Coronary Radiography and Endarterectomy

Postmortem Study of Feasibility of Surgery

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In 1925, what was probably the first comprehensive clinicopathologic study of coronary heart disease was reported from this medical school by Benson and Hunter. It is more than a quarter of a century later. Though the personnel have changed and though literally thousands of investigators have added to understanding of the problem, the basic concepts of coronary disease then elucidated have not been changed. Fortunately, neither has the therapy. In view of progress in cardiovascular surgery, the current state of angiography, and the frequency and mortality of coronary arteriosclerosis it is now necessary to examine the feasibility of surgical removal of the intravascular obstruction. The present report describes the methods and findings of a continuing 3-year attempt to appraise the problems as well as the potential of such surgery. The planned objective was to use autopsy hearts in determining (a) whether the functional anatomy and carrying capacity of the diseased coronary bed could be improved by surgery, (b) whether coronary angiography offered reliable preoperative means for defining the lesion.

In order to answer these questions, consideration had to be given to the severity and distribution of lesions as well as their physiologic and anatomic correlation with evidence of myocardial ischemia.

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Supported by U. S. Public Health Grants (H-3496 and H-3275), the Oregon Heart Association, and the Mallinckrodt Chemical Works.


Materials and Methods

Unembalmed human hearts removed at autopsy were perfused with kerosene under 100 mm Hg pressure through cannulas tied in the coronary ostia. Individual and combined perfusion rates were recorded and the figures were used to calculate collateral circulation. Coronary arteriography was then performed by either serial direct radiography (6 exposures in 3 seconds) or cinefluorography (9-inch, 5200X intensifier, 16-mm. film, 16 fps). Injections were separately and rapidly given into each coronary artery and consisted of 4 ml. of a conventional type water-base contrast agent containing 48 per cent (w/v) iodine and used at a room-temperature viscosity of 14.4 cps (MI-5373, Mallinckrodt Chemical Works, Inc.). When cinefluorography was employed, conventional direct radiographs were also exposed before, between, and following the injections, the last of these stereoscopically. During angiographic examination, the uncut heart was positioned to approximate as much as possible an "in vivo" frontal radiographic projection and thereby to facilitate comparison with clinical studies made before death or in other patients. In 51 instances, kerosene perfusion was repeated following angiography. In hearts not subjected to "surgery" red and blue latex containing 30 per cent barium sulfate (w/v) was then injected through the right and left cannulas respectively. Following 4 hours submersion in a latex solidifying mixture the hearts were cut open, unrolled, examined radiographically, and dissected. The arteries and their distal ramifications were examined by transverse sectioning, gross and radiographic findings being compared at the time.

In 31 cases, coronary angiography was followed by simulated surgery. Initial efforts at resection and repair by tube grafting exacted a prohibitive toll of branch arteries and were abandoned in favor of endarterectomy through a longitudinal incision.

Results

A total of 189 hearts was studied and, of these, 88 exhibited myocardial infarction and

*Glacial acetic acid, 2 per cent; 95 per cent alcohol, 85 per cent; formaldehyde, 4 per cent; water 9 per cent.
form the principal basis of analysis. The foregoing figures do not indicate the incidence of myocardial infarction in autopsies done at this institution, inasmuch as selection of cases for the study was on a nonrandom basis. This would not be likely to limit the validity of an analysis directly concerned with the character of the disease rather than with its frequency or correlation with other disease.

**Number of Coronary Arteries Involved**

When the main coronary arteries originate normally, the assignment of branch names on the basis of order and direction of branching generally makes possible a "fit" between standard nomenclature and a given set of coronary arteries. While this fit may be nominally perfect, it fails to provide anatomically and functionally consistent terminology appropriate to the important variations that exist. To permit useful tabulation of the number of coronary arteries involved, we have arbitrarily regarded not only the two main coronary arteries but the left anterior descending branch and the less constant left circumflex (or left marginal) branch as separate vessels. The left main coronary artery was often so short as to warrant "name-only" consideration. Considered in terms of its "segments of principal risk," coronary flow takes place via one right and one to three major trunks on the left (with considerable individual variation in the relative roles of these) (figs. 1-4). In every one of the 88 hearts with anatomic evidence of myocardial infarction, there was gross involvement of at least one major branch of the left coronary system. In only seven of the 88 cases of infarction was significant luminal narrowing

