Julius Jeffreys and the physiology of lung volumes

by D. Zuck

Last year I spoke about Julius Jeffreys, who invented the principle of the heat and moisture exchanger, and on whose volute humidifier John Snow based his first ether vaporizer. (1) Towards the end I mentioned that in 1843 Jeffreys had published a book entitled Views on the Statics of the Human Chest, (2) but that to discuss it was a subject in itself.

When I started to read it I was astonished to see that Jeffreys appeared to have made three fundamental contributions to the understanding of lung volumes for which he nowadays receives no credit at all. I had been taught, and I suppose like everyone else I believed, that the study of lung volumes, at least in their modern aspect, had originated with John Hutchinson, who demonstrated his spirometer, and published his first reports, in 1844. (3) Hutchinson's last work on this subject was published in 1846, (4) after which I think it is fair to say that virtually nothing of an original nature was done in this field for almost one hundred years. So it was a great surprise to find that Jeffreys had apparently anticipated some aspects of Hutchinson's work by a year or two, and that he demonstrated a far greater understanding of its physiological implications.

We are all familiar with the modern diagram that appears in the physiology textbooks to illustrate the relationship between the various lung volumes. But this dates back only to 1950, when the meeting of respiratory physiologists was held at which it was agreed to standardize the nomenclature. (5) Those who learned physiology before then will remember that what we now call the inspiratory and expiratory reserve volumes were known as the complementary and supplementary volumes, or in some textbooks complemental and supplemental, and some of us often had difficulty remembering which was which. I had always assumed the terminology to have been part of Hutchinson's package deal. But now here was Jeffreys giving what appeared to be the first coherent account of what we would today understand as lung volumes, complete with his own nomenclature, which remained in use for over one hundred years.

However, being very careful nowadays about attributing priorities, I felt it would be wise to look into the history of research into lung volumes. It soon became obvious that this is a subject in its own right, and could only be briefly summarised here.

For convenience, because there was no accepted nomenclature until after
1843, I may from time to time anachronistically use modern terminology; I hope this won't cause confusion.

The early researchers
The seventeenth century Italian mechanistic physiologist Borelli is credited with being the first to attempt to measure what we now call tidal volume. His work was published posthumously in 1680. The English physician James Jurin repeated and refined his method, and also demonstrated 'that there is more air in the lungs that can be expelled by an ordinary expiration.'

Stephen Hales measured the dead space of a calf's lungs by filling the air passages with water, and he also tried to measure the total pulmonary capacity by inflating the lungs under water and measuring the volume displaced. (6) He also recognised the existence of the residual volume.

The person generally and erroneously credited with initiating the study of lung volumes is Edmund Goodwyn. (7) Goodwyn measured the residual volume in several cadavers, by collapsing the lungs and filling the pleural cavities with water. He showed that even after a complete expiration the lungs contained a considerable volume of air. To measure the volume of an ordinary inspiration he devised an apparatus in which air drawn from a closed metal container was replaced by water drawn into it through a tube; the water was then weighed, and the volume calculated. So Goodwyn had measured the residual volume, the tidal volume, and was aware that a larger volume than tidal could be inspired. Most writers credit him with being the first to describe and measure the residual volume but as we have seen, Hales had recognised it before this. Goodwyn's treatise had a practical purpose, resuscitation from asphyxial death, and attracted a lot of notice.

The work that became accepted as a standard was published by Robert Menzies in 1790. (8) He used an allantoid, a large membranous container, of known volume, to measure the tidal air. He breathed into it via a valved connector until it was full, and calculated the tidal volume by dividing the known volume of the container by the number of breaths. He checked his results by a plethysmographic method, immersing a man in a hogshead of water up to his chin. He may have been the first to use this technique. Although little known today, Menzies' work was widely accepted, and quoted in the physiology textbooks as the most accurate available, for the next forty years.

A quite different method of measuring lung volume was used by Humphry Davy. (9) The method that he invented, breathing an inert gas, hydrogen, and
calculating the lung volume from the percentage and quantity that remains in them, is in principle still in use today. Allen and Pepys during 1808-9 (10,11) showed that successive samples taken during a single exhalation contained different proportions of oxygen, nitrogen, and carbon dioxide, so establishing the difference between dead space and alveolar air. They then went on to a remarkable study of nitrogen washout. Thackrah (12) measured the vital capacity of flax workers, and showed that it was reduced to a third of that of healthy persons.

