The Human Bronchial Circulation in Health and Disease

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Foreword

The last 25 years have witnessed an unprecedented growth of all forms of medical knowledge. In thoracic surgery great technical advances have been made and these have led to a demand for more and more information about abnormalities of respiratory function. As a result an ever growing interest has been aroused in the long neglected fields not only of abnormal but also of normal respiratory function and many new methods of investigation have been derived. No field of medical advance better illustrates the truth that the structure and function of any organ are indissolubly associated and that combined anatomical, physiological and pathological studies, such as those presented in this book, can provide invaluable contributions towards the better understanding of disease processes.

The bronchial-arterial circulation, for so long a neglected or at best a controversial subject among anatomists, has now been shown by Dr. Cudkowicz to play a most important part in pulmonary disease. By combining information obtained during life by means of the newer methods of investigating cardiopulmonary function with that provided postmortem by the older methods of morbid anatomy, he has demonstrated the important role of the bronchial circulation in such divergent conditions as, to name but a few, bronchiectasis, pulmonary hypertension, lobar pneumonia and lung cancer.

His study of the bronchial circulation has led Dr. Cudkowicz to investigate other related matters. From being regarded as organs almost entirely concerned with respiration the lungs have now been shown to possess other functions some of which can still be no more than vaguely guessed at. In a series of investigations of patients with finger clubbing the author has found indirect evidence for the existence of a causative humoral agent which normally is probably destroyed in the lungs but circulates generally when pulmonary vascular shunts are present. He has also studied the pulmonary nerve supply—a much neglected system—in relation to its probable function in regulating the lung circulation.

Dr. Cudkowicz is to be congratulated on the clarity with which he

presents the results of the painstaking studies he has made over a period of many years. His book provides in accessible form much new information about the bronchial circulation in both health and disease. It will also serve as a stimulus and a model to those interested in the many still unsolved problems of respiratory pathophysiology.

H. SPENCER, M.D., Ph.D., F.R.C.S., F.C.Path. St. Thomas' Hospital, London

Preface

The structural relationship between the bronchial and pulmonary circulations engaged the interest of numerous investigators for many centuries and essential contributions were derived from the anatomical approach, particularly in the last 15 years. The extraordinary speed with which both the human heart and lungs have been explored by clinical investigation and modern surgery in the course of the last decade, also sharply brought into focus the functional difference between the two circulations in the human lung. Whereas the functions of the pulmonary circulation alone understandably influence the major efforts of pathologists, surgeons and clinical investigators, those of the bronchial circulation remain in relative obscurity. Much of the physiological information concerning the bronchial circulation has necessarily been provided by experimental animals and data from this source have slower access to clinical thought and require critical scrutiny prior to their clinical acceptance. Nevertheless the impact of techniques enabling the study of the bronchial circulation to be conducted in man itself, and the surgical observations during thoracotomy and open heart surgery contributed to the quest for a closer understanding of the functional significance and possible practical importance of the bronchial circulation in man.

The lung, like the liver, is an organ which possesses a dual circulation, and the bronchial arterial circulation, like the hepatic and the coronary arterial circulations, subserves the metabolic needs of the lungs. At the same time it comes into hemodynamic relationship with the major pulmonary circulation. The bronchial flow component streaming into the pulmonary veins augments the left ventricular inflow from the pulmonary arteries and thus alters the respective minute flows of the two ventricles. This unbalance of the ventricular minute flows is particularly large in such disorders as bronchiectasis, and resembles a snall patent ductus arteriosus. In total agenesis or occlusion of a pulmonary artery, the bronchial arterial collateral flow is sufficiently large to participate in effective respiratory gas transport. A large bronchial venous component to the pulmonary veins is calculated to reduce the arterial oxygen tension and the

viii PREFACE

true significance of this physiological fact, particularly in such diseases as tuberculosis and primary lung cancers, still requires adequate elucidation. Apart from the compensatory enlargement of the bronchial circulation in different lung disorders and the effects of this on overall lung function and pulmonary hemodynamics, an equally intriguing and possibly more practical problem is posed by the concept of a compromised systemic blood supply to the lungs. The information concerning lung ischemia in man is very slender, but the use of temporary bypass procedures in open heart surgery without a vent of the left atrium, and future lung replacement surgery, are calculated to bring this problem to attention and to quantitative analysis. Refinements of technique for the measurement of bronchial arterial blood flow in man are needed in order to have reliable estimates of reductions from normal bronchial arterial blood flow, which would permit the concept of lung ischemia to become applicable to such clinical disorders as pulmonary emphysema.

