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Pneumatics vs. "Aerial Medicine": Salubrity and Respirability of Air at the End of the Eighteenth Century

The history of the eudiometer, the method of testing devised by Joseph Priestley in order to measure the quantity of dephlogisticated air (oxygen) in closed rooms, is a useful example of how extensive the role of theory was in eighteenth-century experimental practice. Scientific instruments were the means for manipulating phenomena and represented at the highest degree a renewed and positive attitude towards experimental practice. However, eighteenth-century naturalists often used instruments for theoretical purposes which, in many cases, had very little to do with the phenomena that could be investigated with the instrument in question. The case of the eudiometer is interesting because it not only conveyed a multiplicity of theories and practices often in opposition with each other, but also the genealogy of its naming, far from being conventional, encouraged the emergence of this tension.

In 1772 Joseph Priestley presented to the Royal Society of London his *Observations on Different Kinds of Air*[1] in which, among other things, he announced a new method for testing the salubrity of air. This method was derived from Priestley's isolation of nitrous air (NO) and his later observation that this gas had the property of absorbing dephlogisticated air. By this combination it was easy to ascertain with precision the diminution of the quantity of dephlogisticated air in common air. The volume of common air diminished in proportion to the quantity of dephlogisticated air it contained. One of the consequences which could be drawn from this was that a small diminution of common air after the reaction denoted the presence of a small quantity of dephlogisticated air and therefore the insalubrity of air. Marsilio Landriani, professor of experimental physics at the Scuole Palatine in Milan,[2] was probably the first to realise the technical possibility of creating, out of this observation, an instrument and a theory of its scientific implications. In 1775 he

[1] PRIESTLEY (1772).
[2] On Landriani see: BELLONI (1960); PESSINA (1981); BERETTA (1995).

published a small booklet entitled *Ricerche fisiche intorno alla salubrità dell'aria*.[3] Since 1772 he had been working together with Pietro Moscati, a physician employed at the Ospedale Maggiore in Milan, on a series of experiments to verify the therapeutic use of gases in medicine.[4] We are neither informed of the results achieved by these tests nor by their possible applications, however, Milanese interest in the question of the salubrity of air is well known and richly documented. The quality of the air in Milan was in fact considered insalubrious because of the exhalations of the many rice-fields surrounding the city. The most representative poet of the period, Giuseppe Parini, published in 1754 an ode entitled *La salubrità dell'aria* in which he denounced the noxious effect of the technical progress achieved in agriculture.[5] In 1766 the Milanese naturalist Giuseppe Visconti published in *Il Caffè*, the most enlightened periodical in eighteenth-century Italy, an article which explained the natural reasons for the noxious exhalations of the Milanese atmosphere.[6] Visconti's explanation was not particularly original, since it resorted to the laws of meteorology and the capacity of winds to transport contagious particles, but the appearance of his article in a periodical engaged in political and social reforms shows that the salubrity of air was an important subject for the learned of Milan long before the appearance of Priestley's memoir. Although belonging to the aristocracy, Landriani was acquainted with Pietro and Alessandro Verri, the editors of *Il Caffè*,[7] and he followed attentively the ongoing scientific debates in the capital of Habsburg Lombardy. It is in this context that we should consider Landriani's fortunate combination of two fashionable themes, the chemical analysis of gases and the salubrity of air.

Following Priestley's discovery that the quantity of dephlogisticated air could be measured using relatively accurate procedures, Landriani developed this experimental technique into a more ambitious research program. In 1775, with his newly invented and newly named *eudiometro*, Landriani hoped to be able to measure the salubrity of air and consequently to prevent epidemics and contagion. The name of the new instrument was

[3] LANDRIANI (1775).

[4] On their collaboration, see BELLONI (1961).

[5] Parini displayed in the poem good scientific knowledge as testified in the following verses: "Al piè de' gran palagi/ Là il fimo alto fermenta/ E di sali malvagi/ Ammorba l'aria lenta/ Che a stagnar si rimase/ Tra le sublimi case./ Quivi i lari plebei/ Da le spregiate crete/ D'umor fracidi e rei/ Versan fonti indiscrete;/ Onde il vapor s'aggira,/ E col fiato s'inspira./ Spenti animai, ridotti/ Per le frequenti vie,/ De gli aliti corrotti/ Empion l'estivo die:/ Spettacolo deforme/ Del cittadin su l'orme", in PARINI (1754), pp. 212-3.

[6] VISCONTI (1766).

[7] On the other hand, the judgment by Pietro Verri of the young naturalist was not particularly positive: "Questo Landriani presso di me è un giovane di limitatissimo ingegno, che ha la ciarlataneria chimica e letteraria al segno di ridicolo e che parla di sè medesimo come d'un genio scopritore e inventore. Dagli una spinta piccola e diventa pazzo dichiarato", in VERRI (1910-), VIII, p. 132.

derived from the Greek word *eudios* meaning "goodness of air".[8] The function of this new instrument was to overcome the difficulties encountered by meteorological instruments in detecting the sources of noxious air. Eudiometric experiments, by contrast, did not confine their action to the quantitative determination of the variations of temperature and density in the atmosphere but also indicated the degree of respirability of air, wind and, more generally, the salubrity of a season.[9] In order to test this ambitious program, Landriani made several experiments on animals and used different mixtures of gases. In this respect he not only tried to establish the difference between noxious gases and respirable airs but also the therapeutic effect of those gases which his contemporaries thought to have exclusively toxic effects. This was the case, for instance, of fixed air which, if used in due quantities, could stop the process of putrefaction. On the wave of enthusiasm for his own creation, Landriani even announced that the eudiometer could lead to the foundation of a new discipline, "aerial medicine", by which the therapeutic action of different kinds of air on the human body could be regulated with the greatest accuracy.[10] In the first part of his treatise the Italian natural philosopher recognised that Priestley had been the first to establish the difference between respirable and vitiated airs, but he blamed him for having performed his experiments on different kinds of air too randomly.[11]

The eudiometer constructed by Landriani is a complex device, the function of which was a relatively simple test. The eudiometer (figure 1) consisted of a long glass tube CD, to the upper extremity of which was attached a small crystal recipient AB containing water of the same volume as the tube and as the bladder PN containing nitrous air, the circulation of which was regulated by a tap. At the lower end of the eudiometer Landriani posed a brass cylinder HL connected with the glass tube CD filled with common air. By

[8] "Con tal nome io chiamo la mia Macchinetta da *Eudios*, parola Greca significante bontà dell'aria", in LANDRIANI (1775a), p. 58. Elsewhere (p. 66) he wrote: "questo istromento io chiamo Eudiometro, cioè Misura-salubrità dell'aria, non già perchè questi indicar possa tutte le cause vizianti l'aria […], ma bensì perchè per mezzo di esso determinare possiamo con qualche precisione le principali alterazioni che l'aria subisce rispetto alle principali funzioni del corpo umano".

[9] Eudiometric experiments are surely more useful and important than meteorological observations since they are not merely restricted to the "sterile curiosità di sapere di quanti linee o pollici il Barometro ed il Termometro sieno stati più alti un giorno dall'altro, ma indicano la maggiore o minore respirabilità dell'aria, di un vento, la salubrità di una stagione ec., oggetti tutti della maggiore importanza, e che bene studiati possono prevenire infiniti abusi, e forse anche pronosticare e riparare le più terribili epidemie", in LANDRIANI (1775a), p. 60.