So what was the approach to this subject at the beginning of the 1840s? The most highly regarded physiology textbook was Bostock's *Elementary System*, first published in 1826. This devoted 14 pages to the subject of lung volumes, much of it a review of previous work, taken largely from the *Essay on Respiration* that he had published in 1804. Bostock discussed the average bulk of a single inspiration, which we now call the tidal volume, and showed that he was aware also of the residual volume, and the expiratory and inspiratory reserve volumes. He doesn't attach any special names or significance to these volumes, and describes them only as observational phenomena; but he does suggest further lines of research.

Bostock's book was gradually replaced by the more modern textbook written by William Carpenter, *Principles of Human Physiology*, the first edition of which was published in 1842. Carpenter's whole discussion of lung volumes is 22 lines long. It is mainly concerned with listing the discrepancies between the various attempts to measure the volume of what he calls the ordinary respiratory movement. Clearly he was profoundly uninterested in the subject.

**Jeffreys' Contribution**

Jeffreys' book was published in the following year, 1843, but had been in preparation for some time, because it was to have been the introduction to the series of papers on Artificial Climates that he had been persuaded to publish separately in the London Medical Gazette. (13)

He begins by explaining that people have hitherto studied the contents of the chest, liquid, or blood, and gaseous, separately, and have obtained only a partial view of their importance. By the term *Statics* he intends to denote a comprehensive study, encompassing the relations and proportions that these contents bear to each other. He
could have used the word Condition, or Status, but this, he says, is scarcely yet an English word. Since Statics is the accepted term for the balance of pressures, and the maintenance of the condition of things, which is his subject, that is the word he has chosen.

He continues on page three:

Every time a person yawns or sighs an experiment is unconsciously made, and a curious and important fact declares itself, inviting further attention. . . . Without the aid of any nice apparatus to determine the quantities concerned, every person may, and often unconsciously does, make the following experiment. At the moment when he has completed an act of inspiration . . . he may . . . [instead of breathing out] force himself to continue to inspire air, when he will find that his chest can take in, before it is distended, a quantity of air very much larger than that of any ordinary breath.

Again, after an act of expiration, at the moment when he would instinctively inspire, he may, instead . . . continue to breathe out for a great length of time . . . [and] . . . if it has not occurred to him to make the experiment before, he will find to his surprise, that, [when he supposed his chest to be empty,] it still contained a vast quantity of air.

He continues that the mechanism of the chest is such that there is still a considerable quantity of air which cannot by any effort be expelled. This is the quantity which remains in the body after death. To these several quantities we have to add the space occupied by the air of ordinary respiration. . . . We have then before our view four distinct quantities, which it is necessary we should distinguish by certain terms by way of reference.

Commencing with the bulk of air which we cannot expel, and which remains in the body after death, we may call this by a term which has been employed by others – the residual air. Then we have, on the top of this, the large bulk, which we can expel after an ordinary outward-breathing; this may be named the supplementary air, it being the quantity filling the chest below the region of respiration. Upon this comes the ever-fluctuating air of respiration, which, in its influent state, may be known as "the fresh breath," and in its effluent state as "the stale breath." [Later he uses the expression "tidal or respired" air, and appears to have been the first to do so.] Over and above all this we have the capability of the chest to receive, when the fresh breath is already in, the occasional quantity which enters with a yawn or a sigh, and which may be termed the complementary air.

When we shall duly consider the importance of each of these several bulks of air, the fact must appear curious that it is the breath alone which is made the subject of speculation, and upon which the present theories of respiration up to the present hour are built.
He goes on to review the values arrived at for these volumes by earlier researchers, and mentions his own researches, which, he says, involved numerous trials, carefully made, with an apparatus constructed to insure accuracy, but about which he gives no information at all. The one volume he omits, and shows no recognition of, is the Dead Space, and this was to lead him rather astray, as we shall see.

He gives the following as being in his opinion the best values, derived from his own and the researches of others.

<table>
<thead>
<tr>
<th>Cubic inches</th>
<th>cc equivalent</th>
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<tbody>
<tr>
<td>Residual air</td>
<td>120</td>
</tr>
<tr>
<td>Supplementary air</td>
<td>130</td>
</tr>
<tr>
<td>The Breath</td>
<td>26</td>
</tr>
<tr>
<td>Complementary air</td>
<td>100</td>
</tr>
</tbody>
</table>

He next points out that Bostock has already expressed surprise "with good reason" that the large volume "which I have ventured to name the supplementary air," has been overlooked by a number of writers, including the great Liebig, all of whom regard the total volume of the chest as being made up of the residual air and the air of respiration. But since during normal breathing the lungs contain both the residual and the supplementary air, he proposes that these two volumes be called the resident air. Nowadays, of course, we call this the functional residual capacity (FRC).

