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# RELIABILITY AND GENERALIZATION IN EARLY MODERN ANATOMY[1]

## Introduction

Recent literature on $17^{th}$-century investigations of nature has focused on the dichotomy between singular contrived experiment conducted at specific places and times versus generalized experience, observing nature in its normal course: the former has often been characterized as primarily active and interventionist, the latter as a more passive recording of nature undisturbed. Probably Charles Schmitt and Peter Dear have written the most influential pages on this topic. Schmitt drew a distinction between Jacopo Zabarella's (1532-1589) neo-Aristotelian emphasis on the investigation of the normal course of nature versus Galileo's (1564-1642) contrived experiments, probing nature in unusual or peculiar settings. Dear has discussed a number of strategies to tackle the problem of induction, or to bridge the gap between individual cases and general statements; these strategies were both rhetorical and in the experimental practice, with the emphasis on appropriate narrative styles, witnesses, and repetition, for example. My primary aim in this paper is to take this dichotomy as a starting point to examine problematic evidence in anatomy and related areas, including natural history and medicine.[2] In this paper I

[1] Preliminary versions of this paper were presented at Caltech, the University of Milan, Northwestern University, and Indiana University, Bloomington. I am grateful to all those who offered comments and suggestions following my presentations and in informal discussions, especially Marco Bresadola, Giuliano Pancaldi, and Heinrich von Staden.

[2] C.B. Schmitt, *Experience and experiment: a comparison of Zabarella's views with Galileo's in 'De motu'*, «Studies in the Renaissance», 16, 1969, pp. 80-138; P. Dear, *Discipline and experience. The mathematical way in the Scientific Revolution*, Chicago, University of Chicago Press, 1995, especially chapter 1; L. Daston, *Baconian facts, academic civility, and the prehistory of objectivity*, «Annals of Scholarship», 8, 1991, pp. 337-363. At an early stage, specifically in the 1588-1590 *De motu antiquiora*, Galileo's experiments were marked by the expression *periculum facere*, or "making the test",

use the term anatomy in its early modern meaning, including what today we would refer to as physiology.

Why focus on anatomy in the first place? Anatomy required extensive experimentation involving a range of devices and techniques. Probably the first problem that springs to mind in the case of dissection and especially vivisection is that of ethical issues; this, however, is not my primary concern here. Anatomy is especially interesting because of its difference from the physico-mathematical sciences in that it deals with organisms involving variability at many levels and in many respects. Carrying out an experiment or even a simple investigation or inspection, or repeating and generalizing a result from one individual case, may work in different ways in the two disciplinary domains. Admittedly, issues arose with rolling and falling bodies too: bodies of different sizes, materials, and shapes behaved differently from expectations and this led to new conceptualizations about motion. I suspect that to generalize from experiments involving rolling spheres along planes with different inclination, as Galileo tried to do in *De motu antiquiora* and elsewhere, however, was quite a different matter from drawing general conclusions from a given dog or a given human to all dogs, all humans, and indeed all animals: such generalizations involve a specific set of issues dependent on the object of study, the techniques employed, and therefore the period in question. Newton (1643-1727) put the matter thus: «The causes assigned to natural effects of the same kind must be, so far as possible, the same. Examples are the cause of respiration in man and beast, or of the falling of stones in Europe and America;» respiration, however, may work quite differently in land animals and fish, for example, which have gills rather than lungs and whose circulatory system is quite different, or even insects, which lack both lungs and gills. Although they are not «beasts», respiration occurs in plants too, a finding preceding by just a few years the publication of Newton's *Principia* in 1687 and involving a different set of problems to do with structures and the chemistry of air.[3]

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a construction from Ciceronian Latin surprisingly encountered also in legal terminology. See R. Goclenius, *Lexicon philosophicum*, Frankfurt, typis viduae Matthiae Beckeri, 1613; W.R. Newman, *Promethean ambitions*, Chicago, University of Chicago Press, 2004, pp. 238-242 raises specifically the issue of Aristotle's animal dissections.

[3] I. Newton, *The Principia. Mathematical principles of natural philosophy. A new translation by I. Bernard Cohen and Anne Whitman assisted by Julia Budenz*, Berkeley, University of California Press, 1999, the second of the "Regulae philosophandi", p. 795; D. Bertoloni Meli, *Thinking with objects: the transformation of mechanics in the seventeenth century*, Baltimore, Johns Hopkins University Press, 2006, pp. 50-79; Id., *Mechanism, experiment, disease. Marcello Malpighi and seventeenth-century anatomy*, Baltimore, Johns Hopkins University Press, 2011, chapters 7 and 9.

The issue was not simply one of generalizing from one domain where knowledge was uncontroversial to other cases. Anatomy could involve such heavily tampered cases that several contemporary scholars questioned whether investigations were at all meaningful in the first place: in such cases the problem was that of the reliability of the knowledge acquired.

This essay analyses the problem of knowledge in anatomy, focusing on the reliability of anatomical investigations and the generalization from individual or limited cases to different animal species, to other individuals within the same species, and even within individual bodies – in moving from organ to organ, for example. I have identified six areas in which establishing solid results and drawing general conclusions proved problematic and generated debates and controversies. In many cases the issues early modern anatomists faced can be traced to antiquity; in some cases they encountered new problems, as with microscopy, the first truly novel technique since antiquity. In all cases, however, early modern examples offer distinctive and original perspectives on assessing problematic evidence. Ultimately, I believe that this study offers a richer and more varied picture of observation and experimentation in the early modern period, one going beyond the themes and periodization relevant to the physico-mathematical disciplines and offering new perspectives on the entire issue.

## 1. In vivo, in mortuo, in vitro

Anatomy is intrinsically problematic in that it deals either with a dead body, in which death may have introduced substantive changes, or a live animal, in which the surgical knife may lead to such dramatic effects as to invalidate any observation. Although such issues were known and debated since antiquity, the 17$^{th}$ century witnessed renewed reflections on them. In the 1665 *Micrographia*, for example, Robert Hooke (1635-1703), curator of experiments at the Royal Society, praised the novel technique of investigation that was the subject of his work over vivisection (Fig. 1):[4]

I could perceive, through the transparent shell, while the Animal surviv'd, several motions in the head, thorax, and belly, very distinctly, of differing kinds which I may, perhaps, elsewhere endeavour more accurately to examine, and to shew of how great benefit the use of a *Microscope* may be for the discovery of Nature's course in the operations perform'd in Animal bodies, by which we have the opportunity of obser-

[4] R. Hooke, *Micrographia*, London, John Martyn and James Allestry, 1665, pp. 185-186.