[10] By "Medicina aerea" Landriani meant "la maniera di introdurre per mezzi più tenui ossia per altri veicoli i rimedi nel corpo umano e renderli così più attivi", in a letter by Landriani to Volta dated 11 August 1775, in *VE* (see Abbreviations), I, p. 92.

[11] "Le nuove e belle sperienze ultimamente pubblicate dal suddetto Dr. Priestley, quantunque mi dessero tutti quei lumi che mi mancavano circa l'analisi dell'aria nitrosa, pure abbastanza non mi soddisfecero riguardo all'uso di essa come indice delle delicate differenze della salubrità dell'aria", in LANDRIANI (1775a), pp. 57-8.

this contrivance it was possible to fill the two recipients AB and PN respectively with water and nitrous air and to control their quantitative proportions. The diminution of the common air contained in CD was measured against a graduated scale in ivory placed parallel to CD. By combining the nitrous air enclosed in the bladder PN with the common air contained in CD the oxygen was absorbed and transformed into nitrogen oxides, which, due to their high degree of hydro-solubility, combined with the water contained in the recipient AB. The effect of this reaction provoked an increase in the volume of the water which grew in the tube in proportion to the quantity of oxides which it absorbed. The higher the level reached by the water on the scale, the greater the quantity of oxygen absorbed and therefore the greater was the salubrity of the air.[12]

The eudiometer was presented by Landriani to Count Firmian, counsellor of state of Habsburg Lombardy, and one copy of it, dated 1775, is now kept in the Istituto e Museo di Storia della Scienza in Florence. It is difficult to believe, as has been recently maintained,[13] that Landriani's program and Firmian's patronage were tangible signs of an enlightened season of social reforms. Landriani was in fact an aristocrat, who later became an active opponent of political reforms and fled Austrian Lombardy when the revolutionary army of Napoleon invaded Milan.[14] Moreover, due to its components in ivory and crystal his eudiometer was an extremely expensive devise which, after its invention, was never used, not even by its inventor, for social purposes. Last but not least, the philosopher Pietro Verri, together with Cesare Beccaria, the most authoritative supporter of enlightened reforms and ideals, dismissed Landriani's research on eudiometry as charlatanism.[15]

The ambitious program promoted by Landriani to found aerial medicine, through the introduction of his instrument, was probably more the result of an attempt to publicise his invention than a deliberate campaign to reform the role of science in Milanese society of the Old Regime.

[12] On Landriani's eudiometer and its comparison with those by Volta, Fontana, Ingenhousz, Spallanzani and others, see CAPUANO and CAVALCHI (1998).

[13] According to Simon Schaffer [SCHAFFER (1990)] Landriani's program of eudiometric research combined with the patronage of Firmian proves that the Enlightened government of the Habsburgs was enthusiastically promoting social and political reforms and that such a program would meet its final defeat with the Restoration. As I argued elsewhere (BERETTA (1995) pp. 42-9) the first concrete measures to introduce eudiometry into practice were not taken by Enlightened governments but only by nineteenth-century capitalists who regarded salubrity as a vital component of the productivity of mechanized labour force.

[14] Landriani in fact died in Vienna in 1815.

[15] "Don Marsilio Landriani è fatto lettore di Fisica sperimentale con tremila lire, credo, di soldo e di più stipendio separato per fare un viaggio nella Toscana. Vedi se si paga bene l'aria fissa. [...] So che l'abate Fontana asseveramente crede che l'eudiometro di cui ha data la descrizione, non fosse fatto, che le sperienze sopra i gradi di calore dei diversi raggi separati col prisma non solamente sieno false ne' risultati e contrarie a quello che dimostra, ma che non fossero fatte, anzi impossibili a farsi col metodo di Landriani diceva di aver seguito", in VERRI (1910-), VIII, p. 132.

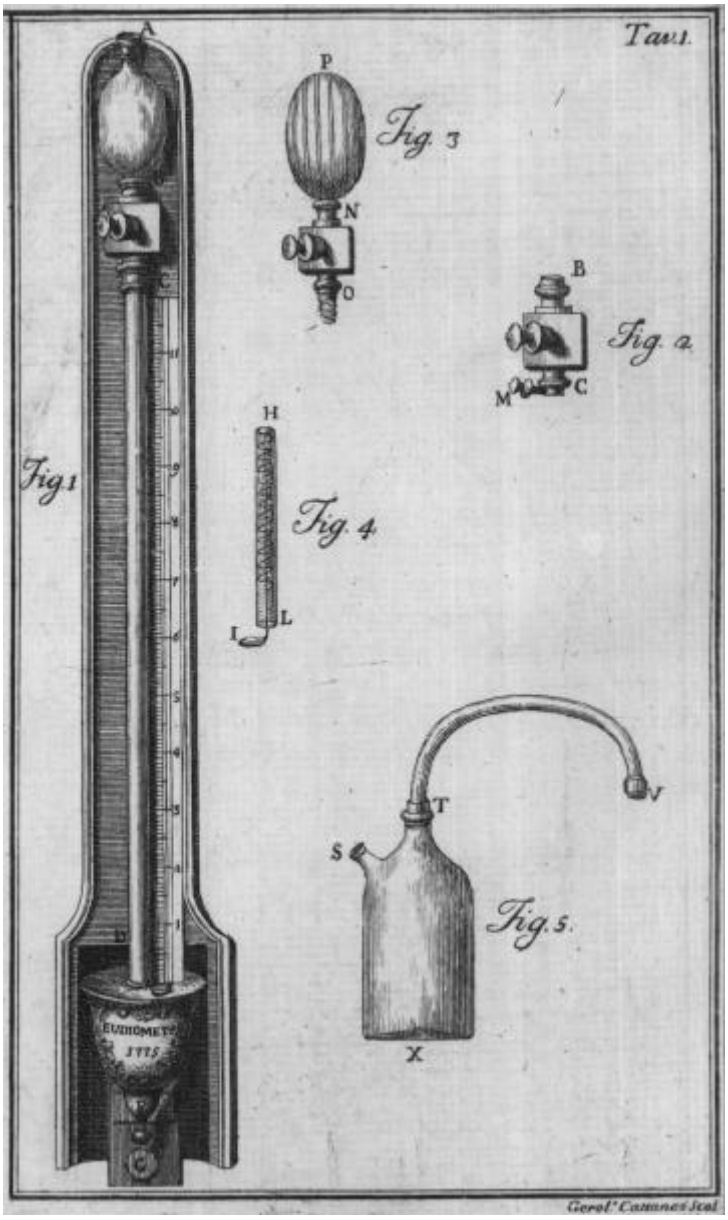

Figure 1 Landriani's eudiometer as it appeared in his *Ricerche fisiche sulla salubrità dell'aria* (1775).

Whatever the reasons, Landriani's eudiometer had, at least at the beginning, little success. The first to react to the new invention was Alessandro Volta. Although Volta's interest in pneumatic chemistry had been intermittent, his insights on specific experimental issues paved the way to a correct, often insightful, interpretation of the nature of gases.[16] This is also the case for the discussions on eudiometry.