Now, he continues, (and here he begins to go astray in two directions), because physiologists have always concerned themselves with the tidal volume only, they have assumed that it is this air only that enters the alveoli at each breath and effects changes on the blood gases. But there is no way known to physics whereby fresh air introduced through the throat can shoulder aside the gases already present in the lungs, and enter the alveoli. The fresh air of each breath must gradually mix with the resident air, descending further and further into the lungs.

Similarly the stale air will gradually ascend and be exhaled. The advantage of such an arrangement is that the alveolar gases reach a state of homeostasis, and can exchange smoothly with the blood during all stages of the respiratory cycle. In contrast, the current view implies that gaseous exchange with the
blood will be constantly fluctuating, being maximal during inspiration and minimal at the end of expiration. To be efficient this would require a tidal flow of blood through the pulmonary vessels to match the varying supply of oxygenous air. But we know that there is no sudden ebbing and flowing of blood through the lungs to correspond with the extreme ebbing and flowing of the breath. So now we may surely perceive the beauty of the arrangement which lodges a large quantity of resident air in the chest.

At this point he embroils himself in the sort of circular argument that he was occasionally prone to, by following a mistaken premise to its logical conclusion. If fresh air is much diluted before it reaches the depths of the lungs, it follows that the concentration of gases is much different at that level. We know that exhaled air contains about 5% carbon dioxide; therefore in the alveoli it must contain more, perhaps 10% – and hence only 10% oxygen, since the nitrogen percentage is invariable. Now our first instinct is to reject the idea that the air in the alveoli, which after all is where gaseous interchange with the blood is taking place, can be so stale, but logically it must be so. Since it is so, the Creator must have had a good reason for making this arrangement, and the reason can only be that a higher content of oxygen than 10% would be harmful to the delicate lining of the lungs; and this is why the Creator had provided the resident volume, to dilute the atmospheric air to a safe level.

He continues with a discussion of the functions of the various volumes. The resident air is important because, as we have just seen, it dilutes the tidal air, diluting also any irritants that it might contain, and allowing also for warming and humidification. Then he points out that normal breathing takes place at a certain position in the range of total lung volume, and asks why this is so, whether it varies from time to time in the same individual, and whether it occupies the same locality in all persons. For example, we could breathe only on our residual air, and we can do so voluntarily for a brief period. But this would exclude the diluting effect of the supplementary volume, and also would cause the pulmonary vessels to become convoluted and compressed, so that the circulation would become obstructed, as in the foetal lung.

The reason why we do not normally breathe with a full chest, at the top of the complementary volume, is that our demand for air fluctuates, as during exercise, or coughing, or when we are drowsy and need to yawn. Also, both complementary and supplementary spaces may be required during speech, and are essential for the art of oratory, and for the playing of wind instruments.
As regards variations in the location of the tidal volume in the range of total lung capacity, he points out that the chief muscles of the trunk arise from the chest wall, and the larger their base, the greater their power; so that if we wish to make a considerable effort, we take a deep breath first, and retain all or most of it. It follows that people who are accustomed to heavy work or strenuous exercise tend to be deep- or broad-chested, with a larger volume of supplementary air, and a greater potential capacity for complementary air. He concludes that he is quite sure, from his experiments and observations, that the location of ordinary breathing in the range of total lung capacity, varies between persons, and in the same person in different circumstances. In general, both in health and disease, he thinks it is an advantage to have a large volume of resident air, and he suggests exercises to this end. (Flow-volume studies during the past thirty years [13,14] have demonstrated that in conditions where the elasticity of the lungs is decreased, as in asthma, emphysema, or chronic bronchitis, patients usually increase their end-tidal volume, which is to their benefit because airway resistance decreases as lung volume increases. Doctors also cause an increase in FRC by the application of positive end-expiratory pressure (PEEP.)

Conversely, Jeffrey's continues, sedentary workers tend to have a smaller resident volume, especially those who sit doubled over at their work. He mentions the work of Thackrah, and his own visit to Sheffield to study the effects of stone and steel dust on the lungs of the cutlery grinders. He is scathing also about the effects on young women of tight lacing, whose folly nearly reduces the figure to that of an insect, and whose countenance betrays the state of the lungs.