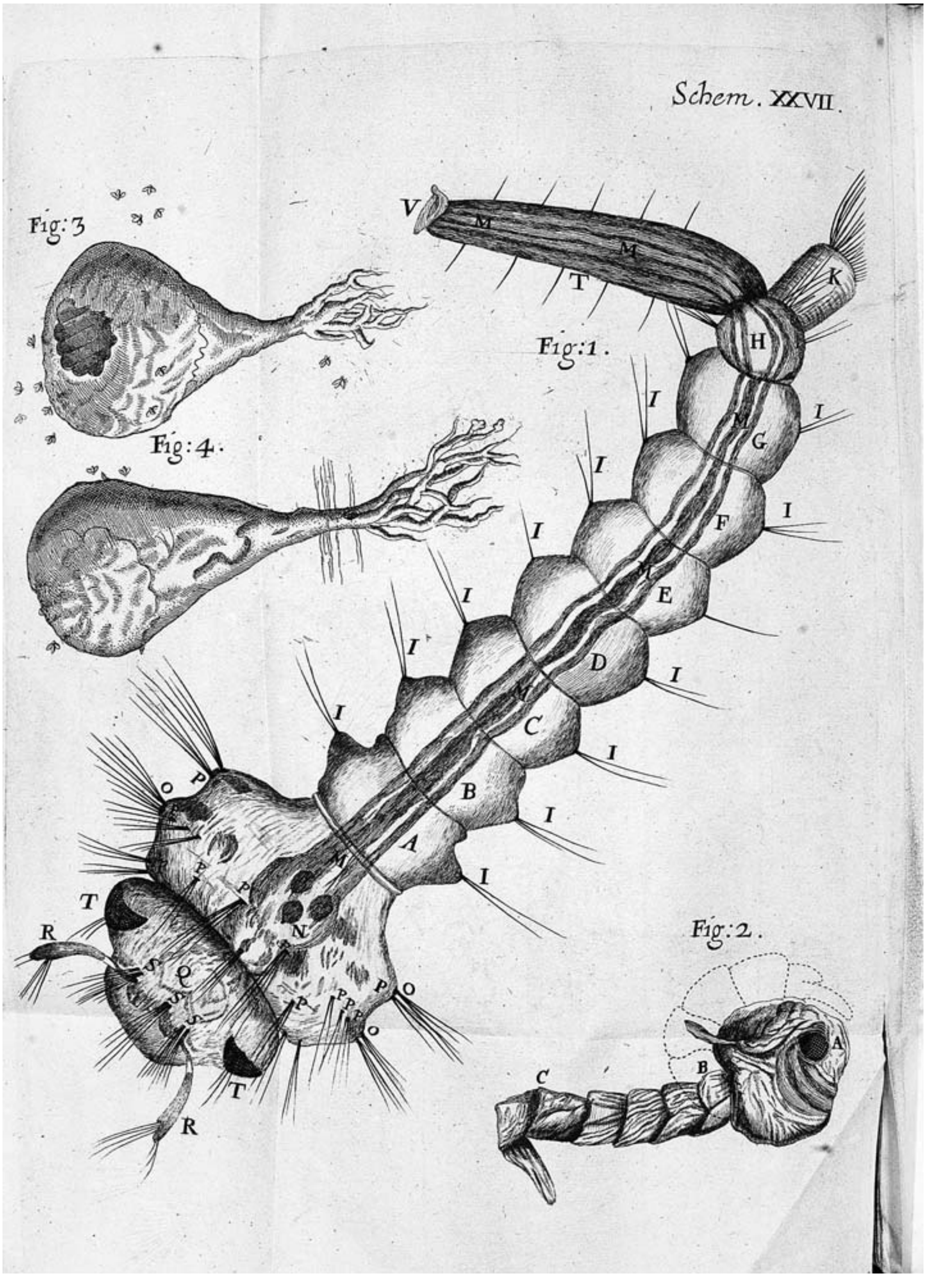


Fig. 1. Hooke's water gnat, from R. HOOKE, *Micrographia*, London, John Martyn and James Allestry, 1665.

ving her through these delicate and pellucid teguments of the bodies of Insects acting according to her usual course and way, undisturbed, whereas, when we endeavour to pry into her secrets by breaking open the doors upon her, and dissecting and mangling creatures whil'st there is life yet within them, we find her indeed at work, but put into such disorder by the violence offer'd, as it may easily be imagin'd, how differing a thing we should find, if we could, as we can with a *Microscope*, in these smaller creatures, quietly peep in at the windows, without frighting her out of her usual byas.

Here Hooke contrasted the microscope with vivisection in admittedly a rather peculiar case, that of the water gnat, whose pellucid or transparent membranes allowed the observer access to its interior. In this way one could see its digestive tract, for example, without cutting into its body and dramatically altering «by the violence offer'd» the very features one wanted to investigate. Hooke was not the first to raise objections against interventionist techniques and vivisection in particular: William Harvey (1578-1657) too, despite his extensive reliance on vivisection, was attentive to this problem when he mentioned some shrimps found in the river Thames whose transparent body allowed one to witness «with the least possible impediment» the motion of the heart.[5]

Vivisection dates from antiquity and has been accompanied by a long history of debates: the Roman physician Cornelius Celsus (1$^{st}$ century), for example, defended the dissection of dead bodies but labeled vivisection both cruel and superfluous. An old tradition of vivisection, possibly dating from Aristotle himself, consisted in assessing the heat of different organs by inserting a finger in the live animal. This procedure was questioned already in antiquity and medieval times: the brain, for example, was deemed to be moist and cold through a number of arguments, one of which was empirical and consisted in touching it through an open skull. Both Galen (129-217) and Ugo Benzi (1376-1439), however, argued that the brain is hotter than air and by opening the skull the brain can get cooler, or the trauma of the operation may make it appear cooler than it is in reality.[6] Specific as this example is, it captures the key problem that vivisection alters the object of study.

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[5] W. HARVEY, *De motu cordis*, Frankfurt, Wilhelm Fitzer, 1628, translated by Kenneth J. Franklin with introduction by Andrew Wear in *The Circulation of the Blood and Other Writings*, London, Everyman, 1993, p. 29.

[6] H. VON STADEN, *Herophilus. The art of medicine in early Alexandria*, Cambridge, Cambridge University Press, 1989, pp. 144-145; T. MANZONI, *Cuore caldo o cervello freddo? Antiche controversie alla nascita delle neuroscienze*, in *Neuroscienze controverse*, a cura di Marco Piccolino, Torino, Bollati Boringhieri, 2008, pp. 1-48: 31, 39.

In spite of its problematic nature and of the difficulty in performing elaborate experiments while keeping animals alive, vivisection proved crucial in many instances throughout the early modern period. The traditional usage of vivisection involved the study of the motions and, through them, of the purposes of different organs. The anatomist and surgeon Realdo Colombo (ca. 1516-1559) was an especially prominent vivisectionist in the 16$^{th}$ century: he defended his views about the pulmonary transit by showing that the pulmonary vein (the *arteria venosa* or vein-like artery) contained blood rather than pneuma or sooty vapors; he removed the heart of a dog to show that, in the few seconds left before it died, it could still bark, against Aristotle's views that the voice came from the heart; by dissecting a pregnant bitch he displayed the overwhelming strength of her motherly instinct, since she cared more for her pups than her mortal wounds. Possibly the difficulty and rarity of the procedure made Colombo mention reliable witnesses. Further, a number of anatomists from Harvey to Hooke and Richard Lower (1631-1691) relied on vivisection to study the motions, and in some cases the purposes, of the heart and lungs. Colombo was not alone in using vivisection to explore the purpose of organs by excising them: some removed the spleen, finding no notable effects, while Johann Conrad Brunner (1653-1727), in a celebrated experiment, excised the pancreas of a dog, finding no major consequences, with the possible exception of increased urination.[7]

However, it would be reductive to see vivisection exclusively in this light. In fact, vivisection played a key role in at least three additional areas: the investigation of structures so ephemeral that they would rapidly decay with death; the localization and magnification of processes and body parts too small to be seen without aid; and the collection of bodily fluids in sufficient amount to enable chemical analysis. I now examine briefly these cases in turn.

The first area was especially significant, starting from Gasparo Aselli's (1581-1626) work on the milky veins (1627), vessels allegedly carrying chyle coming from digested food away from the intestine, and the subsequent works by Jean Pecquet (1622-1674) and Thomas Bartholin (1616-1680) and others on the lymphatics. Aselli was able to see the milky veins during the vivisection of a dog both because the animal had eaten just a few hours earlier and because it was alive. In fact, the dog died during the vivisection and the

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[7] R.K. FRENCH, *Dissection and vivisection in the European Renaissance*, Aldershot, Ashgate, 1999, pp. 204-209; A. CUNNINGHAM, *The anatomical Renaissance*, Aldershot, Ashgate, 1997, pp. 147-160: 159; C. WEBSTER, *The Helmontian George Thomson and William Harvey: the revival and application of splenectomy to physiological research*, «Medical History», 15, 1971, pp. 154-167; J.C. BRUNNER, *Experimenta nova circa pancreas*, Amsterdam, Wetstenius, 1683, pp. 6-11, 26.

milky veins disappeared in front of his eyes as if by magic: at this early stage pressure in the vessels of live animals was crucial to detecting their existence. Jean Pecquet too found the thoracic duct – one of the most important and influential anatomical findings of the entire century, which challenged the traditional role of sanguification of the liver – with the help of vivisection. Once those ephemeral structures had become known, it became possible to study them in dead animals too with the help of injections, whose pressure distended the vessels and made them visible with the help of colored fluids. Other organs too were pertinent to similar concerns. The Renaissance anatomist and surgeon Niccolò Massa (1485-1569), possibly in response to Berengario da Carpi's (1470-1530) rejection of the existence of the *rete mirabile*, attributed its lack of visibility to the fact that with death the red spirits filling the arteries retreat to the heart, thus pointing to a possibly crucial difference between the living and the dead body; Massa was especially attentive to the techniques of anatomy. Andreas Vesalius (1514-1564) focused on the pericardium, which decays rapidly with death; he waited patiently – or may be not so patiently – at the bedside for a patient to die so that he could study it, and when he opened the chest he found that the heart was still beating, thus almost resurrecting the ancient practice of human vivisection by Herophilus and Erasistratus. Another relevant and problematic case involved the alleged glands in the cerebral cortex; when the Bologna physician Giovanni Girolamo Sbaraglia (1641-1710) argued that injections show that those glands do not exist, the young anatomist and physician Giovanni Battista Morgagni (1682-1771) replied that vivisection of the brain was essential in view of its rapid decay after death.[8]