Volta, who was a friend of Landriani, reacted quite coldly to the enthusiastic announcement of the qualities of the new instrument. He immediately pointed out the distinction between respirability and salubrity, and showed his younger colleague that the action of the eudiometer should have been restricted merely to the detection of the presence, or absence, of dephlogisticated air. Volta wrote a letter to Landriani in which he praised the accuracy of the eudiometer in measuring the degree of respirability of air but in his view it was impossible to determine, with the sole help of Landriani's instrument, when air was unhealthy. Fixed air, nitrous air and the phlogistication of the atmosphere indicated the insalubrity of an environment but they could not be regarded as the sole viable indicators. Furthermore, according to Volta, the mephitic airs must have been more numerous than Landriani thought and included any gas which did not allow the survival of animals. Such were the airs corrupted by putrefaction, the vapours emanating from flame, inflammable gases etc. Unhealthy air, by contrast, was a gas which, though respirable for animals, bore seeds of fevers, epidemic and contagion. These kinds of air could neither be detected nor measured by the use of Landriani's eudiometer.[17]

> Imagine – Volta wrote – that you use it to examine the air of some closed room, in which someone has been sleeping or several lamps have been burning, and you then compare the night air of some open place: doubtless the eudiometer would decide in favour of the latter. Yet who does not know that the risk of contracting disease is much greater sleeping in the open air than in that of a closed room, corrupted as it would be by respiration and the lamps? I am persuaded that all the respect and devotion I have for your eudiometer, dear Marsiglio, would not tempt me to sleep with the windows open; and, further, that I would be bold enough to sleep some time not merely in closed air but in the suffocating pit of your Milan theatre, even if the air of that place has already been found by your eudiometer no less bad than that of tombs.[18]

[16] On this, see ABBRI (1984), pp. 275-83 and the edition of VOLTA (1995) by Ferdinando Abbri. An original but outdated view of Volta's contribution to pneumatic chemistry is the edition of VOLTA (1928) by Aldo Mieli.

[17] "All'incontro per aria propriamente *malsana* io ho tutte quelle, che forse non avranno alcun vizio per conto della *respirabilità*, nè non estingueranno un candela ec., nè perciò si manifesteranno infette alla prova dell'aria nitrosa: quelle arie che non affetteranno gli organi respiratori sensibilmente, non recheranno in una parola danno istantaneo all'economia animale; ma sì col tempo ci produrranno alterazioni d'altro genere e vere malattie, come febbri, disenterie ec. Convien dunque distinguere quello che è *respirabilità* dell'aria da ciò che è *salubrità*", in *VO* (see Abbreviations), VI, p. 9.

[18] *VO*, VI, p. 10, translated into English in SCHAFFER (1990), p. 311.

Thus the name given to this instrument was, according to Volta, totally misleading because the causes of the salubrity of air evaded any attempt at quantitative analysis. Volta's criticism was, at the experimental level, conclusive but it did not convince Landriani who still did not accept a too sharp distinction between respirability and salubrity, although he eventually gave up his eudiometric researches. Dissatisfied with the difficulty of using Landriani's eudiometer,[19] Volta began to devise new kinds of instruments which he intended to use for both meteorological observations and pneumatic experiments on the nature of inflammable airs. In April 1777 Volta announced, in a letter addressed to Francesco Castelli, the invention of a pistol or gun functioning by the discharge of electricity in presence of inflammable air (*moschetto ad aria infiammabile*)[20] which allowed powerful detonations of the air (figure 2). The experiments performed by Volta with his electric gun were guided by different aims. In the first place, he wished to prove that the combination of electrical discharge and different kinds of inflammable airs could provide military warfare with a viable alternative to the use of gunpowder.[21] In the second place, the electric pistol was thought to be an effective instrument for the transmission of signals at long distance. In the third place, such an instrument could serve to measure the different degrees of inflammability of gases.[22] Finally, the electric pistol

[19] In a letter to Landriani dated 18 November 1777 Volta in fact declared: "a Ginevra, nè altrove non ho veduto alcuno de' vostri eudiometri. Il sig. Senebier se n'è costrutto uno, ma diverso dal vostro: e non gli riesce di tirarne partito. Il vostro pure si considera di assai difficile costruzione, e molto imbarazzante; tutti convengono che sia assai meglio prender l'aria dei diversi siti in alcune caraffe, e farne poscia il saggio a casa alla maniera di Priestley. Vi dirò la verità, abbiam fatto molte sperienze col vostro eudiometro io e l'ab. Venini nel viaggio, oh che pena! E poi le sperienze abbiam veduto che variano nei risultati nel medesimo luogo. Non avremo forse usato forse tutte le attenzioni, tutta l'accuratezza; ma dunque è ben difficile far l'esperienza a dovere. Io temo perciò che tal vostro stromento non farà molta fortuna. Debbo dirvi un'altra cosa; quantunque le sperienze fatte coll'ab. Venini non ci soddisfacessero per ciò che ho detto dei risultati niente costanti, ci è parso però all'ingrosso che l'aria delle alte cime, anzichè segnare maggior salubrità, come voi fiduciosamente avanzate, segni salubrità minore", in *VO*, VI, p. 168.

[20] Volta also called his instrument "pistola elettrico-flogopneumatica", "pistola elettrico-aereo-infiammabile", "pistola elettrico-infiammabile". Among these names, "pistola elettrica" remained the most successful.

[21] "Or se l'aria infiammabile potesse essere da tanto di supplire alla polvere per simil uopo [warfare], non dovrebbe più aversi in conto di inutile. Molto meno inutile potrebbe dirsi quando facendo intervenire l'aria infiammabile e la deflogisticata non già sole, ma in compagnia e di concerto colla polvere all'opera delle mine, si giungesse con ciò a procurare o la maggior forza d'esplosione, o un più sicuro riparo ai pericoli che sovrastan non di rado ai minatori", in VOLTA (1995), p. 31 (*VO*, VI, p. 143).

[22] "Cotesta pistola può servire ad uso di un *provino*, ossia paragonare la forza di esplosione delle arie infiammabili di diversa fatta, della metallica, di quella estratta da' vegetali e animali colla distillazione, della nativa delle paludi, miste in tutte le proporzioni coll'aria comune, colla deflogisticata, con altre arie", in VOLTA (1995), p. 33 (*VO*, VI, p. 146).

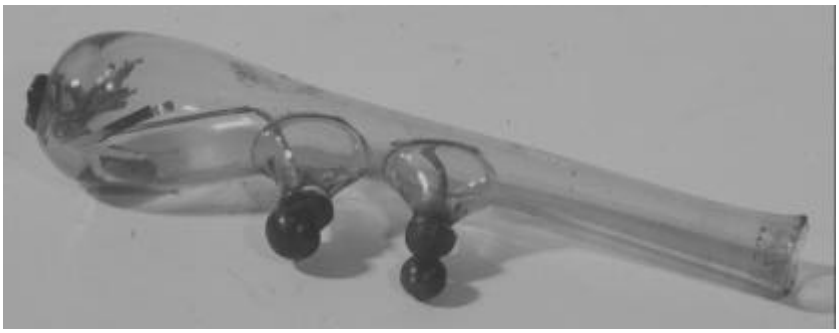

Figure 2 Volta's electrical pistol (Museo per la Storia dell'Università di Pavia).