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**Figure 1**

*Arteriosclerosis confined to proximal large coronary arteries: A 67-year-old man (autopsy no. 65-MA-59) died 34 days after myocardial infarction. A. Radiograph of injected, cut, and unrolled heart. B. Tracing. Infarcted area shaded. Only vessels of more than 3 mm., outside diameter, were involved by sclerosis (yellow). Arrow points to subacute, incomplete thrombotic occlusion in left anterior descending artery, distal to which there is mixing of right (red) and left (blue) injection masses. Total perfusion rate: 0.5 ml./Gm./min.: calculated collateral 0 per cent.*

**Figure 2**

*Severest encountered instance of distal disease: A 72-year-old man (autopsy no. 61-OA-188) entered the hospital with acute urinary retention, no definite previous history of serious illness, but mild precordial pain; BP 120/80, and mild congestive heart failure. Left axis deviation and nonspecific ST- and T-wave changes compatible with myocardial ischemia. Found dead 1 hour after complaint of weakness. Large, single, acute infarct involves anterior, lateral, and posterior left ventricular walls; patchy myocardial fibrosis present in same area; severe generalized coronary arteriosclerosis extends into many branches. Arrows indicate old left circumflex and recent right coronary artery occlusion. Perfusion rates: right 97 ml./min.; left, 116 ml./min.; both, 200 ml./min. (0.37 ml./Gm./min.); collateral flow 6.5 per cent of total flow.*

**Figure 3**

*Multiple sites of involvement: A 46-year-old man (autopsy no. 61-A-171) whose sudden death terminated 5 years of progressively more severe angina, with episodes of infarction at 4 and 3 years prior to death, and heart failure for 1 year. A and B. Proximal 9 cm. of right coronary artery has multiple irregularities. Distal to three small incomplete thrombotic occlusions (arrows) filling occurs from the left (blue) despite severe involvement of proximal left vessels with old complete occlusion of the anterior descending branch (arrow). C. Prior stereoscopic coronary angiograms had revealed poor filling in this area.*

(See illustrations on pages 192, 193 and 194)
restricted to one vessel. The left anterior descending artery was the most commonly involved (table 1).

There were numerous instances in which arteriosclerotic obstruction involved one or more major coronary trunks in the absence of clinical or anatomic evidence of infarction (fig. 4).

Distribution of Coronary Narrowing

In 85 of the 88 hearts with infarction, coronary narrowing was studied in relation to the size of affected vessels. It was found that in 21 hearts luminal narrowings were restricted to "large" arteries (OD of 3 mm. or more) (fig. 1). In 64 hearts there was irregular, but never uniform and continuous, narrowing of both "large" and "small" arteries (figs. 2 and 3). In not one of the 85 hearts was narrowing confined to coronary arteries less than 3.0 mm. in diameter. Thus, all patients with anatomic evidence of myocardial ischemia also had one or more lesions large enough to be considered operable (table 1).

Total and Collateral Coronary Flow

The ranges and averages in different diagnostic groups for total perfusion rates (ml./Gm. of heart per minute) and collateral flow (expressed as per cent of total flow) were calculated and examined. Total flow was generally lower in infarcted hearts (average 0.44 ml./Gm./min.; 80 observations) than in the infarct-free group (average 0.71 ml./Gm./min.; 95 observations) but overlapping existed. With one exception, the total perfusion rate in infarcted hearts was 0.63 ml./Gm. per minute or less, excluding cases with other significant cardiovascular or pulmonary disease, since these conditions may make the myocardium more susceptible to infarction. In cases without infarction, however, there was great variation, both lower and higher than this, in the total flow rates for all cases. These findings seem to indicate that other factors as well as a low perfusion rate may be significant in the causation of myocardial infarction. Calculated percentages of collateral circulation varied in all groups of hearts up to 28 per cent and in normal hearts up to 60 per cent. Collateral coronary flow was regularly and easily visible by angiography (with either serial films or cinefluorography).

Figure 3C
was also evident through the demonstration at dissection of mixing of red and blue latex injection masses, occasionally in normal and often in infarcted hearts.

Despite a search, correlations could not be found between variables that included total and collateral coronary flow, the type of disease distribution, and the number of major vessels involved. In the entire series there were only two hearts with two distinctly separate areas of myocardial infarction.*

Of the 35 hearts from which perfusion rates were obtained before and after angiography, identical readings were obtained from 12, one had an increase of 147 ml./min. (135 per cent) and 16 had an increase averaging 22 ml./min. 19 per cent; one had a decrease of 113 ml./min. (33 per cent) and five had a decrease averaging 12 ml./min. (5 per cent).

