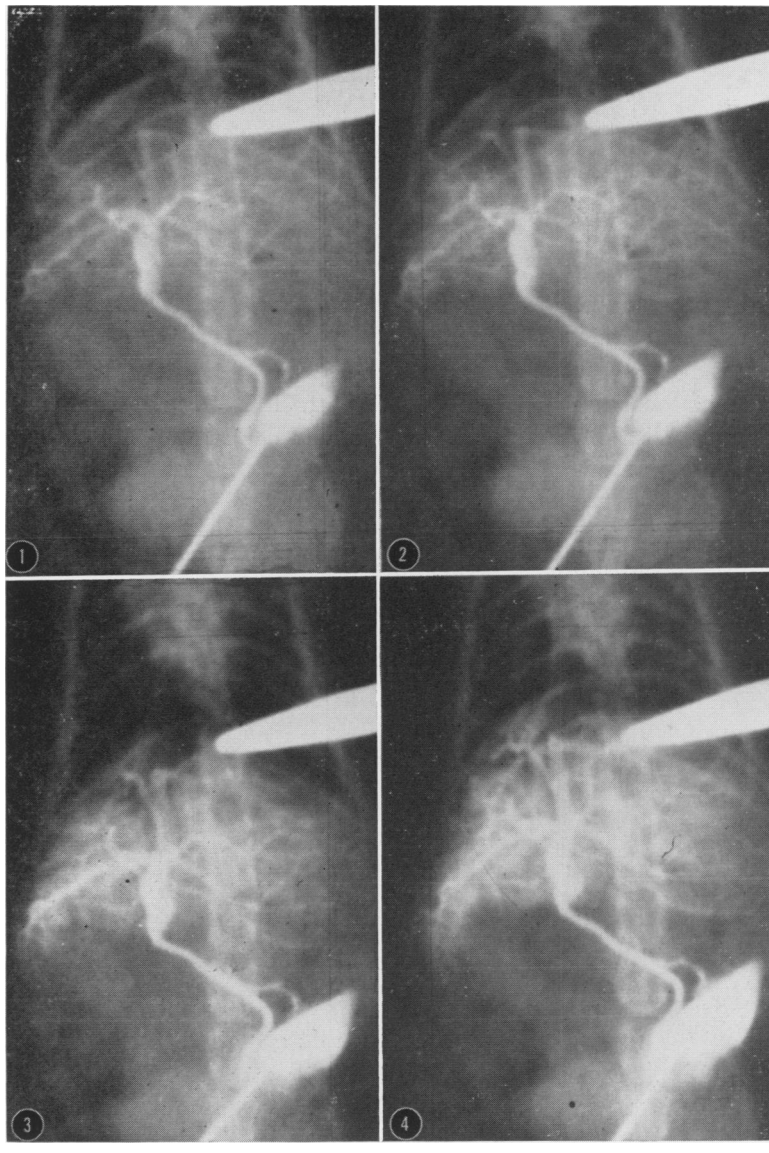

FIG. 8. Study comparing changes in the intrahepatic portal vasculature (splenoportogram) and changes in the hepatic vein system (delineation of outflow tracts by the intraparenchymal injection of contrast medium) in a cirrhotic rat. Both studies were performed during the same radiological session. a) shows the splenoportographic study. Distortion of the intrahepatic portal vasculature corresponds to the degree of cirrhosis observed in histological studies performed in this animal. No evidence of extrahepatic portal collaterization is seen.

Significant changes from the normal patterns were seen in the group of cirrhotic animals. For the most part, these changes appear to indicate varying degrees of obstruction to the hepatic outflow tracts. In the cirrhotic animal, either the time elapsing before the dye left the liver was prolonged or the amounts of dye leaving the liver were reduced. The combined incidence of these two hemodynamic changes was proportional to the degree of hepatic involvement by the cirrhotic process. In certain animals the time elapsing before the dye left the liver was prolonged to such an extent that no contrast medium was seen to abandon the liver throughout the entire duration of the study (Fig. 7). In other animals, although some contrast medium reached the vena cava, most of it remained inside the liver (Fig. 8). Occasionally, retrograde flow of the dye remaining in the liver filled the entire hepatic

vein system (Fig. 9). In no instance was reversal of flow into the portal vein observed.