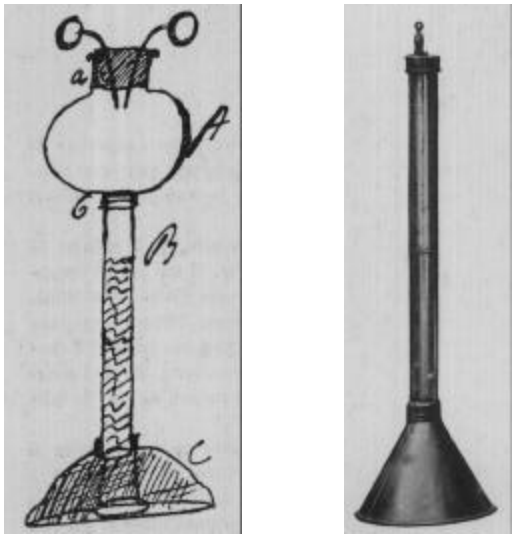

Figure 3 Volta's sketch of his inflammable air eudiometer (from *VO*, VI, p. 294) and picture of one of the different shapes in which he constructed the instrument (from *VO*, VI, p. 392).

could, through different tests and experiments, shed light on the nature of inflammable air.[23] In this last respect, the only one directly related with pneumatic chemistry, Volta successfully repeated some of his earlier experiments and observed that, when the electrical pistol was filled with inflammable and common air, the former was decomposed and disappeared.[24] In order to ease the result of this experiment Volta modified his pistol and created an instrument which one year later was to be named *eudiometro ad aria infiammabile*. This eudiometer was an extremely simple construction. It consisted of a graduated glass tube which ended in a vase (figure 3). The upper extremity of the tube was closed by a cork in which Volta inserted two small iron rods. A short gap was left between the extremities of these rods inside the tube. Volta filled the vase with water and the tube with 8 volumes of common air and one of inflammable air, so that the volume of the air contained in the tube reached the highest degree of the scale. With the help of a Leyden jar, Volta passed a spark though the gap between the two rods and ignited thus the inflammable mixture inside the tube. He then observed that the level of the water reached level 8 on the scale and concluded that both the common air and some of the inflammable air were absorbed during the combustion.[25] The instrument was extremely ingenious and easy to use. Unlike Landriani's instrument and Priestley's

[23] "Non è di poca importanza il sapere qual mutazione accadde all'aria infiammabile nell'accensione, e in quale stato dopo si ritrovi. Cresce essa, o diminuisce di volume? Si scompone, come fa l'aria nitrosa in contatto delle comune, o no? In tutto, o in parte? Fassi alcuna precipitazione? E di che?", in VOLTA (1995), p. 34 (*VO*, VI, p. 146).

[24] "[…] l'aria infiammabile non che scemarsi di volume, tutta si scompone, perde l'abito aereo, sparisce […] e di più anche diminuisce, in conseguenza di flogisticare l'aria comune entro a cui s'accende", in VOLTA (1995), pp. 34-5 (*VO*, VI, p. 147).

[25] "In un tubo cilindrico di vetro, che termina in un vaso larghissimo a base aperta a foggia d'imbuto, ho segnate varie divisioni, che corrispondono ad altrettante eguali misure d'acqua o d'aria. Alla sommità aperta del tubo ho masticato un turacciolo infilzato da due fili di ferro, che vanno colle punte ad incontrarsi entro al tubo medesimo. […] Riempiuto d'acqua tutto il vaso, e rizzato in piedi in una tinozza d'acqua, vi ho introdotto di sotto per la grande apertura a imbuto otto misure d'aria comune, e una sola d'infiammabile metallica. Così disposte le cose, e toccando il limite di tutt'insieme il volume d'aria il num. segnato 9., con una boccettina di Leyden ho messo in fiamma quell'aria confinata: l'acqua è stata violentemente commossa; ma niuna bolla d'aria si fatta strada a sortire. […] L'acqua si è alzata nel tubo alquanto al di sopra del num. 8., cioè il volume totale dell'aria si è diminuito di tutta la quantità dell'infiammabile, e un poco più. All'aria così scemata ho introdotto una seconda misura d'aria infiammabile; e portatavi come prima l'accensione, più di prima ne è rimasto diminuito il volume, poichè si alzò l'acqua al 7 e mezzo. Finalmente arrivò presso a poco al 7 dopo la terza accensione d'una nuova misura d'aria infiammabile. Insomma oltre il volume di tutte tre le misure d'aria infiammabile è sparito un ottavo della stessa aria comune. La quarta prova sopra il medesimo residuo non ebbe effetto: l'aria infiammabile rifiutò d'accendersi […]. Così esser doveva alla fine; poichè l'aria comune diminuita ossia flogisticata a un certo segno non è punto più atta a mantener la fiamma; avverrà dunque che soffochi anche l'aria infiammabile", in VOLTA (1995), pp. 35-6 (*VO*, VI, p. 147-8).

method of testing which were both extremely slow, the reaction caused by the electrical discharge on inflammable air needed only a few seconds to produce a reliable quantitative result.

Encouraged by the results achieved in the laboratory, Volta wrote a letter to Joseph Priestley on 2 September 1777 in which he presented a perfected model of the eudiometer. He also presented the results of some new experiments in which the effects of the combustion of inflammable air in the presence of dephlogisticated air were studied. Volta, in fact, increasingly focussed his attention on the nature of inflammable air and he adapted his instrument to the needs of this particular research program. By the end of 1778, the Italian natural philosopher had accumulated an impressive series of pneumatic experiments, which he hoped to continue in the near future. His project to multiply the experiments of combustion in closed vessels was aimed, among other things, at determining whether the combustion of inflammable air could reveal any formation of vapours and drops of liquids.[26] In May 1778, Volta found a partial solution to these problems and, in a letter to the Swiss naturalist Jean Senebier, he established that the combustion of inflammable air in closed vessels filled the recipient with vapours.[27] Volta was unable to understand the implications of his observation and to identify water as the result of his experiment, since, as Ferdinando Abbri rightly observes,[28] he saw exclusively what he was looking for, i.e. the phlogistication of air. In retrospect, in a letter to van Marum dated 1798, Volta reconstructed the history of events as follows:

> I am very fond of chemistry, and particularly pneumatic chemistry which I was the first to cultivate in Italy. You will probably know my discoveries and my experiments on inflammable air. Was not I the first to discover by a series of experiments with my pistol and my inflammable air lamp, and those with an eudiometer or apparatus to burn this air in closed vessels, mixed in different proportions of common air, or vital air, likewise my invention – who had discovered, I say, and found before 1781 that all inflammable air disappears and takes with it the destruction of a volume of vital air which is approximately half of its own volume? … This is the point at which I had arrived with my experiments several years before Lavoisier … He only verified or completed my discovery; in the same way that with regard to the machines he only perfected my lamp light using inflammable air or combined this with my eudiometer.[29]

[26] "[…] si potrà vedere se alcun vapore s'attacchi alle pareti, e si figuri in goccie, o checchè altro si deponga in forma solida o liquida", in VOLTA (1995), p. 37 (*VO*, VI, pp. 149-50).
[27] *VO*, VI, p. 271.
[28] "Volta *vedeva* lo stesso processo di riduzione volumetrica, di flogisticazione dell'aria. […] Volta non isolò quindi l'acqua per motivi teorici, non sperimentali: egli considerava i gas particolari modificazioni, operate dal flogisto, dell'acido primitivo e non sostanze chimiche specifiche. Ammetteva soltanto pochi elementi quali costituenti della materia: il mutamento chimico era affidato soprattutto al flogisto", in ABBRI (1984), p. 282.
[29] VOLTA (1798), p. 360.