Some of the material incorporated in this book has appeared in various journals but is discussed again in the light of new data in a rapidly expanding field. The references selected are by no means exhaustive and represent the scaffolding deemed essential to a discussion of the human bronchial circulation. It is sincerely hoped that the inevitable omissions, particularly in the experimental field, will not engender the ire of the many investigators unnamed but sharing a common interest.

It gives me great pleasure to express my gratitude for earlier collaboration to Dr. J. B. Armstrong, Dr. D. F. Wraith, Dr. F. D. Gray, Jr., the late Dr. A. Field, Dr. R. Nims, Dr. M. Calabresi, Professor O. Storstein, Dr. G. Levinson and Dr. W. H. Abelmann.

I would also like to thank Sir John McMichael, F.R.S., Professor J. Crofton and Professor B. Lennox for providing facilities for the early investigations at the Royal Postgraduate School of Medicine, London, England.

The physiological studies concerning the measurements of bronchial arterial blood flow would have been impossible without the generous support, lively discussions and skillful help which I experienced during the tenure of fellowships in the United States at the Departments of Pathology and Internal Medicine, Yale University School of Medicine, and the Thorndike Memorial Laboratory, Harvard Medical School. For these opportunities I would like to thank Professor A. A. Liebow and Dr. Frank D. Gray, Jr. at Yale and Dr. L. Ellis and Dr. W. H. Abelmann of the Harvard Medical Service, Boston City Hospital.

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PREFACE ix

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L. C.

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Surgery, Gynaecology and Obstetrics, Figure 2.1

Thorax

Figure 1.4

Figures 2.2, 2.4, 2.6, 2.7, 2.9, 2.10, 2.11, 2.12, 2.14, 2.15, 2.16, 2.17, 2.18, 2.19, 2.21 and 2.22

Figures 6.5, 6.6 and 6.7; Tables 6.1, 6.2, 6.3, 6.4 and 6.5

Figure 8.4

Figures 9.4, 9.6, 9.7, 9.8, 9.9, 9.10, 9.11, 9.12, 9.15, 9.16, 9.17, 9.18 and 9.19: Tables 9.1 and 9.2

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Many members of the Cardio-Pulmonary Laboratory, Dalhousie University, have been of great assistance in the many studies published from this laboratory. I would like, in particular to thank Dr. A. O'Neill and Dr. J. Holland as well as Mrs. J. Gopaul, née Thomasson, for her skill in carrying out routine blood gas analyses and lung function tests. Finally I wish to express my gratitude to the Librarian, The Royal Society of Medicine, London, for the provision of some of last century's references; the Canadian Heart Foundation, the Canadian Tuberculosis Association and the Medical Research Council of Canada for their support of the research programs conducted in the Cardio-Pulmonary Laboratory, Dalhousie University.

Key to Tables*

| RR—Respiratory rate/minute |
|--|
| TV—Tidal volume in milliliters |
| \dot{V}_A —Alveolar ventilation in liters/minute |
| VC—Vital capacity in milliliters |
| MBC—Maximum breathing capacity in liters/minute |
| V_{PD} —Physiological dead space in milliliters |
| \dot{V}_E —Minute ventilation in liters/minute |
| RV—Residual volume in milliliters |
| TLC—Total lung capacity in milliliters |
| I_{IPM} —Index of intrapulmonary mixing for percentage of N_2 |
| FRC—Functional residual capacity in milliliters |
| D _L co—Pulmonary diffusing capacity for carbon monoxide in milliliters/ |
| minute/1 millimeter of Hg |
| MPAP—Mean pulmonary artery pressure in millimeters of Hg |
| MPCP—Mean pulmonary capillary pressure in millimeters of Hg |
| TPVR—Total pulmonary vascular resistance in dynes/second ¹ /centi- |
| meter ⁻⁵ |
| PAR—Pulmonary arteriolar resistance in dynes/second ¹ /centimeter |
| \dot{Q} —Cardiac output in liters/minute |
| QRV—Right ventricular output in liters/minute |
| QLV—Left ventricular output in liters/minute |
| QBF—Bronchial arterial blood flow in liters/minute |
| QBF _{precap} .—Anastomotic precapillary bronchopulmonary blood flow in |
| liters/minute |
| $\dot{Q}BF_{\text{Postcap}}$. Bronchopulmonary venous anastomotic flow in liters/minute |
| pAo_2 —Alveolar oxygen tension in millimeters of Hg |
| pAco ₂ —Alveolar carbon dioxide tension in millimeters of Hg |
| paO ₂ —Arterial oxygen tension in millimeters of Hg |
| paco ₂ —Arterial carbon dioxide tension in millimeters of Hg |
| pA-ao ₂ —Alveolar-arterial oxygen gradient in millimeters of Hg |
| pA- a CO ₂ —Alveolar-arterial CO ₂ gradient in millimeters of Hg |
| 2 Branches Williams |