The issues of localization and magnification were central to many investigations: Dutch surgeon and anatomist Anton Nuck (1650-1692) performed a celebrated experiment on a bitch soon after copulation: he ligated the Fallo-

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[8] G. Aselli, *De lactibus sive lacteis venis, novo invento*, Milan, apud Iohannem Baptistam Bidellium, 1627; J. Pecquet, *Experimenta nova anatomica*, Paris, Sebastian and Gabriel Cramoisy, 1651; N. Massa, *Liber introductorius anatomiae*, Venice, Bindoni and Pasini, 1536, translated in L.R. Lind, *Pre-Vesalian anatomy*, Philadelphia, American Philosophical Society, 1975, pp. 241b-242a; R. Palmer, *Nicolò Massa, his family and his fortune*, «Medical History», 25, 1981, pp. 385-410; R.K. French, *Berengario da Carpi and the use of commentary in anatomical teaching*, in *The medical Renaissance of the sixteenth century*, edited by Andrew Wear, Roger K. French, and Iain M. Lonie, Cambridge, Cambridge University Press, 1985, pp. 42-74: 51. While seeking the passages for urine in the kidneys, Massa stated (p. 197b): «perhaps these passages are open in a living creature; in the dead body I could not penetrate them with a rod», implicitly suggesting that vivisection – which he did not practice – may have been a more effective tool in this case. See also K. Park, *The criminal and saintly body: autopsy and dissection in Renaissance Italy*, «Renaissance Quarterly», 47, 1994, pp. 1-33: 19.

pian tubes and then closed the incision. After a few weeks he opened the bitch again and found fetuses above the ligature, close to the ovary. He took this result to show that fecundation could not be due to semen, which would not be able to reach so high in the Fallopian tubes, but was more likely due to an *aura seminalis*.[9]

Marcello Malpighi (1628-1694) too relied on vivisection for purposes other than the study of motions: in one instance he employed a procedure involving vivisection as a magnification device. In his study of the kidneys Malpighi discovered by means of injection and the microscope some microstructures – the glomerules – which he identified as the sites of the separation of urine. His problem was to understand how that process occurred by peering into those glomerules. To this end traditional magnification devices such as the microscope failed him, and he had recourse to unconventional ones. He ligated the ureters and renal veins of a dog, in the hope that the excess fluid accumulating in the kidneys would distend and magnify the glomerules and reveal their internal structure. However, when he opened the bitch again, he still failed to see and understand through which mechanism urine is produced. This experiment captures Malpighi's key anatomical concern: understanding the process of secretion.[10]

The Delft physician Reinier de Graaf (1641-1673) used the live dog as an apparatus for the production of pancreatic juice, in order to underpin the views about digestion by his teacher Franciscus Sylvius de le Boë (1614-1672). Unlike saliva or bile, pancreatic juice is produced in sufficiently small quantities as to make chemical testing arduous. In a remarkably challenging experiment, de Graaf attached a glass vial to the belly of a dog, with a tube reaching to the pancreatic duct (Fig. 2). This setup enabled him, after several failed attempts, to collect enough juice to allow chemical assaying by taste.[11]

It is helpful to go beyond the dead-living dichotomy by considering experiments that were performed *in vitro*, in glass or ceramics containers outside any body, whether dead or alive. Here too de Graaf proves useful since his attempt to display the effervescence of the mixture of bile and pancreatic juice *in vitro* failed. De Graaf realized that the heat of his hand increased

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[9] A. NUCK, *Adenographia curiosa*, Leiden, Luchtmans, 1691, in D. LE CLERC – J.J. MANGET, *Bibliotheca anatomica*, 2 vols, 2nd ed., Geneva, Johan. Anthon. Chouët et David Ritter, 1699, vol. 2, p. 838b; J. NEEDHAM, *A history of embryology*, New York, Abelard-Schuman, 1959², p. 144.

[10] M. MALPIGHI, *De renibus*, in *Opera Omnia*, 2 vols, London, Robert Scott et George Wells, 1686, facsimile edition, Hildesheim, Olms, 1975, vol. II, p. 93; M. FOURNIER, *The fabric of life*, Baltimore, Johns Hopkins University Press, 1996, p. 58.

[11] R. DE GRAAF, *De succi pancreatici natura et usu, exercitatio anatomico-medica*, Leiden, Officina Hackiana, 1664.

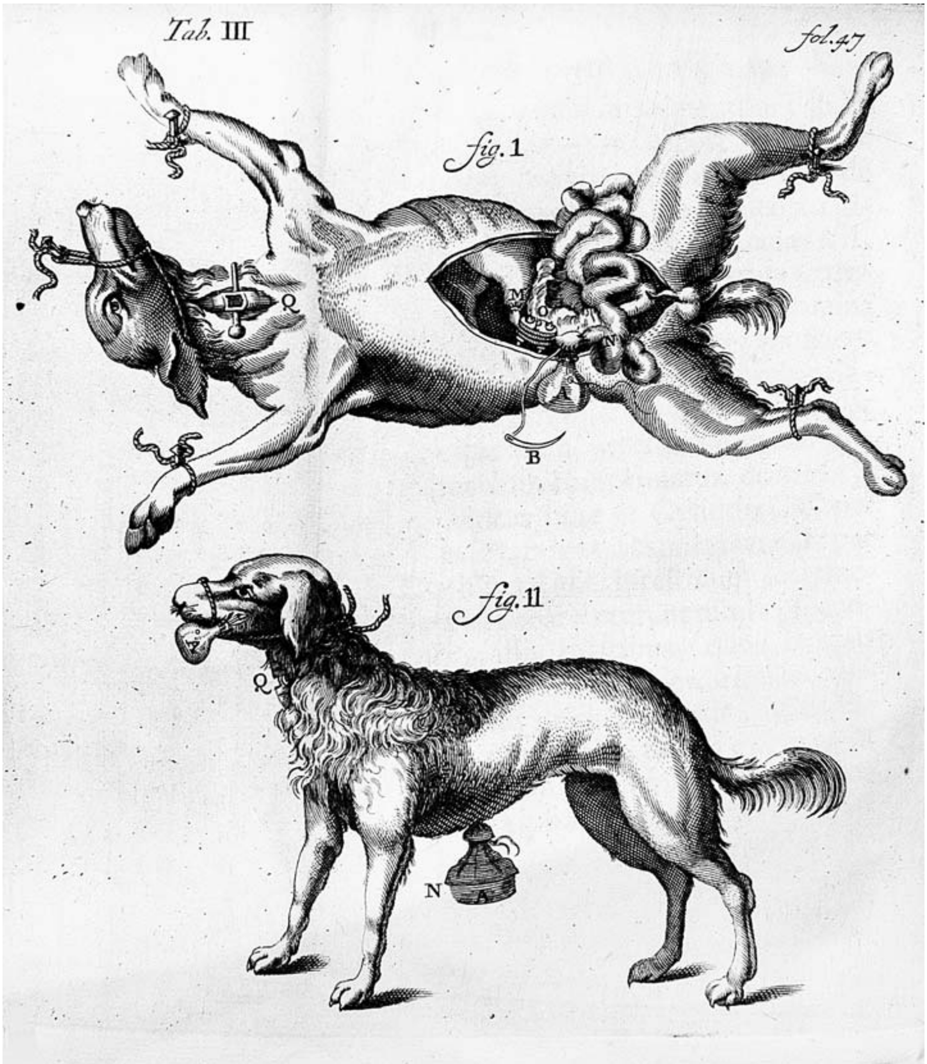


Fig. 2. De Graaf's pancreatic fistula, from R. de Graaf, *De succi pancreatici natura et usu, exercitatio anatomico-medica*, Leiden, Officina Hackiana, 1664.

somewhat the effervescence, suggesting that heat was a key factor. Thus he did not defend a difference in quality between *in vivo* and *in vitro* phenomena, as many adherents to the chymical tradition, but only one in the degree of heat. His contemporary Florentius Schuyl (1619-1669) performed similar experiments in hybrid systems composed of dog intestines with vials containing different chemicals.[12]

Malpighi had no qualms about experimenting *in vitro*; in fact, he preferred such procedures over *in vivo* experiments involving injections because he could see what was happening. Both in his treatise on the heart polyp and in a medical consultation he referred to experiments consisting in mixing blood with several compounds in order to study their effect on its fluidity. The plague, he argued, makes blood less fluid; therefore substances that increase its fluidity would be suitable antidotes. He also studied gout, which he attributed to an excess of acid in chyle, and investigated the effects of austere acids such as spirit of vitriol when they are mixed with other liquids.[13]

The three categories we have just surveyed – *in vivo*, *in mortuo*, *in vitro* – should not be seen in isolation but rather as involving a variety of what Evan Ragland has called «hybrid cases»: de Graaf's dogs and the vivisection performed by Lower and Hooke involved live animals with pieces of apparatus – flasks, pipes, bellows – attached to them, forming a hybrid live animal-apparatus. Such experiment were not new in the 17$^{th}$ century; Galen – and Erasistratus before him – inserted a reed or a thin bronze tube inside an artery that was subsequently ligated to it in order to show that pulsation is due to a faculty transmitted by the heart through the artery, because below the ligature the artery allegedly stopped pulsating. Arguably this was one of the first experiments in which a body part – a portion of an artery – was *de facto* replaced by a mechanical device during a vivisection.[14] Placing an animal in the glass evacuated container of an air pump could be seen as another example of a hybrid *in vivo-in vitro* apparatus, quite literally so.