Volta further complained that the reason why he had been unable to see the water was because he could not replace water with mercury during the experiment, as eventually was done by Lavoisier. Both the reconstruction and the vindication of priority are based on, to say the least, a selection of the historical facts[30] and, since Lavoisier had died in 1794 and the fathers of the discovery of the synthesis of water were increasing, the events were too old to be fairly judged.

After 1779 Volta's eudiometric researches were temporarily abandoned but in 1783, at the request of Giovanni Antonio Scopoli, chemistry professor at the University of Pavia, he agreed to write the article "Eudiometro" as an addition to the Italian translation of Pierre Joseph Macquer's *Dictionnaire de chymie*.[31] In this article he only mentioned in passing his own experiments on inflammable air in closed vessels and preferred to insist on a new function he attributed to the use of the eudiometer. After a long introduction in which he criticised the improper use of the eudiometer in the quantitative determination of the salubrity of air, and, more generally, in medical research, Volta reported some new experiments in which he observed that the air at higher altitudes was less respirable than on the plain. This experiment had probably been made between 1781 and 1782, during the trip which brought Volta to Paris and London through Switzerland and the Alps. Thanks to the use of the eudiometer, which here became a meteorological instrument, the Italian natural philosopher established that the lower degree of respirability of the air in the Alps was due to a low degree of dephlogisticated air in the atmosphere.[32]

In order to understand the technical evolution of Volta's eudiometer, it is important to stress the changes of perspective which occurred in his research program. Initially the electric pistol was a curious instrument, which seemed to be destined either for military use or learned entertainment. In a second phase, struck by the experimental results achieved by testing the pistol with different kinds of air, Volta concentrated his attention on the pneumatic nature of the instrument and, finally, he turned to meteorology. The only discipline which was deliberately excluded by Volta's use of the eudiometer was medicine. Until the end of his scientific career, in fact, Volta stressed his firm criticism against those naturalists who insisted on using the eudiometer to measure the healthiness of airs.

A case which further complicates the story of this controversial instrument is the position of Antoine Laurent Lavoisier, who was in correspondence with both Landriani and Volta and an attentive reader of their memoirs on eudiometry. There is no record of Lavoisier using the eudiometer until 10 May 1777 when, in presence

[30] On the relation between Volta and Lavoisier see my forthcoming article "From Nollet to Volta: Lavoisier and Electricity", in *Revue d'histoire des sciences*.

[31] NEVILLE and SMEATON, (1981); ABBRI (1991).

[32] "È assai più verisimile che trovisi a quelle altissime regioni d'un poco più scarsa la dose di aria deflogisticata [oxygen] a cagione della lontananza de' vegetali che la forniscono", in VOLTA (1783), p. 74. Volta's article "Eudiometro" is reprinted in LANDRIANI (1775a), pp. 109-24.

of Emperor Joseph II, he presented before the *Académie Royale des Sciences de Paris* a memoir entitled "Observations sur les altérations qui arrivent à l'air et sur les moyens de ramener l'air vicié à l'état d'air respirable".[33] Bachaumont reported on Lavoisier's presentation with the following words:

> Monsieur Lavoisier eut l'honneur de démontrer, par des expériences multipliées … comment on pouvoit décomposer l'air de l'atmosphère en demi-portions, l'une salubre, respirable, susceptible d'entretenir la vie des animaux, la combustion & l'inflammation; l'autre, au contraire, funeste pour les animaux qui la respirent …. Il fit voir que la respiration des hommes & des animaux avoit la propriété de convertir en air fixe la portion salubre de l'air; de sorte que dans les salles de spectacles, par example, ou dans les dortoirs des hôpitaux, où l'air a été long temps respiré, il existe deux especes d'air nuisibles; savoir, la partie nuisible propre à l'air, & qui entre dans sa composition; & la portion d'air fixe qui s'est formée par l'effet de la respiration.[34]

It is an interesting coincidence that, while Volta was publishing his letters on the new eudiometer and its application to experimental physics, Lavoisier's memoir revived Landriani's idea of using the new instrument to measure the salubrity of atmospheric air. Lavoisier's perspective, however, was different and original. He established, first of all, that several species of airs existed and that they were composed of "toutes les substances susceptibles de se vaporiser à la température actuelle de la planète que nous habitons";[35] secondly, the respiration of man and animals and the combustion of bodies had in common the property of transforming the respirable part of the air into fixed air. This explained why a large number of people breathing for a long time in closed rooms consumed the respirable part of the air and created a noxious atmosphere. Thus, in addition to ordinary nitrogen contained in the atmosphere, which was a noxious gas, animal respiration replaced oxygen with fixed air. Lavoisier brought his observation even further. From the beginning of his career as a chemist, he insisted on the importance of determining the chemical identity of a substance by taking its specific gravity into consideration.[36] In the case of eudiometry Lavoisier remarked that the airs created by the breathing and consequent decomposition of common air did not combine with each other but "ils se disposent au contraire relativement à leur pesanteur spécifique".[37] Accordingly, since nitrogen was lighter than the atmosphere, it tended towards the ceiling of the rooms while fixed air, being heavier, tended to deposit itself on the floor. The air which had not been decomposed by breathing remained at

[33] The original title was eventually changed by the editor of Lavoisier's collected works, Edouard Grimaux, into "Expériences et observations sur les fluides élastiques en général et sur l'air de l'atmosphère en particulier", see LAVOISIER (1777).
[34] BACHAUMONT (1784), pp. 130-1.
[35] LAVOISIER (1777), p. 274.
[36] The genealogy of this approach is studied in BERETTA (1994).
[37] LAVOISIER (1777), p. 276.

a medium height.[38] For the purpose of determining, through eudiometric measurements, the salubrity of closed rooms, Lavoisier's observations had consequences which reinforced Landriani's conviction that the eudiometer could be usefully employed in medical research. Lavoisier, in fact, made experiments on the specific gravity of different gases in the halls of a theatre and in hospitals. Architects and physicians were to be aware of the fact that nitrogen was lighter and fixed air was heavier than common air when they projected hospital rooms. "Il faut d'abord que les ouvertures des fenêtres montent jusqu'à la partie supérieure de la salle pour éviter qu'il ne reste des portions d'air nuisible stagnantes dans les voisinage des planchers. Si ces salles sont voûtées, les voûtés ne doivent point être parfaitement horizontales; elles doivent avoir une inclinaison d'un côté qui détermine l'écoulement du courant d'air léger; enfin elles doivent aboutir à un dôme ou à une ouverture quelconque par la quel l'air puisse s'échapper".[39] But also the floor of the rooms and the doors were to be designed in such a way that the fixed air, the heaviest fluid, could be got rid of easily.