CaO₂—Oxygen content in arterial blood in volumes %

 $C\bar{v}o_2$ —Mixed venous oxygen content in volumes %

Caco₂—Carbon dioxide content in arterial blood in volumes %

Cvco-Mixed venous carbon dioxide content in volumes %

RO—Respiratory quotient

 \dot{V}/\dot{Q} —Ventilation/perfusion ratio

TVC-Timed vital capacity in milliliters after 1, 2, and 3 seconds

AVI—Air velocity index or percent of MBC/percent of VC

Vo₂—Oxygen consumption in milliliters/minute

VCO₂—CO₂ elimination in milliliters/minute

 \dot{V}_{DS} —Dead space ventilation in liters/minute

BSA—Body surface area in square meters

SV—Stroke volume in milliliters/heart beat

* All lung and respiratory volumes are expressed at *BTPS* (body temperature/ambient barometric pressure/full water vapor saturation) whereas Vo_2 and Vco_2 are given at STPD (0°C./760 mm. Hg/dry.

Contents

| Fo | reword | v | |
|---------------|--|------|--|
| Preface v | | | |
| Ac | knowledgments | ix | |
| Ke | y to Tables | xi | |
| 1 | A Historical Review of the Bronchial Circulation | 1 | |
| 2 | The Anatomy of the Normal Human Bronchial Circulation | 28 | |
| 3 | The Physiology of the Normal Bronchial Circulation | 61 | |
| 4 | The Pharmacology of the Normal Bronchial Circulation | 84 | |
| 5 | The Measurement of Bronchial Arterial Blood Flow in Man | 105 | |
| 6 | The Embryology and Behavior of the Bronchial Circulation in | | |
| | Congenital Abnormalities of the Heart and Pulmonary Circula- | | |
| | tion | 138 | |
| 7 | The Bronchial Circulation in Lobar Pneumonia | 158 | |
| 8 | The Bronchial Circulation in Bronchiectasis and Pulmonary | | |
| | Infarction | 174 | |
| 9 | The Bronchial Circulation in Pulmonary Emphysema and | | |
| | Chronic Bronchitis | 197 | |
| 10 | The Bronchial Circulation in Pulmonary Tuberculosis | 229 | |
| 11 | The Bronchial Circulation in Lung Tumors | 251 | |
| 12 | The Bronchial Circulation in the Collagen Diseases | 270 | |
| 13 | The Bronchial Circulation in Pulmonary Hypertension | 295 | |
| 14 | The Bronchial Circulation and the Innervation of the Lung | -319 | |
| 15 | Finger Clubbing and the Bronchial Circulation | 337 | |
| 16 | Clinical Aspects of the Bronchial Circulation | 379 | |
| Ind | dex of References | | |
| Subject Index | | | |
| | | | |

1

A Historical Review of the Bronchial Circulation

The classical monograph by Miller (1) gives an admirable review of the history of the bronchial circulation. Miller points out that Galen (2) (A.D. 130-201) first observed systemic blood vessels to the lung but failed to name them. In the *Tractat de Arteria et Vena Dissectione* he wrote: "Arteria, quae secundum vertebras dorsi descendit, prima et tenuis propago, devitur ad thoracis partes, quibus pulmones adjacent, extremo vero abeunt in asperam."

Columbus (3) in 1559 disagreed with this contention, and stated categorically that the aorta does not send branches to the lung: "Ab aorta arteria ramus nullus, neque magnus, neque parvulus ad pulmones mittitur"

Dominico de Marchettis (4) in 1654 renewed interest in these vessels and discovered not only arterial but also venous radicles emerging from the lung and fusing with the systemic venous channels of the thorax.

In Anatomia Patavii he wrote: "Venas arterias possident pulmones, tum ob arteria venosa, tum a vena arteriosa, quae ut diximus per substantiam pulmonun dirimuntur sed observabiles sunt duae, aut res arteriae ab arteria magna productae, quae substantium pulmonum propagantur."