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12 E. RAGLAND, *Experimenting with chemical bodies: Reinier de Graaf's investigations of the pancreas*, «Early Science and Medicine», 13, 2008, pp. 615-664: 648-654.

13 M. MALPIGHI, *De polypo cordis*, in *Opera Omnia*, cit., vol. II, pp. 130-132; ID., *Correspondence*, edited by Howard B. Adelmann, 5 vols, Ithaca, Cornell University Press, 1975, vol. III, pp. 1268-1269, Malpighi to Tarantino, 29 March 1687.

14 GALEN, *On anatomical procedures*, VII, 16; *Whether blood is naturally contained in the arteries*, VIII, 4; P.M. AMACHER, *Galen's experiment on the arterial pulse and the experiment repeated*, «Sudhoff's Archiv für Geschichte der Medizin», 48, 1964, pp. 177-180. According to Harvey, Galen had already used bellows to inflate the lungs of an animal, W. HARVEY, *The circulation of the blood and other writings*, cit., p. 13, from *De motu cordis*; R.G. FRANK, *Harvey and the Oxford physiologists*, Berkeley, University of California Press, 1980, chapter 8; E. RAGLAND, *Experimenting with chemical bodies...*, cit., p. 649.

Other experiments were performed joining a piece of apparatus to a dead animal or body part. Lower's and Hooke's enactment of respiration on a dead dog, in which they inflated the lungs of the deceased dog while pumping venous blood into the lungs, witnessing arterial blood exiting from them, is an example of a hybrid dead animal-apparatus experiment, one that became standard in many eighteenth-century investigations such as those performed by Albrecht von Haller (1708-1777), Luigi Galvani (1737-1798), and Alessandro Volta (1745-1827). The apparatus employed by Galvani and Volta – different metals – proved problematic and generated a celebrated controversy about the source of electrical stimuli. These hybrid cases call for a more careful and extensive reflection.[15]

This bird-eye view of early modern examples highlights the wide range of purposes for which vivisection was performed, the variety of special techniques associated with it, and some of the problems encountered. Vivisection was broadly accepted as a legitimate investigation technique, even by Hooke, who claimed: «dissecting and mangling creatures whil'st there is life yet within them, we find her indeed at work, but put into such disorder by the violence offer'd, as it may easily be imagin'd».[16] However, vivisection was also leading to problematic and inconclusive evidence in a number of cases, from the purpose of the pancreas and spleen to the microstructure of the kidneys. Opposing Sbaraglia, Morgagni deemed vivisection, as opposed to dissection, essential in the study of the brain; thus in this case it was experiments *in mortuo* that came under attack. Besides *in vivo* and *in mortuo* experiments, also *in vitro* ones offered advantages but proved contentious and problematic in other respects, as did hybrid cases: no procedure went unchallenged.

## 2. Minimalist versus interventionist techniques

Peculiar as Hooke's water gnat was, it was also to some extent representative of his approach to microscopy, in that the curator of experiments at the Royal Society employed it on outer surfaces, such as those of seeds, feathers,

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15 Galen, *On the usefulness of the parts of the body*, VII, 4, had already used bellows to insufflate the lungs of a dead animal; M.T. Monti, *Congettura ed esperienza nella fisiologia di Haller*, Florence, Olschki, 1990; H. Steinke, *Irritating experiments: Haller's concept and the European controversy on irritability and sensibility, 1750-90*, Amsterdam-New York, Rodopi, 2005; M. Piccolino – M. Bresadola, *Rane, torpedini e scintille. Galvani, Volta e l'elettricità animale*, Turin, Bollati Boringhieri, 2003.

16 R. Hooke, *Micrographia*, cit., pp. 185-186.

leaves, or the outside of an insect, rather than the microstructures of organs. Matters changed quite dramatically from the early 1660s, when microscopy became associated with interventionist techniques aimed at peering inside hidden structures of the viscera. This new mode of microscopic investigation is captured by a well-known quotation of 1683 by London physician Gideon Harvey (ca. 1640-ca. 1700):[17]

> The necessary point of Anatomy consists chiefly in the temperament, Figure, Situation, connexion, action, and use of the parts; and not in superfluous, incertain, and probably false, and indemonstrable niceties, practiced by those, that flea Dogs and Cats, dry, roast, bake, parboil, steep in Vinegar, Lime-water, or *aqua fortis*, Livers, Lungs, Kidneys, Calves brains, or any other entrails, and afterwards gaze on little particles of them through a microscope, and whatever false appearances are glanced into their eyes, these to obtrude to the World in Print, to no other end, than to beget a belief in people, that they who have so profoundly dived into the bottomless pores of the parts, must undeniably be skilled in curing their distempers; whereas those pretended Anatomical Physitians, who have so belabour'd and tortur'd the particular parts, are generally the least knowing in the whole body of Anatomy.

It is striking to notice the shift of attitude to microscopy in less than twenty years between Hooke and Gideon Harvey. What was perceived as an exemplary form of unobtrusive investigation in 1665 had become by 1683 a cluster of unacceptable interventionist techniques whose results looked pointless and misleading. Indeed, in those years microscopy had changed dramatically, largely through the hands of Malpighi, and started to rely on techniques such as boiling, scraping, staining, maceration in water, vinegar, and other solutions, and injections. Notice that the reference to «torture» in Gideon Harvey's passage expresses his rejection of excessive tampering with nature and is unrelated to ethical concerns. It is worth recalling that those techniques may have been used in especially interventionist fashion in the 17$^{th}$ century, though many predate that time: Berengario da Carpi relied on injection and Massa on boiling, for example.[18]

Alongside microscopy, injections too had become increasingly interventionist and problematic. Injection techniques required fluids used singly and in elaborate mixtures, involving mercury, alcohol, ink, wax, and several dyes, as well as injection apparatus sophisticated enough that it could be used in insect organs as well. The result of injections led anatomists such as Freder-

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[17] G. HARVEY, *The Conclave of Physicians*, London, James Partridge, 1683, pp. 30-31.

[18] R.K. FRENCH, *Berengario da Carpi and the use of commentary in anatomical teaching*, cit., p. 54. N. MASSA, *Liber introductorius anatomiae*, cit., pp. 179a, 191a, 194b, 201a.

ik Ruysch (1638-1731) in Amsterdam to believe in a largely vascular structure of the body (Fig. 3). Excessive pressure, however, may lead to extravasations and to the compression of soft parts surrounding the vessels, thus creating artifacts, as the Geneva physician and anatomist Jean-Jacques Manget (1652-1742) warned early in the 18$^{th}$ century: injections did not reveal but created a vascular structure of the body.[19]

Thus both key techniques of *anatomia subtilis*, microscopy and injections, became embroiled in controversies because they were seen as altering the object of study. The diminutive size, soft texture, rapid decay, and entanglement of body parts required special techniques that had to be invented and tested on a one-by-one basis. However, how could one attain reliable knowledge if the object of study was irremediably tampered with?

## 3. Healthy versus diseased

My next case concerns diseased states. Diseased states were at the basis of pathology; in addition, they were also used as tools to investigate the healthy body, as a window into the workings of nature, for example, or a magnifying lens. Let us examine some examples.