Lavoisier pointed out that such measures could be taken immediately in the reconstruction of the rooms of the Hôtel-Dieu which had been destroyed by fire in the early 1770s. He concluded that it would be humiliating if the Académie des Sciences were not consulted and if a theory and experiments so well grounded could not help to avoid the mistakes made in the past in the construction of hospitals.[40] In August 1777 the Minister Jacques Necker decided to nominate a commission for the improvement of the Hôtel-Dieu and of the other Parisian hospitals, but it was only in 1785 that a new commission, this time guided by the Académie des Sciences, was put in charge of a plan for the construction of a new Hôtel-Dieu.[41] Eventually the plans proposed for the attention of the Minister and the King were not supported, and the life of the patients in Parisian hospitals continued to be as miserable as before.

In his memoir of 1777, Lavoisier was aware of Volta's objection that most contagious diseases were not due to a decrease in respirable air but to the spread, through common air, of noxious particles. Despite this awareness, the French chemist was confident that new methods of disinfection could be introduced.[42]

[38] "La partie nuisible, propre à l'air comme la plus légère, gagne le haut de la salle; l'air le moins décomposé occupe la partie moyenne; enfin l'air fixe, comme le plus pesant de ces trois airs, occupe la partie la plus basse", *ibid.*, p. 276.
[39] *Ibid.*, p. 277.
[40] "Il serait sans doute bien humiliant pour la nation qu'après la théorie sur l'air fondée sur des expériences exactes et sûres, on tombât dans le XVIIIe siècle dans des défauts de construction qu'on avait prévus et évités dès le XVIe", *ibid.*, p. 278.
[41] On this, see VALENTIN (1993) and TENON (1788).
[42] "Ce n'est pas assez d'avoir des caractères certains pour reconnaître l'état de l'air; les découvertes modernes nous fournissent encore des méthodes assurées pour ramener à l'état

Thus, Lavoisier's position on the use of the eudiometer seems to escape any rigid sociological classification.[43] As a distinguished member of the academic establishment and of the Parisian scientific community, one would expect that he would have chosen Volta's position and restricted the use of the eudiometer to mere investigation of gases. Since Landriani's ambition to use the instrument for measuring the salubrity of air had been demonstrated by Volta as illusory, any concession to this position could have been regarded, in the best of cases, as provocative. That this was not the case is demonstrated by the constitution, in 1777 and in 1785, of commissions for the construction of a new hospital and, more generally, by the reputation which Lavoisier was able to achieve on issues directly related to applying the study of the effect of gases on public health.[44]

During the early 1780s Lavoisier extended his views on the possible uses of the eudiometer. In spring 1782, he met Volta and collaborated in a series of experiments on the absorption of electricity and the vaporisation of fluids.[45] The experiments on water vaporisation and the use of several electrical instruments suggest that during his stay in Paris, Volta had demonstrated his electrical eudiometer, or electric pistol as he called it, to Lavoisier and other French scientists. Some time between 1782 and 1784, Lavoisier used Volta's electrical eudiometer and, in August 1784, the chemist Jean D'Arcet sent the Italian natural philosopher, on behalf of Lavoisier, a report on the latest experiments made by Lavoisier and Jean Baptiste Meusnier de la Place on the decomposition of water.[46] In the accompanying letter, dated 16 August 1784, D'Arcet showed not only that he was aware of Volta's eudiometer but also of its possible consequence for Lavoisier's work on the synthesis of water:

> Je me suis rappellé fort bien de cette vapeur nebuleux qui resulte de la destruction entiere ou presque entiere, des deux airs, en les enflammant à l'aide de l'etincelle electrique, dans votre nouvel appareil, que vous aviez eu la complaisance de faire porter chez moi.[47]

It is clear from D'Arcet's testimony that while in Paris, Volta had shown his eudiometer and made the experiments which allowed him to synthesise water. It is very

respirable l'air le plus vicié", in LAVOISIER (1777), p. 279. Also Louis Jurine was convinced of the practical and therapeutic usefulness of eudiometry; see JURINE (1789).

[43] In his sociological reconstruction of the eudiometer Golinski significantly ignores Lavoisier's contribution (as well as those by Seguin and Jurine) and reaches the conclusion that, after the eudiometric researches of Cavendish and Volta, "the connections with medical reform programs, which had originally sustained the aim of determining differences in atmospheric quality in different locations had been severed. The project had failed to achieve anything like its originators' aims and had unravelled in disillusionment and disappointment", in GOLINSKI (1992), p. 127.

[44] A good survey of Lavoisier's activities may be found in DUVEEN and KLICKSTEIN (1955).

[45] The collaboration between Volta and Lavoisier is the object of my forthcoming article "From Nollet to Volta: Lavoisier and Electricity", in *Revue d'histoire des sciences*.

[46] *VE*, II, pp. 235-6.

[47] *Ibid.*, p. 237.

unlikely that Volta showed these experiments to D'Arcet and not to Lavoisier, but even if he did, it is more than probable that D'Arcet would have told his colleague at the Académie about them. Moreover, it is interesting to note that in the unpublished inventory of Lavoisier's laboratory, compiled in November 1794, we find an "eudiomètre de Volta", one "pistolet de Volta en cuivre" and one "pistolet de Volta en fer blanc".[48] Thus, some time after 1782, Lavoisier used Volta's eudiometer to replicate with a different and much cheaper apparatus the experiments on the synthesis of water. However, even after his appreciation of the scientific importance of this particular use, Lavoisier did not abandon the idea that eudiometric experiments could reveal an effective means of measuring the salubrity of air. On 15 February 1785, in fact, the French chemist presented to the Société Royale de Médecine in Paris a paper entitled "Mémoire sur les altérations qui arrivent à l'air dans plusieurs circonstances où se trouvent les hommes réunis en société"[49] in which he proposed, on the basis of eudiometric experiments, new methods for ventilating theatres, hospitals and, more generally, all those large rooms in which men gather together. Lavoisier's experiments, contrary to what Volta and other natural philosophers might have expected, led to some interesting results:

> Nous en avions conclu – wrote Lavoisier – que l'air salubre consiste en une juste proportion entre l'air vital et le gaz azote, et qu'il est important, pour les animaux qui respirent, que cette proportion, qui est de 25 parties environ d'air vital sur 75 de gaz azote, ne varie pas beaucoup, ni en dessus ni en dessous.[50]

With the help of his younger assistant Armand Seguin, Lavoisier also demonstrated that the sensation of fatigue and other accidents which occurred in these closed rooms were caused by the noxious action of fixed air which was formed during animal respiration.