Little more was heard of the bronchial circulation until Ruyisch (5), who claimed for himself the primary honor of discovering the bronchial arteries. "Adac arteriam a nemine adhunc esse observatami intrepide affirmo." In his *Epistola Anatomica* in 1696 he denied the existence of bronchial veins.

The functional significance of these arteries appears to have remained unknown until 1808 when von Sömmering and Reisseissen (6) defined the bronchial arteries as "die vasa nutritia der Lungen."

Thus a great deal was written before the 19th century regarding the anatomy and possible physiological significance of these structures, but no references appear in these texts to the remarkable observations made on the bronchial circulation by Leonardo da Vinci nearly 500 years ago.

Leonardo da Vinci and the Bronchial Circulation (7)

In the Quincentenary Exhibition held in 1952 at the Royal Academy, London, and devoted to the drawings of Leonardo da Vinci, exhibit 301 showed a reproduction (7) of a drawing from the Quaderni d'Anatomia II. I.r., Royal Windsor Library (Fig. 1.1), in which Leonardo depicts the heart, the coronary arteries, the tracnea and the bronchial tree of the left lung with its accompanying bronchial arteries. The bronchial arteries are shown to arise from the aorta and to follow the individual bronchi to their termination (Fig. 1.2).

In the same drawing (see Figure 1.1) a circle, which surrounds a terminal basal bronchus, is seen at the inferior margin of the lung. A line runs from this circle to the adjacent script which, translated on p. 85 of the Catalogue, (8) reads as follows: "Nature prevents the rupture of the ramifications of the trachea by thickening the substance of this trachea and making thereof a crust, like a nutshell, and it is cartilaginous and in the interior remains dust and watery humour." This, the Catalogue emphasizes, is one of the "earlier descriptions of a tuberculous cavity" (Fig. 1.3).

Closer scrutiny of this cavity (see Fig. 1.3) reveals the additional and somewhat distorted features of small bronchial arteries within its periphery. It is impossible to say whether Leonardo deliberately intended to show these systemic arteries reaching the walls of the cavity, or whether the vessels depicted were merely branches destined to follow the bronchus containing the peripheral cavity. The latter explanation is probably the more likely.

Microscopy of the vasculature in the vicinity of tuberculous cavities has shown that the pulmonary arteries in the surrounding lung have usually undergone occlusive changes, and that the only true patent arteries in the walls of tuberculous cavities are dilated bronchial arteries (9).

The circle indicating tuberculous cavitation in Figure 1.3 is, therefore, of some interest in that it indicates, either by chance or deliberately, Leonardo's awareness of the existence of cavities, their relationship to . the bronchial tree and possibly also their correct blood supply (Fig. 1.4).

Keele (10) in 1952 in his monograph on Leonardo's study of the heart and blood reproduces this same drawing and, as in Figure 1.1, quotes from Leonardo's notebooks relevant passages appertaining to the bronchial circulation:

"Why nature duplicated artery and vein in such an instrument one above the other, finding themselves for the nourishment of one and the same member (the lung)."



Fig. 1.1. Drawing by Leonardo da Vinci from the Quaderni d'Anatomia H. I.r., Reproduced by gracious permission of Her Majesty Queen Elizabeth H.

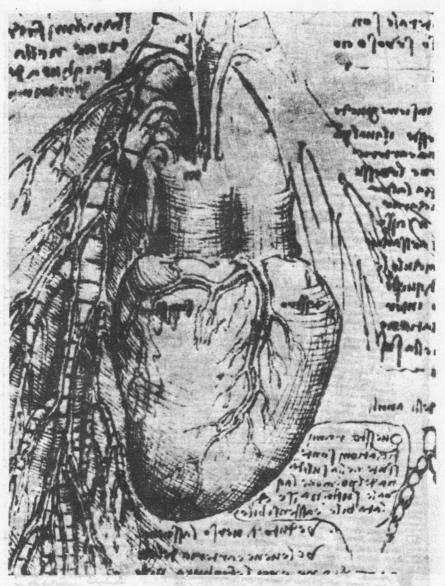


Fig. 1.2. Detail of drawing by Leonardo da Vinci of the heart, aorta and left bronchial arteries. The aortic origin of the left bronchial arteries is depicted as well as their course along the bronchial tree. (This is a mirror image drawing, therefore showing the apex of the heart and the aorta on the right hand side.) Reproduced by gracious permission of Her Majesty Queen Elizabeth II.