When a sudden acute artificial load was imposed upon the hepatic circulation, namely, acute obstruction of the thoracic segment of the inferior vena cava, a number of facts became evident. In both normal and cirrhotic animals, the response to sudden occlusion was characterized by extreme dilatation of the intrahepatic branches of the hepatic vein system. In addition, retrograde flow filled branches not draining the area of injection to such an extent that, on occasion, the entire hepatic vein system was visualized (Fig. 10). Reverse caudal flow in the vena cava was observed. Finally, despite these extreme artificial conditions of total mechanical obstruction of the normal outflow tract reverse flow into the portal venous system, as an accessory outflow tract, was never observed in either the normal or cirrhotic animal.

The intraparenchymal injection of contrast medium performed in dead animals rendered considerably different results from those obtained during life. Instead of the exclusive visualization of the hepatic vein outflow tract consistently observed in live animals, the dye was seen either to simultaneously enter the hepatic vein and portal vein systems (Fig. 11) or to produce an anatomical demonstration that even included remote branches of the systemic circulation.

Discussion

The validity of a method such as the one used in this investigation for the demonstration of the hemodynamics of the outflow tracts of the liver may be questioned. In general, any radiological method of visualization based on the injection of contrast medium is subject to a variety of artifacts. Despite this legitimate objection, accumulating experience has led to the belief that the intraparenchymal deposition

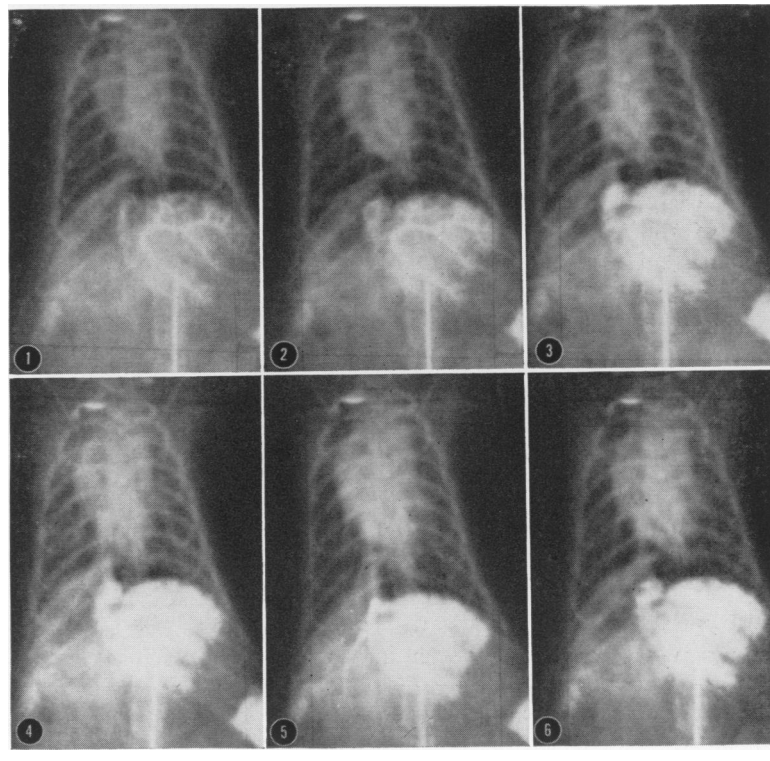

FIG. 8b. As a result of the intraparenchymal injection dye is seen accumulating in the finer branches of the hepatic vein system. Although some contrast medium reaches the vena cava, most of it remains inside the liver for the duration of the study. No evidence of the portal vein being used as an accessory outflow tract can be derived from this study. (Same animal as in 8a.)