> On est effrayé – concluded Lavoisier – quand on pense que dans une assemblée nombreuse, l'air que chaque individu respire a passé et repassé un grand nombre de fois, soit en tout, soit en partie, par le poumon de tous les assistants, et qu'il a dû se charger d'exhalations plus ou moins putrides.[51]

The nature of these exhalations and the mechanism of the deterioration of the salubrity of air were still unknown but the extraordinary progress achieved in public health envisaged a promising research program.[52] Lavoisier's later

[48] Inventaire et estimation des instruments de physique du Cabinet de Lavoisier. Archives Nationales. Paris. F 17/1219 Dossier 10, fol. 2-3. On Lavoisier's laboratory, see TRUCHOT (1879), DAUMAS (1950), ID., (1955), SCHWARTZ (1989), LEVERE (1992).
[49] LAVOISIER (1785).
[50] *Ibid.*, p. 682.
[51] *Ibid.*, p. 687.
[52] "Tous les arts marchent rapidement vers leur état de perfection: celui de vivre en société, de conserver dans leur état de force et de santé un grand nombre d'individus réunis ensemble, de rendre les grandes villes plus salubres, la communication des maladies contagieuses moins facile,

research on animal respiration were in fact conceived and realised within this philosophical framework. Indeed, after 1785 research on animal respiration intensified and Lavoisier's collaboration with Seguin became closer. Lavoisier also began to show an interest in perfecting the eudiometer. Up to 1785, it seems that, when working on the salubrity of air, he mostly used Priestley's and Landriani's testing method while he preferred Volta's hydrogen eudiometer for the replication of experiments on the synthesis of water. Some time in the late 1780s, probably inspired by Seguin, Lavoisier proposed replacing nitrous air with a new eudiometric method based on the combustion of phosphorous. Given the slowness of the nitric oxide eudiometer and its lack of precision, the French chemist exploited his long standing knowledge of the effects related to the combustion of phosphorous:[53]

> Les eudiomètres établis sur ces principes, c'est-à-dire ceux où l'on profite de la grande affinité qu'ont pour l'oxygène le phosphore, les sulfures d'alcalis et le mélange du soufre et de la limaille de fer, sont bien préférables à ce luis de Priestley, de Fontana et d'Ingenhousz, dont la base est le gaz nitreux … Le phosphore et le mélange de soufre et de fer réunissent presque au même degré les avantages de l'exactitude et de la célérité.[54]

In the concluding remark of this memoir Lavoisier agreed with Marsilio Landriani in observing that, thanks to the application of this new eudiometric method, one would be able not only to measure the salubrity of air but also that of a season.[55] The new eudiometric method also served Lavoisier and Seguin in their crucial experiments on human respiration.[56] Two of the instruments used during these experiments have been described in the famous drawings made by Madame Lavoisier, probably in 1791, although there is no direct evidence of any eudiometric analysis (figure 4).

est encore dans son enfance. Les grans travaux qu'on peut entreprendre sur un objet aussi important ne peuvent être que l'ouvrage des sociétés savantes", *ibid*.

[53] Lavoisier began to make experiments on this field in September 1772; see GUERLAC (1961), pp. 223-30.

[54] LAVOISIER (1790 ca.), pp. 720-1. In the same period Seguin wrote a memoir on the combustion of phosphor employed as a eudiometric method, which has been published for the first time by Madame Lavoisier in her husband's *Mémoires de chimie*, but not in the national edition of Lavoisier's works, see SEGUIN (1803). Of the greatest importance is also the memoir by Seguin which was read at the Académie des Sciences on 15 February 1792 but published only in 1814, see SEGUIN (1814).

[55] "Il est à désirer que quelque physicien ait le courage d'entreprendre, par cette méthode, une suite d'expériences sur l'air atmosphèrique recueilli dans différents lieux, saisons, dans différents circonstances.[…] J'ai eu toujours eu le projet de me livrer à ces recherches, auxquelles j'étais naturellement conduit par les expériences que j'ai faites sur la salubrité de l'air des salles de spectacle et des dortoirs des hôpitaux", in LAVOISIER (1790 ca.), p. 723.

[56] HOLMES (1985), pp. 440-9.

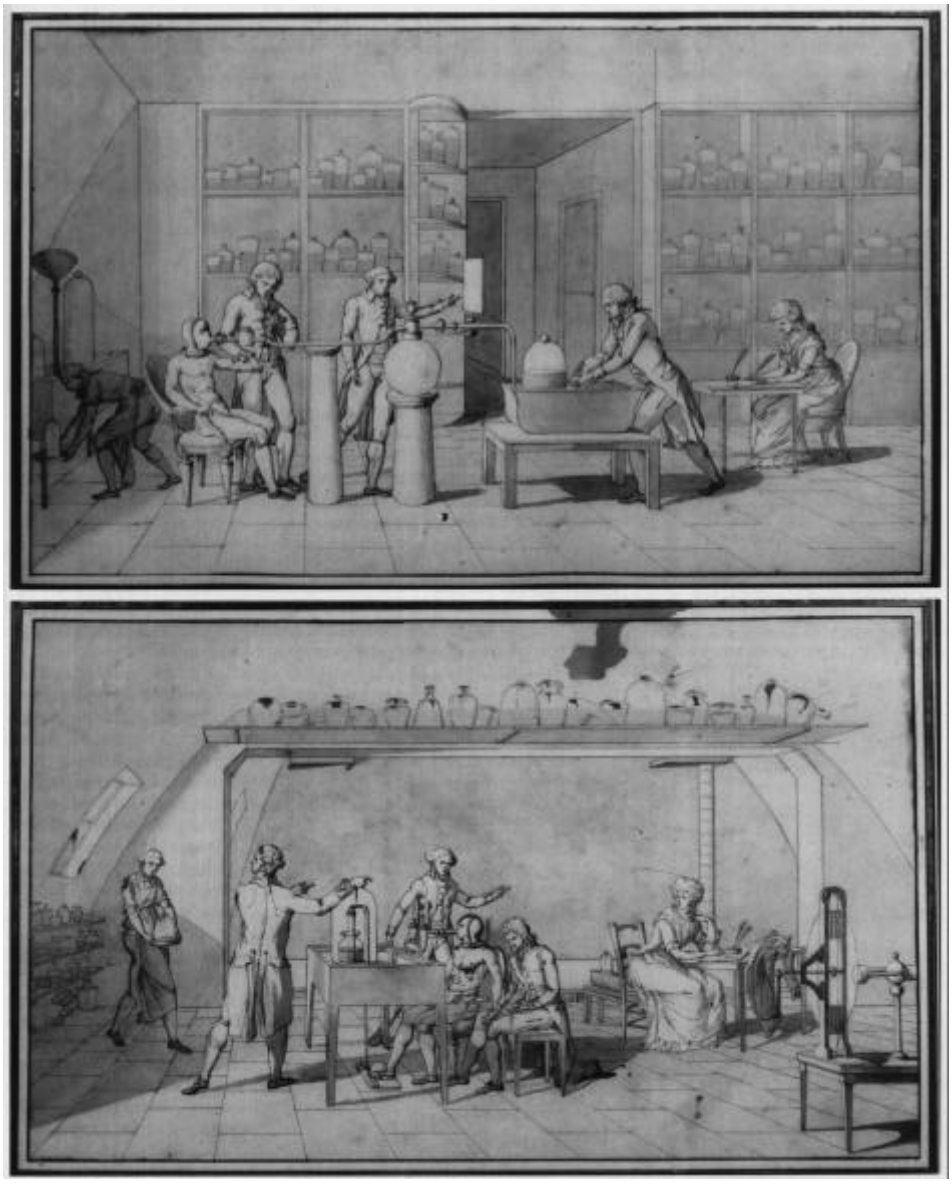

Figure 4 Madame Lavoisier. Experiments on respiration (1791), with a man at rest (above) and a man in motion (below).

