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RESEARCH ARTICLE

Development of a research project on physiological Biophysics of human semicircular canals

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Abstract

The author, now and since 2001 full professor on pedagogy and professional pedagogist, began his academic and research career with the biophysics of the human semicircular canals, with initial reference to problems of space medicine, in the early 1970s as a student of the degree course in physics (at that time, four years after high school) and as an experimental thesis. The results were approved by the competent committee of the Council of Europe, and the thesis was also approved with distinction. The research was rapidly and encouragingly developed both as a mathematical and physical modelling and as a study of situations of vestibological interest, but it had to be abandoned on both sides for reasons not intrinsic to the project and despite the results already achieved. That discourse is resumed, in continuity and for coherent lines, in particular on the evolution of the physical-mathematical models to be used, with regard to concerning the anisotropy of perceptual space, about the possible new ways of experimenting on young volunteers and their innovative equipment, and about the enormous expansion and considerable differentiation of application domains in which abnormal, and even non-physiological, excitations occur, of this small but important human organ of sense.

Keywords: Biophysics, Semicircular canals, Human vestibular apparatus, Physiology, Sense organs.

1 | SEMICIRCULAR CANALS. FROM AEROSPACE MEDICINE TO PHYSIOLOGICAL BIOPHYSICS

The author is known to readers of this magazine as a pedagogist, full professor since 2001. But he began his scientific career with a degree in physics and with biophysics research, the first results o are summarized in particular in *Min. Aerosp.*, vol. 8, no. 1-2, pp. 30-35, January-June 1976 (report to the 9th National Congress of Aeronautics and Space Medicine, Rome. 13-15 January 1975); *Boll. Mal. O.G.N.* , year XCIV, no. 3-4, pp. 135-169, May-August 1976; *Il Valsalva,* year

LII, no. 3, pp. 141-156, July-September 1976; the last biophysics publication came out with the author afferent to the Institute of Pedagogy of the University of Trieste where he began his new academic career, with the advantage of a firm experimental scientific training (*Il Valsalva*, year LXI, no. 1, pp. 65-66, January-March 1985).

The Council of Europe (Committee on Science and Technology -Working Party on Aerospace Physiology and Medicine) promoted in the early 1970s research projects relating to the planned entering into Earth orbit of permanent space stations. There were reasons to suspect the problematic character in many respects of the permanence of the man in a state of imponderability for prolonged periods: it wasthen proposed to build space stations in the toric form to rotate slowly around its axis, thus replacing the centrifugal reaction to the force of gravity: see f. e. A. Graybiel *Biol Med,* 2 (2): pp. 91-138, 1973; E. F. Miller, A. Graybiel, *Aerosp Med.* 44(6): pp. 593-608 1973. The solution was not as simple as it could appear to those who did not know the mechanics, since the centrifugal reaction follows principles other than the force of gravity; and, above all, a rotatory drag motion exposes the motions related to the onset of an additional type of forces, namely the forces named ”Coriolis”, which can produce effects that a medical doctor could classify as pathological. The German or Flemish pronunciation is not infrequent but it’s incorrect: Gaspard-Gustave de Coriolis (1792–1843) was Parisian: he published the first mathematical expression for this force in an 1835 paper, but the physical phenomenon was known at least two centuries before. The Coriolis’ forces, and the resulting accelerations, are also called ”compound centrifugal” or ”complementary”: such alternating designations present obvious explanatory motivations.

It is elementary to calculate the angular drag speed to produce a centrifugal reaction equal to g, i.e. 9.8 m/s^2, in a toric station rotating on its major axis (m ω^2 r if ω is uniform and r is the major radius).