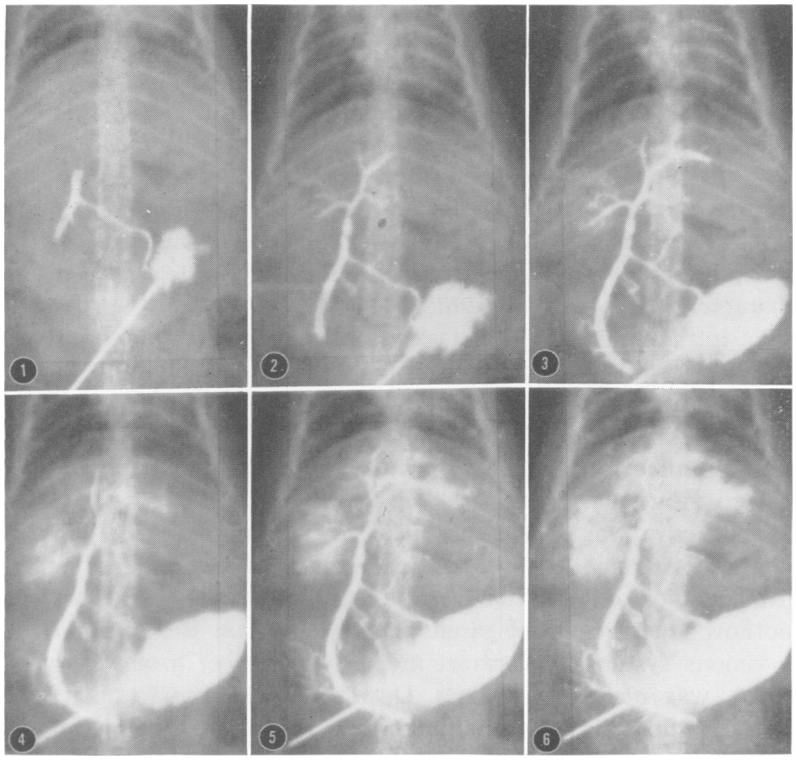

FIG. 9a. Study comparing changes in the intrahepatic portal vasculature (splenoportogram) and changes in the hepatic vein system (delineation of outflow tracts by the intraparenchymal injection of contrast medium) in a cirrhotic rat. Both studies were performed during the same radiological session. a) The splenoportogram shows intrahepatic changes consistent with cirrhosis of the liver. A state of portal hypertension is demonstrated by the presence of extrahepatic portal collateralization. Retrograde flow into the superior mesenteric vein and its branches and into the coronary vein can be observed.

of radiopaque medium, performed as described, is a valid method for studying these hemodynamic situations. Early in this investigation it was noted that the contrast medium selectively found its way into the hepatic veins draining the area of injection. This selective visualization was a constant finding in all species.

Based on the previous fact of observation, a concept of the rationale of the method was formulated. It was assumed that broken capillaries of the vascular systems in the area of the intraparenchymal injection offered different degrees of resistance to the entrance of the incoming dye (Fig. 12). In this way, the outgoing capillaries of the hepatic vein system, where there was no head of pressure to oppose the ingress of the contrast medium, were preferentially visualized. This phenomenon of visualization was interpreted to represent actual draining of the intraparenchymal pool of dye rather than an anatomical delineation such as is produced by forceful intravascular injections. It was also assumed that since the portal system was acting in its normal role as an inflow tract, it opposed the entrance of the dye and thus was not visualized. Had the portal system been acting as an accessory outflow tract visualization could have been expected. Further support for this concept was provided by the examinations in the dead animal, where in total absence of flow of blood and heads of pressure, the dye was seen gaining access to both the hepatic and portal vein systems.