William Harvey repeated the reed-in-the-artery experiment to reach opposite conclusions to Galen, namely that the artery below the ligated reed still pulsates and that its pulsation is transmitted by the blood. He confirmed his view with the case of a noble gentleman whose aorta with its two femoral branches had turned into a pipe-like bone: this pathological case enacted Galen's reed experiment. Yet Harvey could detect the pulse below the bony artery, as he knew very well because the noble gentleman was his patient. In fact, he even dissected his body after death and conserved the bony portion of the aorta in support of his claim that the pulsation of the arteries is transmitted by the motion of the blood; as he put it, arteries fill like leather bags rather than bellows.[20]

Thomas Willis (1621-1675) noticed during a postmortem that despite an occlusion in the left carotid artery, blood had still reached all the parts of a

[19] F. Ruysch, *Epistola problematica quarta*, Amsterdam, Joann Wolters, 1696; D. Bertoloni Meli, *Mechanism experiment, disease*, cit., section 10.5; F.J. Cole, *The History of anatomical injections*, in *Studies in the history and method of science*, edited by Charles J. Singer, 2 vols, Oxford, Clarendon Press, 1917-1921, vol. II, pp. 285-343.

[20] W. Harvey, *The circulation of the blood and other writings*, cit., p. 114. The passage is from Harvey's second reply to Jean Riolan the Younger.

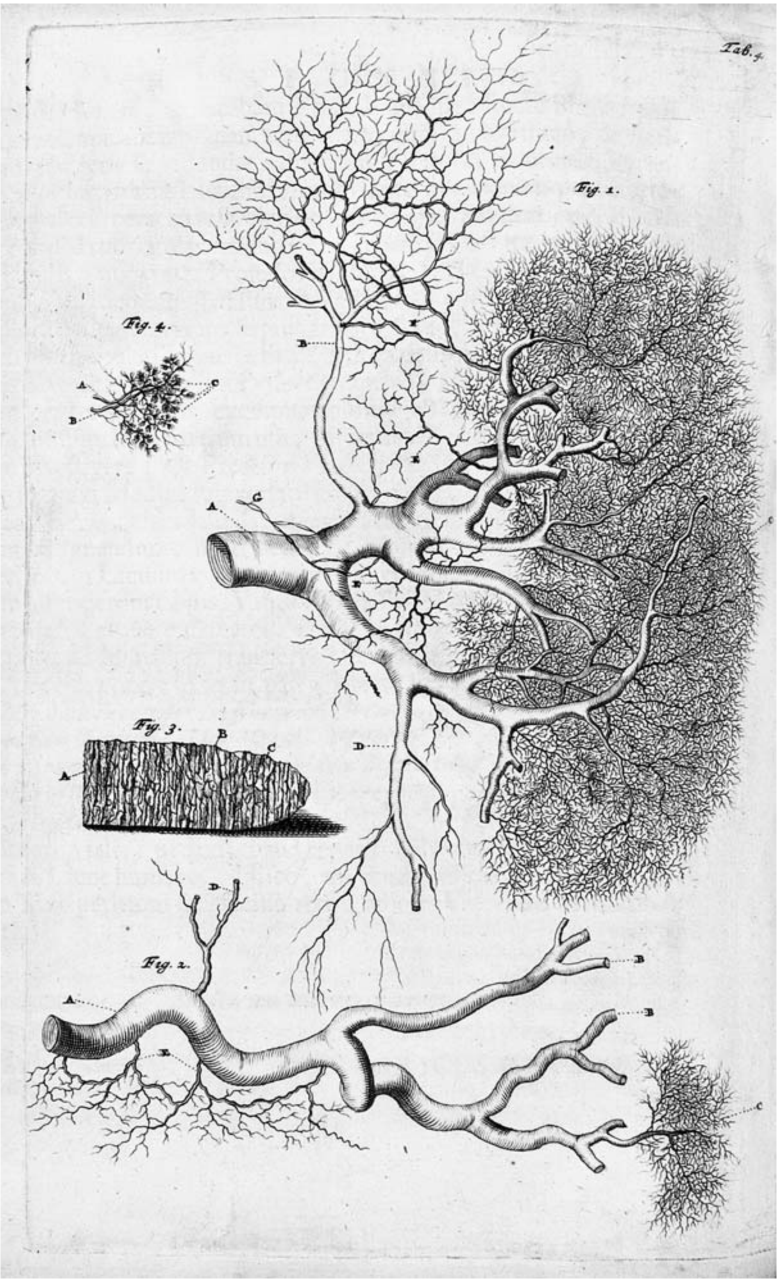


Fig. 3. Ruysch's injections of the spleen, from F. RUYSCH, *Epistola problematica quarta*, Amsterdam, Joann Wolters, 1696.

man's brain while he was alive. With the assistance of Lower, Willis confirmed his suspicion of the existence of anastomoses among the four arteries supplying the brain by means of vivisection experiments involving colored injections on a dog: the colored fluid was found to descend from the opposite side from the one where it has been injected. In this case a 'clinico-pathological' observation led to an anatomical discovery, later known as the circle of Willis. The role of the brain is so crucial that nature arranged for blood to reach all its part even if some major arteries are occluded. Another case involving Willis concerned the vexed question of how the nerves work in the operations of sense perception and motion. The traditional view from antiquity to the 18$^{th}$ century was that they operate through a fluid flowing through them; the first inklings that such transmission would proceed via electric signals was a few decades away. Unable to find evidence of a material fluid through traditional methods of cutting and ligating, Willis relied on clinical observations: he noticed that the urine of patients affected by nervous complaints turns clear and watery when they recover, a symptom he attributed to the discharge of a watery fluid from the nerves at the end of the disease. Here Willis drew conclusions about nervous transmission not from anatomy but from a clinical observation.[21]

Yet another instance concerns the glandular structure of the viscera and many other body parts. By 'gland' 17$^{th}$-century anatomists understood a filtration device separating a fluid, generally from blood: the liver would filter bile, the pancreas pancreatic juice, the testicle semen, the cerebral cortex nervous fluid, and the kidneys urine. To us the secretion of all these fluids may appear a rather heterogeneous set of processes: urine is indeed filtered in the kidneys, pancreatic juice is synthesized in the pancreas, and no nervous fluid exists or is filtered in the cerebral cortex. 17$^{th}$-century anatomists saw the matter differently: perhaps the view that filtration was accompanied by an elaboration of the fluids often described as fermentation may help bridge part of the gap with modern views. This, however, is not my aim here. Rather, I wish to argue that 17$^{th}$-century anatomists identified a number of glands – at times microscopic ones – in organs throughout the body. Diseased states helped in this identification in two ways: at times they enlarged glands, making them easier to identify and raising the hopes of uncovering their inner structure; tartar incrustations would obstruct fluid flow, engorge and therefore enlarge the gland, much like Malpighi's ligatures of the ureters and renal veins were

21 D. Bertoloni Meli, *Mechanism, experiment, disease*, cit., Introduction, section 6; on the history of electric nervous signals see M. Piccolino – M. Bresadola, *Rane, torpedini e scintille*, cit.

meant to unlock the micro-structure of the glomerules – or renal glands. By analogy with the so-called 'microscope of nature', whereby anatomists moved from species to species in search for the larger and more convenient structure of an organ to investigate, we can speak of a 'microscope of disease', or the idea that disease can enlarge body parts and make them available for investigation. Further, disease also led to the hardening of glands, which became stony or bony, enabling anatomists to preserve and display them. Malpighi was especially active in the study of glands and donated several hardened specimens to the Aldrovandi Museum in Bologna, as permanent witnesses to his views, much like Harvey had preserved the bony aorta of his patient.[22]

By contrast, Ruysch was skeptical about the existence of glands and also about many methods used to investigate them, especially diseased states. He argued that disease generated those structures, which did not exist beforehand, as shown by vascular injections, of which he was a recognized master; in his opinion obstructions of fluids in the vessels led to tumors that were mistakenly identified as glands by anatomists. His injections too preserved body parts: thus visitors to the Aldrovandi Museum in Bologna and Ruysch's Museum in Amsterdam would be exposed to contrasting and irreconcilable forms of hard evidence, one glandular, the other vascular.[23]

The evidence offered by highly interventionist investigations involving vivisection, microscopy, injections, and diseased states in order to understand the healthy organism were problematic but also offered tempting opportunity for unlocking nature's secrets. Taming those techniques was a desideratum in the eye of many anatomists.

## 4. Differences and knowledge transfer among species

Problems did not end with the taming of interventionist techniques. Even for entirely minimalist ones, issues arose because different species do not exhibit the same features; therefore generalizations proved problematic. Aristo-

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22 A. Cunningham, *The historical context of Wharton's work on the glands*, in T. Wharton, *Adenographia*, Oxford, Clarendon Press, 1996, pp. xxvii-lii; D. Bertoloni Meli, *Blood, monsters, and necessity in Malpighi's 'De polypo cordis'*, «Medical History», 45, 2001, pp. 511-522; Id., *Mechanism, experiment, disease*, cit., chapters 4 and 6.