**Angiography**

In nearly all instances, the simulated "in vivo" coronary angiograms provided immediate and important data concerning the site and character of narrowing (fig. 3). Fresh arterial occlusions were sometimes manifest by abrupt total interruption of the opacified lumen, whereas old occlusions generally permitted the passage of small amounts of contrast agent. Probably the use of watery media favored this demonstration of luminal continuity. The use of stereoscopic filming during the injection of contrast agent into unopened hearts has provided invaluable reference material applicable to the interpretation of clinical angiograms in other patients. During the course of this study it became evident that coronary angiography was not

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*Three cases excluded because of inadequate data.

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*In one of these there was involvement of all four vessels and narrowing was limited to large arteries (3.0 mm. or more diameter). Total perfusion measured in this heart was 0.46 ml./Gm./min. and collateral flow amounted to 8 per cent. In the other heart with two infarcts the left anterior descending, left circumflex, and right main arteries showed local proximal involvement and, in addition, patchy, irregular narrowings were also present in small distal branches. In this instance, the total perfusion rate of 0.95 ml./Gm./min. was so far out of line with all other infarcted hearts as to be suspect of technical error. Zero per cent collateral was found.

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Circulation, Volume XXVIII, August, 1963
Severe coronary sclerosis without myocardial effect: A 102-year-old woman (autopsy no. 333-MA-59) died of pneumonia and atelectasis. Electrocardiogram normal. No history of heart disease. The aortic valve leaflets were calcified but movable and apparently normal functionally; calcification of mitral ring; heart weight 324 Gm. The two vessels on the posterior aspect of the right ventricle (arrows) contain injection mass from the left side, but are obviously branches of the right artery. Perfusion data: right, 35 ml./min.; left, 187 ml./min.; both, 207 ml./min.; 0.63 ml./Gm./min.; per cent collateral 7.

only capable of providing reliable information as to the site and nature of coronary arteriosclerotic lesions—it appeared to be the only means for accomplishing this during life. Rarely a seriously narrowed vessel appeared wide open by angiography due to eccentricity of an atheroma that distorted the lumen so as to present a broad radiographic shadow but obscured a marked narrowing in the axis of the x-ray beam. Sometimes periatheromatous flow of contrast agent occurred, reflecting loose attachment at least in part between core and surrounding vessel. Demonstration of this finding during clinical arteriography, especially with forcible retrograde injection, has provided an interesting area for future detailed study. Perhaps the crescent-shaped “artifacts” often referred to by pathologists in describing atheromatous lesions are actually the result of a potential space. The loose attachment may permit some form of hydraulic removal of part or all of some atheromas.

Surgical Resection

Forty-one resections were done in 31 hearts, coronary angiography having permitted the selection of suitable operative sites. It was soon discovered that separation and removal
of intact atheromatous cores were readily possible even when these involved branch arteries or extended several millimeters beyond the mural incisions. The interior surface of the resulting, greatly enlarged, vascular lumen was also smooth while the remaining arterial wall was tough but thin, pliable, and easily sutured (fig. 5). Angiograms and photographs are presented from one case (fig. 6). In the absence of a clotting mechanism it was necessary to supplement the suture line by means of Eastman 910 adhesive (Armstrong) in order to achieve the fluid-tight closure necessary for significant comparison of perfusion rates before and after the procedure. These comparisons are presented in table 2 and demonstrate clearly that coronary endarterectomy is capable of causing increased flow rates in autopsy material.

Discussion

Except for the operative results, many of the observations made in this study are not new. The inferences drawn from them, however, especially those concerning the operability of coronary artery disease, are in conflict with the conclusions of a number of other workers. Szilagyi, McDonald, and France, examined hearts where clinical evidence of arteriosclerotic heart disease had been present, found theoretical rates of 44 per cent for inoperability, 43 per cent for capability of palliation, and only 13 per cent for possible curability. Swedlund, Achor, and Edwards found rates of 30, 52, and 18 per cent respectively for similar categories.

These workers appear to us to have been overly impressed with the frequency of disease in small branch arteries and with the fact that clinically significant coronary arteriosclerosis generally involves all or a majority of main branches. Our findings support both these observations but not the conclusion that inoperability is the result. With reference to small vessel involvement, we find no examples of even, diffuse, and symmetrical luminal narrowing. The arteriosclerotic proc-
**Figure 6**

Postmortem coronary endarterectomy: A 67-year-old man (autopsy no. A-27-62) died 10 days after onset of infarction. A. Preoperative. B. Postoperative. C. About 1 second later in the postoperative injection. Acute infarct of anterolateral left ventricular wall is indicated incompletely by loss of small vessel shadows; its extent is indicated by the series of arrows in A. Left anterior descending artery repaired by 21-mm. incision (large arrows, B). Poor preoperative filling of small vessels, which might have been interpreted as distal disease is improved (small arrows, B). Retrograde filling of right coronary (arrow, C) (no postoperative right injection). Collateral circulation was not apparent preoperatively by angiogram or perfusion data. D. Shows core removed from left anterior descending artery; some fresh thrombus was lost during removal. Photomicrographs (hematoxylin and eosin, X 20, E), cross section of core taken at level indicated in D, and, F (X 23) section of repaired intact vessel.