In the particular case of the rat, the study of which comprises the main portion of this report, two main factors deserve discussion. In the first place, in the cirrhotic animals the reduced speed of the outgoing flow and the marked retrograde flow into distal branches of the hepatic vein system may be taken as an indication of definite impairment to the exit of blood

from the liver. This diffuse obstruction to the outflow tracts was apparently the result of changes induced by the cirrhotic process and would be in accordance with the postmortem findings of other investigators.[9, 12, 15]

Secondly in these cirrhotic animals, despite severe degrees of obstruction to the hepatic vein outflow tracts, no evidence could be obtained to indicate that the portal vein system was operating as an accessory outflow tract. Even when complete artificial obstruction was added to hepatic outflow by sudden clamping of the vena cava, blood remained confined within a massively dilated hepatic vein system without using the portal pathways as accessory outflow tracts. Although portal backflow was not anticipated in the normal liver of the control animal, it could have been expected to occur in the distorted liver of the cirrhotic animal where abnormal communications between vascular systems have been thought to develop. The consistent nature of these findings may lend itself to speculations questioning the accessory outflow tract role ascribed to the portal vein in cases of human cirrhosis; however, these speculations do not seem warranted on the basis of the evidence so far obtained.

Summary and Conclusion

Under the conditions of these investigations, the radiological visualization of the hepatic outflow tracts produced by the intrahepatic parenchymal deposition of contrast medium appeared to be a satisfactory functional demonstration of the outgoing pathways of the liver. By the use of this method, the operation of the hepatic vein system in rats, dogs, and humans was studied.

In the particular case of the rat, which comprises the main body of this report,

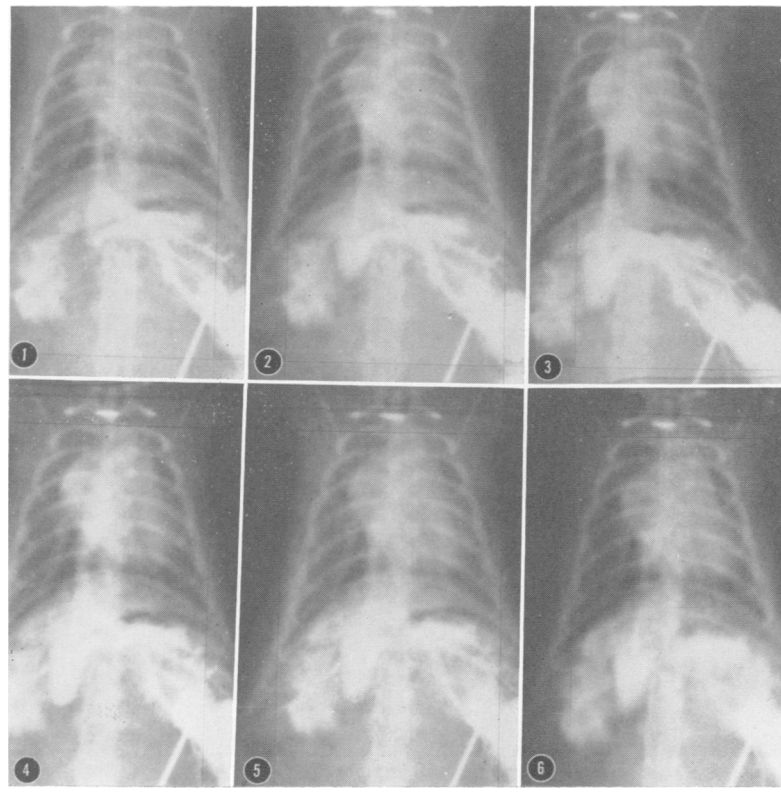

FIG. 9b. In this study, most of the dye remains in the liver. The degree of obstruction to the outflow tracts is revealed more by the extent of backflow and retrograde filling of a severely dilated hepatic vein system than by the speed at which part of the dye reaches the vena cava. Extensive visualization of the hepatic vein system and even reverse caudal flow into the vena cava are seen. Comparison with the normal patterns of outflow shown in Fig. 4, will make pathological changes more evident. (Same animal as in 9a.)

a varying degree of outflow tract obstruction was observed in the cirrhotic animal.

The portal vein system was not demonstrated to act spontaneously as an accessory outflow tract in normal or cirrhotic rats. Not even the addition of complete artificial obstruction of the hepatic vein outflow was followed by reversal of flow into the portal system. Under the latter conditions, reversal of flow was not observed either in the normal liver of the control animal or in the distorted liver of the cirrhotic rat where abnormal communications may have developed.