23 H. Boerhaave – F. Ruysch, *Opusculum anatomicum de fabrica glandularum in corpore humano, continens binas epistolas*, Leiden, Petrus vander Aa, 1722, pp. 56, 77; D. Bertoloni Meli, *Mechanism, experiment, disease*, cit., section 10.5.

tle offered profound reflections on such matters, with his investigation of 'the animal' in its many manifestations. In antiquity humans could be dissected in a systematic way only during a relatively short period in Alexandria at the time of Herophilus and Erasistratus. For this reason many anatomists, even those interested especially in humans and medicine, relied on a range of species in their investigations. Galen had to rely on animals such as monkeys, dogs, pigs, or sheep; this procedure led him to a range of errors about the human body, such as the five-lobed liver, for example, which is found in dogs, and the belief in the existence of the *rete mirabile*, which is found in ungulates and other animals; neither can be found in humans. Although in medieval times and thereafter human dissection became progressively more common, animal dissection was often employed as a substitute, especially for vivisection. Vesalius made of the realization that Galen had not dissected humans the centerpiece of his monumental work, the *De humani corporis fabrica*: it was precisely because humans differ from animals and because Galen had not dissected humans and had been deceived by his monkeys and other animals that his own *Fabrica* was such a key text. Before Vesalius, in the early 1520s Berengario had already highlighted the need to dissect animals of different species, age, sex, both pregnant and not pregnant, living and dead, thus indicating his methodological and epistemological awareness about several themes addressed in this essay.[24]

In the late Renaissance the growing interest in comparative anatomy in the works by Hieronymus Fabricius (1537-1619), William Harvey, and Marco Aurelio Severino (1580-1656) led to a number of investigations on all sorts of animals from insects and shrimps to deer; Fabricius, just to mention one example, identified a huge variability in the placentas of different animals, which he grouped in four different types. The problem persisted in the 17$^{th}$ century as well, fueled by European colonial enterprises, with the growing number of rare and exotic animals filling menageries of princes and kings, from elephants to beavers and camels. It was thanks to a comparative study with oviparous animals that in 1667 Nicholas Steno (1638-1686), while dissecting a female shark, identified the so-called «female testicles» in viviparous animals as ovaries; the striking novelty of his finding can be appreciated by bearing in mind that as late as 1651 Harvey had deemed the «female testicles» as useless for reproduction.[25]

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24 A. VESALIUS, *De humani corporis fabrica*, Basel, Oporinus, 1543, dedication to Charles V; K. PARK, *Secrets of women. Gender, generation, and the origins of human dissection*, Brooklyn, NY, Zone Books, 2006, p. 168; V. NUTTON, *Introduction* to *On the fabric of the human body*, translated by Daniel Garrison and Malcolm Hast, at http://vesalius.northwestern.edu/flash.html.

25 F.J. COLE, *A History of comparative anatomy*, London, Macmillan, 1944; A. GUERRINI, *The*

Humans traditionally occupied a key position because of religious and medical concerns: after all, we have a rational soul and it is our diseases that physicians heal. The 17$^{th}$ century witnessed fresh reflections and concerns about the demarcation between humans and animals: Descartes (1596-1650), for example, located the site of the soul in the pineal gland. His claim led anatomists like Willis and Steno to search for a similar structure in other animals and eventually to question Descartes' views: the pineal gland can be found in other animals, such as fish, which seem devoid of higher functions, and its connections to the rest of the body are similar in different animals and do not justify any special role Descartes attributed to it. Similar concerns involved the organs of speech and the structure of the brain as a whole; speech, of course, was another demarcation point between humans and animals, according to Descartes – though admittedly more because of the way it is used than for the mere ability to articulate sounds, something that parrots can do too. At the turn of the century in London Edward Tyson (1650-1708) took the opportunity to dissect the brain of an orangutan in order to locate fundamental differences with the structure of our brain. These investigations point to renewed concerns about the anatomical basis for our special place in creation.[26]

An area that became especially significant in the 17$^{th}$ century in connection with the new emphasis on the microstructure of organs was the so-called microscope of nature. Anatomists of the Schaffhausen school, such as Johann Conrad Peyer (1653-1712) and Brunner, referred to the variability in the size of organs across species as a microscope provided by nature, as if nature had provided the investigator with a microscope by moving from species to species. This procedure did not necessarily involve larger animals; paradoxically, the useful animals could be quite small, what mattered was that the relevant organs would make certain features more visible. A classic example is the anastomoses of arteries and veins in the lungs of frogs and turtles, observed by Malpighi in 1661, which enabled him to close the circle of Harvey's circulation by claiming that blood always flows inside vessels. Such anastomoses are

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*king's animals and the king's books: the illustrations for the Paris Academy's 'Histoire des animaux'*, «Annals of Science», 67, 2010, pp. 383-404; M. COBB, *Generation. The seventeenth-century scientists who unraveled the secrets of sex, life, and growth*, New York, Bloomsbury, 2006, chapter 4; K.J. EKHOLM, *Fabricius's and Harvey's representations of animal generation*, «Annals of Science», 67, 2010, pp. 329-352.

[26] N. STENO, *Lecture on the anatomy of the brain*, introduction by Gustav Scherz, Copenhagen, Nyt Nordisk Forlag, Arnold Busck, 1965; T. WILLIS, *Cerebri anatome: cui accessit nervorum descriptio et usu*, London, Tho. Roycroft, Impensis Jo. Martyn et Ja. Allestry, 1664; R. SERJEANTSON, *The passions and animal language, 1540-1700*, «Journal of the History of Ideas», 62, 2001, pp. 425-444.

harder to see in higher animals, where the capillary structure is much finer; interestingly, in the *Encyclopédie* the French anatomist Pierre Tarin (1735-1761) questioned whether anastomoses between arteries and veins could be found also in humans and higher animals, since they had been seen only – he claimed – in fish and frogs, which are cold-blooded animals whose heart has only one ventricle. Malpighi was certainly not the first to have recourse to such techniques: Claudius Auberius (died 1658) had dissected the testicle of a wild boar in the mating season in order to see a larger version of structures which are also present in the human testicle, and Massa in the previous century had already relied on a bull in the mating season for similar purposes. Similar techniques are routinely used in recent biological investigations; in 1952 Alan Hodgkin (1914-1998) and Andrew Huxley (1917-1963), just to mention one celebrated example, relied on the giant nervous fibers of the squid in order to study nervous transmission, but Massa and Auberius had relied both on a different species and on a particular time of the year in order to magnify the object of study.[27]

In this case too questions were raised about nature's uniformity: up to what extent could one draw conclusions about the human liver from the liver of a snail, or a lizard, or a cricket, or a silkworm, argued Ruysch challenging Malpighi? Thus variability or differences among species offered opportunities through the microscope of nature, but also posed a threat to hasty generalizations.[28]

The situation for believers in the uniformity of nature became especially problematic in the decades around 1700 with regard to the problem of generation: as shown on the title page of *De respiratione* (Fig. 4), prominently displaying copulating snails with their intertwined penises, Jan Swammerdam (1637-1680) found snails to be hermaphrodites, thus challenging traditional anthropomorphic views about sexual reproduction; Swammerdam also challenged anthropomorphic views about the ruler of the beehive, when he discovered that the alleged 'king' had eggs and was therefore a 'queen'; Rudolph Jakob Camerarius (1665-1721) found that plants, much like snails, were mostly hermaphrodites, since in most instances the same flower contained

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[27] M. MALPIGHI, *Opere scelte*, edited by Luigi Belloni, Torino, UTET, 1967, pp. 24-25; P. TARIN, "Anastomose", in D. DIDEROT and J.-B. LE ROND D'ALEMBERT (eds.), *Encyclopédie*, vol. I, Paris, Briasson, David, Le Breton, Durand, 1751, pp. 407b-408a; N. MASSA, *Liber introductorius anatomiae*, cit., p. 199b; M. PICCOLINO, *Il nervo, l'alcol e la miccia. Le lunghe strade dell'elettrofisiologia del Novecento*, in *Neuroscienze controverse. Da Aristotele alla moderna scienza del linguaggio*, a cura di Marco Piccolino, Torino, Bollati Boringhieri, 2008, pp. 208-248: 243.