Jeffreys had obviously thought deeply about so much, that we may be surprised that he didn't make the simple comparison of the volume of the anatomical dead space, which had already been estimated by others, with the tidal volume, and so have demonstrated to himself that more than half of each breath must indeed enter the alveoli. Also he had disregarded the anatomy of the tracheo-bronchial tree, with its insertion into the lung hilum, and instead visualised successive tidal volumes diffusing into the lungs from the apex downwards; and of course he knew nothing about velocity profiles in fluid flow, which to some extent determine mixing and the tidal component of alveolar ventilation. Nevertheless he seems to have been the first to demonstrate an appreciation of the importance of perfusion matching ventilation, something that was not seriously taken up again until at least the 1930s, if not later.

**Jeffreys' Influence**

Publication of Jeffrey's book brought an attack from a Dr. Calvert Holland,
already well known for his argumentative approach to life, alleging that Jeffreys had plagiarised the idea of the pulmonary mixing of air from one of his own writings. Jeffreys replied politely but entertainingly, saying that he had been quite unacquainted with Holland's book, and pointing out, quite correctly, that in any case there was no similarity at all between what Holland had suggested, and his own thesis.

I have mentioned only two contemporary physiology textbooks, but I have looked at several others, Alison's and Blumenbach's for example, and there is nothing resembling Jeffreys' account in any of them. By comparison their approach is primitive. Even Hutchinson, in the following year, 1844, in his first accounts of spirometry, (3) said that he had confined himself to determining, 'what quantity of air we are able to expel from the lungs by the greatest voluntary effort we are capable of exercising. Owing to the various terms given to designate the different divisions of respiration, I have found it difficult to separate this division from the chaos of physical experiments hitherto made upon the lungs. . . . I have used the term "capacity" to signify the quantity of air which an individual can force out of his chest by the greatest voluntary expiration, after the greatest voluntary inspiration.'

Hutchinson was only interested in using what he called 'capacity,' and the maximum attainable intrathoracic pressure as measured by a sustained expiration into a mercury manometer, as indicators of lung disease. (4) He knew that the capacity varied considerably in the healthy, and he was able to show a direct relationship between capacity and height. It was his ability to predict accurately the capacity of any healthy individual, and to confirm it with his spirometer, that made such a great impression on his first audiences. But by 1846 Hutchinson also was describing the lung volumes, and denoting them residual, reserve, breathing, and complemental air, the last three comprising what he now called the vital capacity. Surely it is a little too much of a coincidence that he was now adopting both Jeffreys' approach, and with a slight modification, part of his terminology.

The eclipse of all earlier work, including Jeffreys' contribution, I think we owe mainly to Kirkes's Handbook of Physiology. First published in 1848, it ran through about twenty editions, eventually becoming Halliburton's, and still on the go up to the 1940s, so it must have influenced several generations both of students and of textbook writers. Kirkes gave a brief account of Hutchinson's work, 'from whom nearly all our information on this subject is derived . . .' and this was repeated not very much changed until after 1900. Even as later as 1924 Halliburton was giving the volumes in both ccs and cubic inches.
For the best part of a century the treatment of lung volumes in the textbooks was dominated by Hutchinson's account of his work, and virtually every one reproduced at least one of his illustrations. But all the many physiology textbooks that I have looked at that were published between the 1870s and 1950 had also adopted Jeffreys' terminology, or with a variation of the suffix, without any attribution. The OED attributes the first use of the word *supplementary* in this context to Dunglison's *Medical Lexicon* of 1857, and of *complementary* and *tidal air* to Huxley's *Physiology* of 1872. As we have seen, all of these are incorrect.

**Summing up**, Jeffreys appears to have been the first to give a clear and coherent account of the lung volumes, the first to attach an accepted nomenclature to them, in other words to have taken the very important step of conceptualizing them, the first to think seriously about their possible functions and significance in the mechanics of respiration, and the first to draw attention to the importance of perfusion matching ventilation.

While it is easy to become carried away, and it would be foolish to exaggerate Jeffreys's importance, I think it is fair to say that no other work on the subject of lung volumes stands out as a comparable landmark.
References


15. HOLMAN RAE, FREEDMAN S, and SPIRO SG. Ventilatory mechanisms during sustained maximum voluntary ventilation and exercise in patients with chronic airflow limitation. *Clinical Science* 1984; **67**: 9P.