Entrance of contrast medium into the portal vein system was observed only when the intraparenchymal injection was performed after the death of the animal. This was interpreted to be due to the absence of an active inflow in the portal vein. The

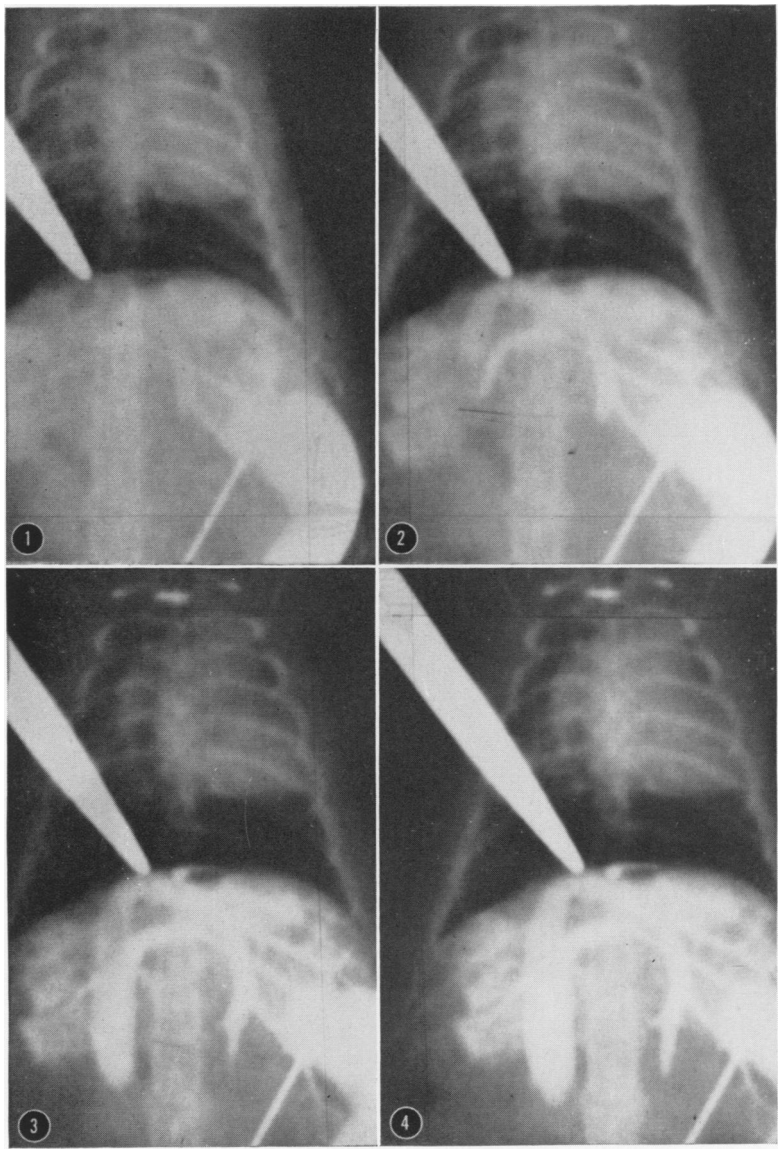

FIG. 10. Sudden occlusion of the thoracic segment of the inferior vena cava in a cirrhotic animal. This is the same animal depicted in Figure 9a and b. Complete obstruction to the outflow tracts of the liver results only in more extensive retrograde flow into branches of the hepatic vein system and the inferior vena cava. Again, no evidence of the portal system being used as an accessory outflow tract can be detected. (The portal anatomy of this animal is depicted in the splenoportogram shown in Fig. 9a.)