<table>
<thead>
<tr>
<th>Perfusion data:</th>
<th>Preoperative</th>
<th>Postoperative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right</td>
<td>100 ml./min.</td>
<td>100 ml./min.</td>
</tr>
<tr>
<td>Left</td>
<td>70 ml./min.</td>
<td>138 ml./min.</td>
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<tr>
<td>Both</td>
<td>170 ml./min.</td>
<td>240 ml./min.</td>
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<tr>
<td>ML./Gm./min.</td>
<td>0.39</td>
<td>0.55</td>
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<tr>
<td>Collateral</td>
<td>0</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Perfusion data:

- Right
- Left
- Both
- ML./Gm./min.
- Collateral

Perfusion is notoriously inconstant in its distribution, with great variation of lumen diameter relative to external diameter and with frequent eccentricity in plaque formation. Our findings are in agreement with the well-known view that narrowing is both most severe and
most common in the proximal 3 cm. of the coronary vessels, and that the majority of fresh occlusions are less than 5 mm. in length. It follows that improvement of flow in the main proximal arterial channels will result in better flow through patent distal branches. Relief of proximal obstruction will result in increased collateral circulation via distal branches, even though some branches may be completely occluded (see Results). The fundamental principles of hydrodynamics apply to all segments of the arterial system. Thus, whether it is aortic, carotid, renal, peripheral, or coronary in location, proximal narrowing causes reduced poststenotic perfusion pressure and thereby reduced flow through open distal branches, regardless of size and the presence of subtotal occlusion. Similarly, uncompensated poststenotic hypertension causes diminution in caliber of distal branches if these possess even the slightest elasticity. Even in a highly rigid system, the relief of a proximal obstruction causing a transstenotic pressure gradient will result in increased flow throughout all patent branches. Luminal narrowing is obviously more significant proximally where it affects flow through all distal branches. In our opinion, relief of major vessel constriction is therefore indicated even in the presence of severe distal small-vessel involvement.

In any given case where coronary arteriosclerosis is severe enough to cause myocardial infarction, successful endarterectomy will result in an increased flow capacity for that vessel. Based upon our own observations, the improvement is likely to be greater than 50 per cent, and with practice it may regularly be more than 100 per cent.

The finding that clinically significant cases tend to have involvement of all or most of the main channels seems to us indication rather than contraindication to surgery, for instead of requiring repair of all lesions, it provides the surgeon opportunity to select the lesion most readily approached. This view is supported by the regular presence of collateral circulation under such circumstances and the fact that myocardial infarction usually requires that a majority of the main vessels be involved (table 1). Therefore, in a living patient with clinically evident coronary arteriosclerosis the clear radiographic demonstration of any operable obstruction is an indication for endarterectomy, regardless of the presence of other areas of coronary sclerosis.

Our quantitations for collateral circulation amount to measurements of the degree of anastomosis between the right and left coronary systems. But the amount of blood which a given segment of myocardium might be able to receive from an unnatural supply line after
obliteration of the original line is greater than can be appreciated by this method, as illustrated by the case of figure 1, in which no collateral circulation could be determined by perfusion but in which there was mixing in one vessel of the right and left injection masses. Our relative collateral flow data support a concept of the coronary arterial system as a complex network of small and medium-sized interconnecting channels hanging from a framework of large vessels rather than as separate end arteries. This opinion is supported by many previous observations. Blumgart, Schlesinger, and Davis first noted the lack of correlation between occlusive arterial disease and physiologic or anatomic evidence thereof (i.e., infarction without occlusion, occlusion without infarction, and infarction at a distance are common). If this is valid, our emphasis on total perfusion rates (obtained through perfusing both arteries simultaneously and expressed in ml./Gm./min.) seems to be warranted. Further investigation may be necessary in order to determine the true significance of this rate.

The observed overlap of perfusion rates for different disease categories relates to the limited number of factors tabulated and the common coexistence of myocardial infarction and other significant cardiovascular or pulmonary diseases.

There remain questions likely to be answered only through clinical experience: To what extent will ischemic, acutely infarcted, or partially fibrotic myocardium exhibit functional improvement following improvement in blood flow? How complete an endarterectomy will be necessary or desirable? While dead muscle fibers will not recover, cardiac power can be expected to improve greatly with improved blood flow to the viable remainder. The required improvement may prove to be considerable in some cases and slight in others.