[28] H. BOERHAAVE – F. RUYSCH, *Opusculum anatomicum de fabrica glandularum in corpore humano*, cit., pp. 30-31, 68-69.

male and female parts, though in some cases, like corn, the flowers were separate on the same plant, in others, like spinach or palms, female and male flowers grew on different plants, and in a few like horsetail the female flowers seemed to be missing altogether; Abraham Trembley (1710-1784) found that fresh water polyps, once cut in half, grew their missing half back; and finally Charles Bonnet (1720-1793) found that aphids reproduced through parthenogenesis.[29]

While clearly hasty generalizations from one species to another on matters of generation proved problematic, pondered generalizations opened new horizons of research and conceptualization: it was the explicit recognition that hermaphroditism was a common occurrence in some species such as snails that led Camerarius to the realization that most plants are hermaphrodites too. As we have seen above, it was comparative anatomy that opened the way to Steno's recognition of the «female testicles» as ovaries. Thus the evidence of generation proved surprising both for the striking differences and the unsuspected similarities across species it offered.

## 5. Differences and knowledge transfer within the same species

Problems of extrapolation from a few cases arose even in the attempt to generalize within the same species. Historians from William Strauss and Owsei Temkin to Nancy Siraisi have addressed the issue in Vesalius, for example, at the time when the small number of bodies an anatomist could dissect in his career could lead to dangerous generalizations. Even among Vesalius's earlier contemporaries, Berengario pointed to the amazing variability of women's uterus in size, texture, and form, while Massa pointed out that the length of the human intestine could vary considerably from case to case, or that nature sometimes doubles the temporal muscles «as a freak». Curiously, in the 17$^{th}$ century Willis still accepted the existence of the *rete mirabile* in humans, but only in those «of a slender wit» or «destitute of all force and ardor of the mind». We see here a case of variability both across species and within the same species, with some humans resembling some animals species. Changing perceptions of the variability among humans involving different races, differences in social status and wealth to do with sensibility of the nervous system or of other anatomical parts, or even the possible distinctive features of the

[29] T.L. Hankins, *Science and the Enlightenment*, Cambridge, Cambridge University Press, 1985, pp. 131-133; M.J. Ratcliff, *The quest for the invisible. Microscopy in the Enlightenment*, Farnham, Ashgate, 2009, chapter 5; D. Bertoloni Meli, *Mechanism, experiment, disease*, cit., sections 7.4 and 9.4.

criminal as opposed to the sane body constitute a huge area of research that cannot be addressed in a short paper.[30]

Sexual differences too follow under this category. Of course, the fundamental differences involved the process and organs of generation, whose understanding underwent drastic changes in the 17th century: the human uterus seemingly stopped behaving in such erratic ways as the ancients had believed. Other matters about sexual differences were reframed according to the new chemical and mechanical understanding of the body that became predominant in the 17th century: the purpose of menstruation in women, for example, was to discard excessively acid and salty particles in blood: a defect of menstruation, for example, led to those acid and salty particles to infect blood and to diseases in the organs of the entire body. Thus generally speaking female and male pathologies differed beyond specific differences related to the genital parts and child bearing, since an affection in the lungs or brain of a woman could ultimately originate from a defect in menstruation. However, as Gianna Pomata has shown, the matter was more complex because some physicians argued that loss of blood in men, from the nose or the anus, for example, was analogous to menstruation. Although such views were not entirely new at the time, I believe they took slightly different forms from those prevalent in antiquity.[31]

Further, the 16th and 17th centuries saw the publication of several *centuriae* of remarkable and unusual cases, whether healthy or diseased; many pertained to teratology. Within the prevailing mechanistic framework of the time, monsters proved especially helpful and revealing: whereas in the Renaissance

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30 W.L. STRAUSS jr. – O. TEMKIN, *Vesalius and the problem of variability*, «Bulletin of the History of Medicine», 14, 1943, pp. 609-633; N. SIRAISI, *Vesalius and human diversity in 'De humani corporis fabrica'*, «Journal of the Warburg and Courtauld Institutes», 57, 1994, pp. 60-88; T. WILLIS, *Of the anatomy of the brain and the description and use of the nerves*, in *The Remaining works of Dr. Thomas Willis*, translated by Samuel Pordage, London, T. Dring, C. Harper, J. Leigh, and S. Martyn, 1681, pp. 85-86; N. MASSA, *Liber introductorius anatomiae*, cit., pp. 189b, 190b, 193b, 232b; K. PARK, *Secrets of women*, cit., p. 181; R.K. FRENCH, *Dissection and vivisection*, cit., pp. 136-137; D. WAHRMAN, *The making of the modern self: identity and culture in eighteenth-century England*, New Haven, Yale University Press, 2006.

31 A critical exam of Plato's views on the wondering womb is in M.J. ADAIR, *Plato's view on the 'wandering uterus'*, «The Classical Journal», 91, 1996, pp. 153-163. S. ROE, *Matter, life, and generation: Eighteenth-century embryology and the Haller-Wolff debate*, Cambridge, Cambridge University Press, 1981. For matters pertaining to generation I refer to K.J. EKHOLM, *Generation and its problems: Harvey, Highmore, and their contemporaries*, Ph. D. Thesis, Bloomington, Indiana University, 2010. G. POMATA, *Menstruating men: similarity and difference of the sexes in early modern medicine*, in *Generation and degeneration: tropes of reproduction in literature and history from antiquity through early modern Europe*, edited by V. Finucci and K. Brownlee, Durham, Duke University Press, 2001, pp. 109-152.

they were often taken as portentous signs to be deciphered at times in religious, political, or medical contexts, announcing reforms, upheavals, and epidemics, in the 17$^{th}$ century they were seen as the products of the same laws applying to normal cases; in fact, precisely because the laws at play were the same but the outcome could be dramatically different, they were seen as potentially revealing of the inner workings of nature. Malpighi made such claims explicit when he stated: «Monsters and other mistakes dissipate our ignorance more easily and reliably than the remarkable and polished machines of Nature». While working in unusual ways, nature was more likely to reveal her secrets.[32]

Individual variability and monsters posed a challenge to generalizations but also presented an opportunity at the same time: an unusual case may lead to error in hasty generalizations, but may also help unlock the secrets of nature. Thus individual variability within the same species worked analogously to variability among species, raising problems while also offering opportunities for research.

## 6. Differences and knowledge transfer within the same body

At times anatomists transferred knowledge not only from species to species or from organism to organism within the same species, but also from organ to organ in the same organism. Malpighi, for example, could observe the anastomoses between arteries and veins only in the lungs of certain animals, such as frogs and turtles: he then generalized this result not only to the lungs of other animals but also to other organs and body parts of the same animal, where the fine capillary network was not visible. Thus the view that blood always flows inside vessels was based on a rather thin body of evidence. Also in the case of the micro-structures or glomerules – the sites of the separation of urine – found in the kidneys, for example, Malpighi relied on generalization and analogy when he identified the glomerules as glandular. Glands, however, have an afferent artery, an efferent vein, and also a nervous termination, which he could not detect in the glomerules; thus he inferred by analogy with other glands in the body that the glomerules too have a nervous termination. We witness here an inference from the structure of a body component (glands) to the specific structure of that component in an organ (the glomerules in the kidneys); in this case Malpighi's inference proved problematic.

[32] D. Bertoloni Meli, *Blood, monsters, and necessity*, cit., p. 151.

Malpighi was by no means the first to draw such generalizations. Once again, Massa is quite useful in this regard, when he states that optic nerves seem to be perforated in large animals, «which reason also persuades us to believe is the case in all other nerves so that their power may be carried down through them». We find here the same form of double generalization both across species and across the very same organism, moving from the optic nerve to other nerves.[33]

Further, individual cases posed problems for generalization because the same body can differ significantly depending on age, season of the year, time of the month, and even geographical location, for example. Such variation posed problems not only in moving from one individual to another but also for the very same individual, in that the anatomical features observed in certain circumstances may not be found in others. This issue was well known since antiquity and renaissance anatomists were acutely aware of it when they sought to dissect a middle-aged (usually male) body at public functions. Cartilages, bones, and muscles could vary considerably depending on age, and the same body could differ also depending on whether it is in a hot and dry or cold and wet climate, such as in winter or summer, or on the phase of the menstrual cycle, as for women: we encounter here another instance of variability related to sexual differences, after different modes of reproduction and differences between male and female bodies. Nor are females the only examples of variability in relation to a sexual cycle: we have seen above that both Massa and Auberius dissected the testicles of a bull and a wild boar, respectively, during the mating season, in order to uncover their structure at a time when all the parts were especially enlarged and distended. Lastly, certain body parts could differ depending on the time of eating, as Aselli realized when he searched for the milky veins in a dog and found none: only in a dog that had been fed a few hours before were such ephemeral vessels visible. Although Aselli was able in this way to provide a detailed analysis of the milky veins, the technique he employed was not new: Galen had already used it long before.[34]

Individual variability had therapeutic implications in that remedies appropriate for a given geographical location, season, and age could be inadequate in different circumstances: would the cures appropriate for a European in

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[33] M. Malpighi, *De pulmonibus*, in *Opera omnia*, cit., II, pp. 140-141, 142, 143; *De renibus*, in *Opera omnia*, cit., II, p. 92. Id., *Opere scelte*, cit., pp. 92, 95, 98, 173; N. Massa, *Liber introductorius anatomiae*, cit., p. 240b.