As part of a collaboration between the E.N.T. Clinic of the University of Padua (dir. Michele Arslan), and the National Legnaro Laboratories of the National Institute of Nuclear Physics (dir. Renato A. Ricci), was assigned to us as a thesis the study of the phenomenon with physical and mathematical models and with experiments that reproduced or simulated the situation. Starting from a head orthogonal position at the axis of rotation, young volunteers carried out three round-trip sessions of the head along the three axes on special rotating seats, blindfolded and in a silent environment. The aim was to study the effects of this force, with detection of the two-dimensional nystagmus, neurovegetative effects by a medical doctor and with the description of subjective sensations. The angular drag speed ranged from $\pi/10\ s^{-1}$ to $\pi/2\ s^{-1}$. We also experienced higher drag speeds, but they were clearly useless for the original application purpose. The speech would have been different for subsequent reflections that were not foreseeable at the time, and which would have covered fields other than space medicine.

Generally speaking, the results were clearly negative as to the sustainability of Coriolis’ forces in general, even for very low drag speeds. The ”Skylab” platform was launched on May 14, 1973 and after the turnover of three crews for 28, 59 and 84 days, from February 8, 1974, it underwent a series of technical experiments until the relapse on July 11, 1979. It was derived from the third stage of Saturn’s missile, essentially a cylinder, which excluded the centrifugal hypothesis. Other platforms followed, but there was no re-enacting of the artificial field.

As is immediately understood by knowing the rudiments of the theory of relative motions, such a substitution would have been affected by all the consequences of the onset of Coriolis’ force every time the head was moved. This force is zero when the two

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vectors are parallel, or one of the two is null: that is, there is no drag rotation, or there is no relative motion. Symptoms similar to those of pathological arousal by Coriolis' force can occur in the medical field: but, in this case, it is more precisely referred to as the "Coriolis effect".

It will be worth remembering that the physical and physiological study of the vestibular apparatus dates back to the XIX century like other similar studies of human physiology, that in the case of sense organs were ascribed to psychology just founded as science. In these physiological studies have distinguished medical physics scholars such as H.L.M. von Helmholtz (1821–1894) and J.L.M. Poiseuille (1799–1869). The pioneer of vestibological physiology was the great physicist and epistemologist Ernst Mach (1838–1916), along with Joseph Breuer (1842–1925), the same doctor who interacted so successfully with Freud, and the chemist Alexander Crum Brown (1838–1922). In the 1900s, research had a great development and intensified recently. Biophysics is the study of biological phenomena with conceptual tools of physics.

2 | THAT RESEARCH AND ITS CLOSURE

Using a rigid-body model, the core of mathematical processing was a complex of calculations that was somewhat long but free of difficulties, also because there were several possibilities of simplistic approximations: see, for example, A.A.J. van Egmond, J.J. Groen, L.B.W. Jongkees, *J. Physiol.* 110, 1, 1949. This exposes physicists' criticism of being a "classic" process, which is, non-quantum and non-relativistic one; moreover, the application of classical mechanics to human physiology had such development mentioned. The result of the convergence of the two studies was the expected and most obvious one: the movement of the head was possible, but only around an axis parallel to the axis of the drag rotation, the effect of which is null; in any other hypothesis there were considerable effects from Coriolis forces, disorientation, dizziness, nystagmus, neurovegetative effects, appreciable even quantitatively. The thesis was dissertated (and approved with distinction) on 24/3/75, but the experimental research was discontinued a few months later due to the unavailability of the machinery, and we continued by ourselves the modellistic researches until the first 80s, that is, until it was materially possible in times when there were neither PCs nor the today the internet nor other equally necessary resources.

Some twenty scientific papers were expressed, between 1976 and 1985, only three of them in English (*N. Arch. Ital. Otol.*, year IV, no 1, pp. 7-18, January-March 1976 (in collaboration with M. Arslan, A. Martini, R. Razzolini), however very concise and with a very bad translation; *Science and Culture*, pp. 9-17. November 1979 (idem); *Annual Report INFN-LNL 1976*, pp. 101-102, http://www.lnl.infn.it/~annrep/read_ar/1977/annual_report_1977.pdf.) , and there were some participations in conferences of both medical doctors and physicists. Those results were widely cited in the most authoritative academic circles and treatises, as we can still find online today. Then the research project was progressively abandoned due to non-intrinsic reasons.. not dependent on the will of the researcher. As mentioned, he began a new academic career as pedagogist, with the advantage of university studies in physics and of an important multi-year experience of experimental scientific research. But that's another story.