Angiography was an indispensable adjunct of this study and is essential to any clinical approach of a similar nature. In addition to further indicated technical refinements in coronary angiography, such as that promised by percutaneous occlusion aortography, a valuable aid to the selection of cases for surgery is available in techniques for measuring intracoronary pressure, for, regardless of the state of the run-off bed, the demonstration of a transatheromatous pressure gradient provides evidence that successful removal of the obstruction will result in increased coronary flow.

In view of the understandable reluctance of physicians to submit patients to dangerous, clinically unproved major surgical procedures and in order that coronary surgery be given an adequate trial it is suggested that knowledge can be gained from operating on patients in whom heart failure due to myocardial ischemia has led to a point where death can only be forestalled through artificially maintained or assisted circulation.

Summary

Postmortem angiography, kerosene perfusion, latex mass-injection radiographic studies and the conventional methods of anatomic pathology have been used in a study of coronary artery disease in 189 hearts, 88 of which had myocardial infarction associated with coronary arteriosclerosis. Analysis was directed to ascertain whether sclerotic lesions appeared to be amenable to surgical removal and whether such removal is likely to result in an increased flow of blood to the myocardium. Affirmative conclusions to these questions were reinforced by 42 postmortem coronary resections done in 31 cases. Fluid-tight closures permitted follow-up perfusion studies in 25 successful resections done for the relief of coronary luminal narrowing, and in 16 of these significant increase in the perfusion rate resulted. Twelve of these 25 were endarterectomies, and increased perfusion rates were achieved in 10 of them. From the logical standpoint, direct relief such as appears mechanically feasible through surgical endarterectomy offers an attractive therapeutic approach to myocardial ischemia from coronary arteriosclerosis. The presence of multiple main-vessel lesions and of distal
small-branch disease does not preclude significant improvement; these are not contraindications to such surgery.

In view of the frequency and mortality of coronary arteriosclerosis and because of the inadequacies of other methods of therapy in use today, the clinical trial of a direct attack upon the occluding lesion appears to be warranted. Current clinical failures provide opportunities while external artificial circulation and other methods for left ventricular assistance or bypass pumping provide means for gaining surgical experience and offering at least a slim chance to patients whose lives would otherwise be lost. Radiographic studies of the coronary system will be essential to any surgical attack likely to succeed.

References
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Circulation, Volume XXVIII, August, 1958
William Withering

The comparative leisure which those years at Stafford had afforded for scientific pursuits now began to bear fruit, and in the summer of 1776 Withering published his first book and the one on which his reputation as a general descriptive botanist rests. This was entitled "A Botanical Arrangement of all the Vegetables Naturally Growing in Great Britain with Descriptions of the Genera and Species according to Linnaeus." This was the first complete flora of the British Isles in English, the works of Thomas Johnson and Ray and others being in Latin, and the herbal of John Gerard being extremely incomplete. In two volumes and bound in what the booksellers called "old sprinkled calf," it was illustrated with twelve fine copper plates. Included was a description and an interesting picture of a microscope devised by Withering for botanical study primarily. Withering also contributed a description of this microscope and figure to the first edition of the Encyclopaedia Britannica. Withering's botany had many readers and passed through three editions in the author's lifetime. A fourth edition revised by his son and containing four volumes was published in 1818. For fifty years it was extensively read. There were several reasons for its popularity. In the first place, natural history and botany had become popular and fashionable pursuits during the eighteenth century. The works of Linnaeus and Buffon, and the descriptions of the flora of India, China, South Africa, Australia and the New World, sent in by amateur and professional botanists, a large number of whom, by the way, were physicians, and the work of such naturalists as Gilbert White, had given natural history more of a vogue than radio-set making or golf has now. An examination of Withering's work shows many reasons why it should have become a best seller. He devoted much space to matters of interest such as natural places of growth of the plants described, their time of flowering, their economic uses as foods and drugs, and their poisonous properties. Methods of botanical investigation and how to dry and preserve specimens were included in his "Elements of Botany." He also gives the different English names used by the former herbalists Gerard, Parkinson, Blackwell, Culpepper and others. His book was in effect a translation of the herbalists in scientific form but written in English and not in Latin, and it was the first time that a really scientific classification and description of British plants had been published in the vernacular.—Louis H. Roddis, M.D. William Withering: The Introduction of Digitalis into Medical Practice. New York, Paul B. Hoeber, Inc., 1936, p. 34.
Coronary Radiography and Endarterectomy: Postmortem Study of Feasibility of Surgery
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Circulation. 1963;28:190-202
doi: 10.1161/01.CIR.28.2.190

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