[34] G. Aselli, *De lactibus*, cit., p. 20; Galen, *On the natural faculties*, III, 4.

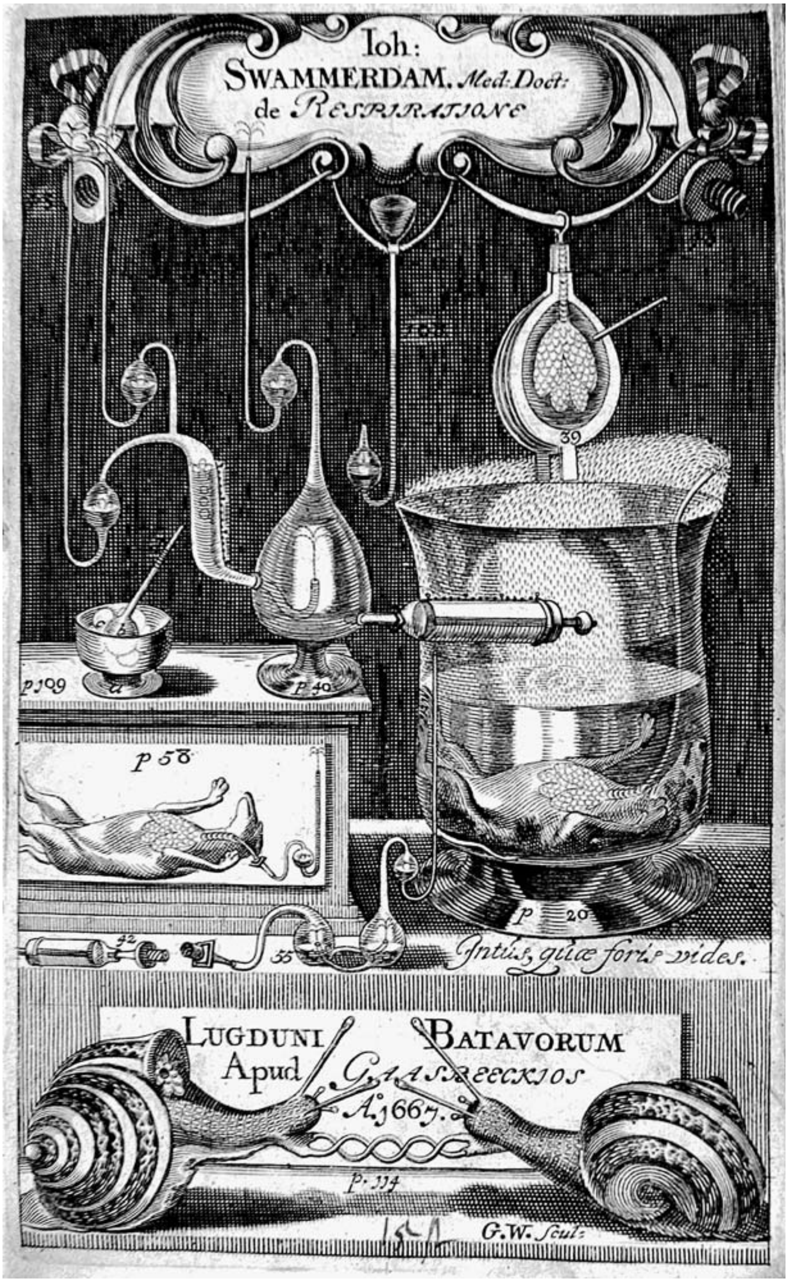


Fig. 4. Swammerdam's title page of *Tractatus physico-anatomico-medicus de respiratione usuque pulmonum*, Ludguni Batavorum, apud Danielem, Abraham, et Adrian. a Gaasbeeck, 1667.

Europe be the same for the same individual in Africa or America? Would a cure for a recurrent disease of the same individual remain unchanged as that individual aged? We witness here a problematic connection between anatomy and medical practice.

## Conclusion

The observations we have encountered highlight the existence of a distinctive set of problems related to the reliability of observations and experiments in anatomy and of generalization from them. In some cases comparative studies led to claims with a broad validity, such as the identification of the so-called «female testicles» in viviparous animals as ovaries and of the key role of eggs in the process of generation in both oviparous and viviparous animals. In most instances, however, the issue was not to move from an individual claim to a universal one, but to define the domain of validity of a claim, and also the domains where such validity would be violated. In this sense the lack of universality of a statement was not seen as a failure: defining the domain where a proposition holds true represented a considerable and often surprising advancement. At times, while beliefs in an area broke down, unexpected patterns and similarities emerged in other areas, such as the recognition that snails and most plants are hermaphrodites.

The problems of dead or living organisms and hybrid cases, minimalist versus interventionist techniques, healthy or diseased states, and the variability across species, within a species and between female and male bodies, as well as within the very same organism, highlight that handling anatomical evidence requires a considerably different set of tools from those we have become more accustomed to from the physico-mathematical disciplines. The differences were not limited to ethical concerns – important as these were – but affected central features of the investigation of nature and the key problem of induction. The fact that nature is so variable and complex posed problems about which anatomists showed considerable epistemological and methodological awareness throughout history and especially since the 1520s, witness Berengario's emphasis on differences and variability at all levels, Massa's frequent discussions of techniques and variability, Vesalius's boastful emphasis on human as opposed to animal dissection, Colombo's focus on vivisection and witnessing, and Fabricius's broad focus on comparative anatomy. 17$^{th}$-century investigators of nature had a large body of material to ponder on when it came to the problems of the reliability of knowledge and generalization from an individual case or limited area to broader domains.

Often thinking of the physico-mathematical sciences we tend to focus on universal laws, such as the law of inertia or Newton's universal gravity. Arguably, other areas involving peculiar and individual properties of matter, such as specific gravity or electrical conductivity, for example, may provide a more useful term of comparison with the life sciences and anatomy in particular, in that they are anchored to the specific features of matter, not only stone or copper in general but that specific stone or that particular batch or copper.

Many problems and concerns we have encountered date from Antiquity. Galen, for example, is an extraordinarily and to me ever surprisingly rich source of anatomical practices and reflections; the range of the techniques he employed and the depth of his analyses made him an influential figure throughout the period of my study. The chemical and mechanical understanding of the body that became dominant in the $17^{th}$ century, however, led to a reframing of many problems. Take the male-female dichotomy, for example: whereas in antiquity the differences were often framed in terms of heat and humidity, in the early modern period chemistry took on a much more prominent role, leading to a reconceptualization of the differences between female and male bodies.

More generally, the $17^{th}$ century witnessed profound transformations in the framework of anatomical investigations; boundaries were challenged in new directions. The demise of the relevance of the notion of the soul and its faculties to anatomy or physiology went hand in hand with the view that the structure and especially the microstructure of organs were key to understanding their operations. Thus while Galen often stopped at macroscopic features and invoked the notion of faculty to explain how the kidneys secrete urine or the liver makes blood, just to mention a few representative examples, $17^{th}$-century anatomists sought the answer to anatomical problems in the inner recesses of the organs using more and more interventionist techniques. Besides the optical microscope, we have encountered the microscope of nature and the microscope of disease as especially significant, and at times problematic, techniques.

Thus in conclusion early modern anatomists were acutely aware of the dangers of dealing with both the living and dead body, of interventionist techniques of investigation such as microscopy, injections, and the cluster of practices associated with them in order to delve into the inner recesses of organs and body parts, of the individual and peculiar nature of living organisms, and of hasty generalization. We have encountered debates and controversies about problematic techniques of investigation and differences among organisms and body parts at all levels. Paradoxically, however, nature's complexity and variability offered at the same time opportunities to exploit, as the many examples we have encountered show.