In the first drawing, illustrating an experiment of the respiration of a man (Seguin) at rest,[57] Lavoisier used a device which served to decompose the oxygen, nitrogen and carbon dioxide from the air which passed through the tube.[58] The second drawing presents a different device which was supposed to analyse the air breathed by a man in motion. This device has not been precisely identified by Prinz and Holmes believes that Madame Lavoisier's representation is "fanciful and useless for elucidating the methods used".[59] Although it is difficult to disagree on the difficulty of interpreting the function of Lavoisier's device without the help of his own explanation, it is worth noting that in the second picture Madame Lavoisier portrayed Lavoisier's electrical machine quite faithfully and accurately.[60] It is therefore doubtful that Madame Lavoisier decided to represent accurately an instrument which was not directly related to the experiment and that she reconstructed in a "fanciful" way the device conceived by her husband and Seguin to perform the experiment. Whatever the interpretation we adopt, the principle which inspired the instrument illustrated in the first drawing, i.e. the decomposition of the atmosphere and the analysis of the quantity of oxygen, was based on eudiometric experimental tests. In addition, we are informed by Seguin himself that during such experiments the two scientists used a new kind of eudiometer based on the combustion of phosphorus.[61] In his *Mémoire sur l'eudiométrie*, Seguin admitted that they were still far from establishing eudiometry as a science. However, the experimental limits of the instrument were to be stimulus for further research rather than a reason for scepticism and disillusionment.[62] One of the reasons for such optimism was that he and Lavoisier successfully applied the new instrument during their experiments on respiration in order to determine the volume of oxygen contained in respirable fluids.[63] According to Seguin the phosphorous eudiometer was much

[57] The title of the drawing is in fact "Expériences sur la respiration de l'homme à repos". In addition to Holmes' work, see PRINZ (1992) which provides convincing evidence of the central importance of eudiometry during these experiments. Prinz has also reconstructed in the minutest detail the apparatus used by Lavoisier and Seguin and painted by Madame Lavoisier. See also NOËL (1997), pp. 437-8.

[58] See the reconstruction of the apparatus in PRINZ (1992), p. 172.

[59] HOLMES (1985), pp. 443-4 and note on p. 546.

[60] This machine was used by Lavoisier in the experiments on the synthesis of water and it is now kept in the Musée National des Arts et Métiers in Paris, Inventory n. 20110.

[61] The instrument was presented by Seguin at the Académie des Sciences on 21 March 1791 and the text of this presentation appeared as SEGUIN (1791); ID. (1814).

[62] "Nous sommes […] encore fort éloignés d'avoir une science que l'on puisse appeler proprement eudiométrie. Les bornes étroites des connoissances que nous avons acquises jusq'ici relativement à cet objet, ne sont cependant pas une raison de les rejetter; nous devons chercher au contraire à les étendre, à les perfectionner, & tel a été le but des nouvelles recherches que je viens soumettre au jugement de l'académie", in SEGUIN (1791), p. 295.

[63] "Dans les premières expériences que nous avons faites, Lavoisier et moi, sur la respiration, nous déterminions, à l'aide du procédé suivant, le volume de l'air vital que contenoient nos fluides respirables", *ibid.*, p. 297.

more effective than both those based on nitrous airs testing and that devised by Volta. We have already pointed out that Lavoisier, too, regarded this kind of eudiometer as more reliable and accurate for determining the salubrity of air. In their work on respiration Seguin and Lavoisier preferred using a eudiometer based on the combustion of phosphorus, but when the matter was related to other experimental domains, they employed a different instrument. This was the case for the series of experiments on the combustion of hydrogen performed in May 1790, the aim of which was to confirm Lavoisier's large scale experiment on the synthesis of water. The main character in this experiment was again Armand Seguin who, together with Fourcroy and Vauquelin, read a long, detailed report to the Académie des Sciences on the use of different gasometers. Interestingly, the apparatus used by Seguin and his colleagues was not exclusively based on gasometers but it also included Volta's eudiometer.[64] The replication of Lavoisier's experiments certainly involved some eudiometric measurement, as testified by Seguin in the following remark:

> Notre expérience a duré 185 heures sans interruption; nous ne l'avons pas quittée un seul instant. Jour et nuit nous étions dans le laboratoire; les remplissages, les pesées, les préparations des fluides permanens; & les essais eudiométriques occupoient tous nos momens.[65]

Regardless of the results obtained by these tedious and demanding experiments, it is interesting that Seguin adopted Volta's eudiometer instead of his own in order to perform an experiment which had nothing to do with eudiometry. As Volta noted himself, his electrical eudiometer could be extremely helpful in assessing the smallest changes which occurred in the quality of inflammable air. Conversely, Seguin remarked that the same instrument was not as effective in measuring the salubrity of air.[66]

The use of two different instruments bearing the same name in two different investigative plans of research is a revealing sign that in Lavoisier's chemical research the speculative ambition of Landriani and the cautious experimental attitude of Volta coexisted and, to a certain degree, became complementary. The measurement of the salubrity of air and the experiment on the composition of water were in fact both manifestations of his new theory of gases.

[64] SEGUIN and FOURCROY and VAUQUELIN (1791), the reference to Volta's eudiometer is on p. 304; SEGUIN (1791a).
[65] SEGUIN (1791a), p. 47.
[66] "M. Volta imagina […] un autre eudiomètre, fondé sur la détonnation du gaz hydrogène; mais en le supposant exempt de toute cause d'erreur, il ne peut, de même que celui dont nous venons de parler, servir à completter l'analyse des fluides respirables, & il n'indique que d'une manière comparative, & jamais d'une manière absolue, la quantité d'air vital contiennent ces fluides", in SEGUIN (1791), p. 296.

Our analysis suggests the following conclusions. The variety of uses of the eudiometer between 1775 and 1790 undoubtedly shows the intrinsic ambiguity of experimental practice, but, to a greater extent, it reveals the hegemonic power of theory. On the sole basis of an effective test for measuring the quantity of dephlogisticated air, Landriani envisaged the creation of aerial medicine. Volta's reaction to this program was not less theoretical. His promotion of the use of his eudiometer as a detonator is revealing enough, and his ideas that the eudiometer was an effective instrument to measure the phlogistication of the air and its different degrees of inflammability was a powerful theoretical assumption which hindered him from *seeing* water as the result of the combustion of inflammable air in closed vessels. Finally, Lavoisier's and Seguin's theory of respiration became a fundamental guide in their appreciation of new potential uses of the eudiometer. Thus, the objective limitation of the instrument did not hinder these naturalists from elaborating and substantiating different theoretical standpoints. In the end, the projection of different theoretical expectations in the uses of the eudiometer were fulfilled and the instrument successfully brought experimental practice from a utopian illusion to a revolutionary research program, the importance of which became apparent throughout the nineteenth century.[67]

[67] On the development of eudiometry during the 19th century see STOLBERG (1994).

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