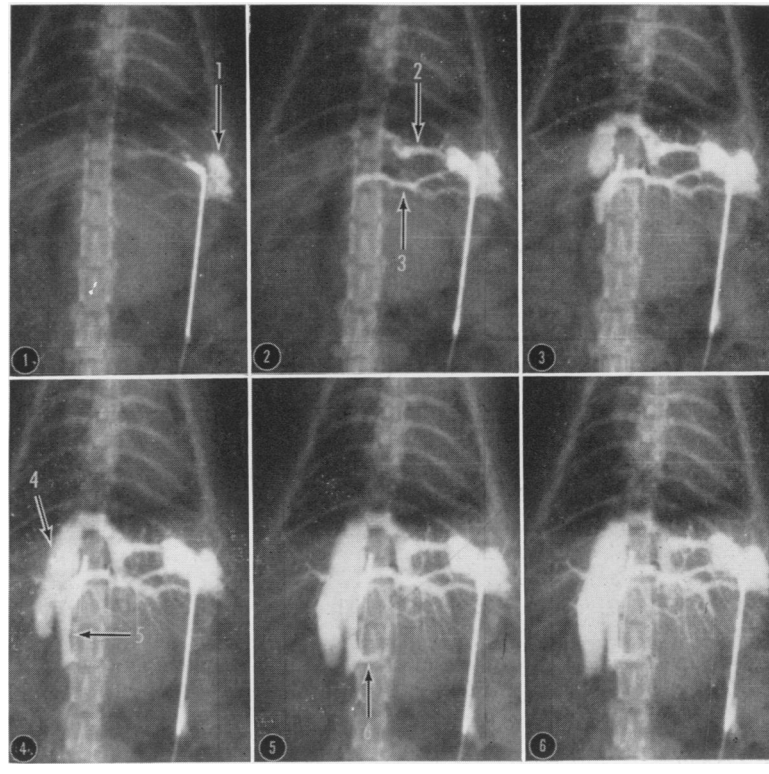

FIG. 11. Intrahepatic parenchymal injection in a dead animal (a series of normal rats was sacrificed for this purpose). Representative films from a multiple exposure radiological study. Films are separated by 1 second intervals. In the dead animal where there was no active blood flow to oppose the entrance of the dye, both the outflow and inflow tracts are visualized. Parallel, progressive, stage by stage filling of the outflow tracts (hepatic veins) leading to the vena cava, and the inflow tracts (portal system) can be observed. Obviously an anatomic and not a hemodynamic demonstration has been obtained. Arrows: 1) pool of dye; 2) hepatic vein; 3) portal branch; 4) inferior vena cava; 5) main portal vein; 6) splenic vein.

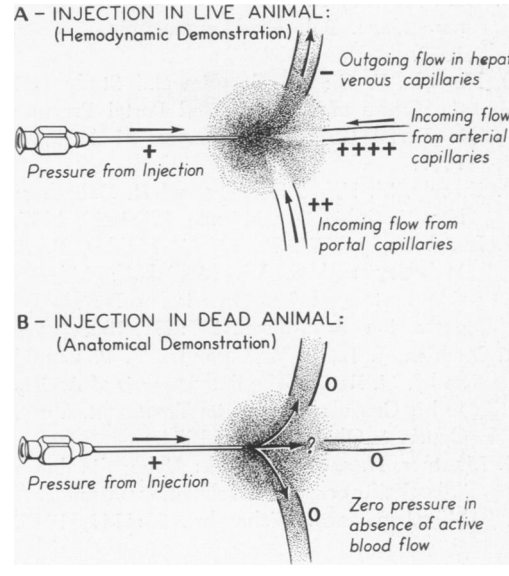

FIG. 12. Diagrammatic representation of the rationale of the method of intrahepatic parenchymal injection of contrast medium. A) depicts the concept of the hemodynamic forces acting during life. Pressure in the inflow vessels (portal and arterial capillaries) opposes the entrance of the dye. The lack of an incoming head of pressure in the outflow vessels (hepatic vein capillaries) permits the dye to be carried in the direction of flow. B) depicts the situation after death. In the absence of hemodynamic forces the contrast medium gains access to ruptured capillary vessels of any system.

same active inflow, even in cirrhotic rats, may have prevented visualization of this system during life.

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