Moreover, the physiological biophysics of the vestibular apparatus is still a field of research whose prospects still open up endless horizons.

3 | FROM SPACE MEDICINE TO AERONAUTICAL MEDICINE WITH EXTENDED DOMAIN

Many interpretations that were then given to that research result and tended to refer the movements of the head with respect to the body, and not to the axis of the drag rotation: "fold the head to the left or to the right" became a kind of warning, instead it should have been formulated alternately as a rotation of the head on the same plane (or around the same axis) of the rotation drag.

That idea of surrogate gravity with the centrifugal reaction was senseless in its simplism, and it would

have had no follow-up. Space stations would have had a future of great interest, even then, especially as an application research, but no one would have proposed those toric forms another time, rotation and surrogate of absent gravity. In the next space station called ”Spacelab”, active on European initiative between ’83 and ’98 hosting 22 missions, a rotating chair was also mounted; the proposal for experiment that we have been able to put forward, in the way in which we have been able to put forward and publish *Notiziario AIF* it. 3. August 1978, suppl. no. 2 *Physics in school*, April-June 1978, vol. XI, p. 7), was not followed up. Research on the head motions in a rotational field with perpendicular axis had, in short, no follow-up to the astronautics and space medicine.

However, this movement of the head in a drag rotation around an axis parallel to that of the head and the erect body was a dynamic situation of obvious application interest in other application fields, where there was also terrestrial gravity as in the experiments that had been conducted in the E.N.T. Clinic. This was already clear to us at the time, at least concerning some critical situations of the Air Force. There are maneuvers in which the aircraft is rotated right around a perpendicular axis, or almost, to that of the pilot’s head, and with angular speeds far greater than conceivable in the fallen space medicine project.

The experts are well aware of these maneuvers: it is the ”tonneau”, the ”barrel” tonneau, the ”Looping” or ”death lap” and, of course, the fall into lives. It may not be frequent for the pilot to anticipate a Looping by swinging its head around the drag axis, which is, tilting it from right to left shoulder and vice versa; but it is certainly of great use in looping the flexing the head backwards as it is a matter of anticipating the vision of the next positions until the resumption of the linear and horizontal route. They are harmful because they generate Coriolis forces the rotator movements of the head around the other two orthogonal axes, which is, back and forth in the tonneau, left and right in looping, and rotating the head around its axis, in both.

Any reference to the possible movement of the head with respect to the body would be misleading. Instead, the possible influence of relative movements of the head as Coriolis forces depends on the orientation of the axis of those movements relative to the drag rotation axis, which is not necessarily parallel to the axis of the human body.

This can be understood, for example, by the car driver, in his movement generally on two dimensions, and that when orders the car to make a drag rotation, more or less narrow and more or less fast, around an axis that is parallel to the axis of its head: to rotate the head around that same axis, better if with the head tilted forward by 30 degrees, it is perfectly a harmless maneuver as it is completely free from accelerations of Coriolis, which indeed must be accomplished to see the turning places first, as the experience of any motorist can confirm.

4 | THE ANISOTROPY OF THE PERCEPTUAL SPACE OF THE SEMICIRCULAR CANALS: A WELL-KNOWN FACT, TO BE STUDIED MORE THOROUGHLY

From the perspective of physiological biophysics, the discourse was more complex than the models that considered the three semicircular canals as if they were whole toruses, while it is well known that they are not independent, all flow into the utricle, and the two vertical canals have a common duct, latine loqui ”crus commune”. A result obtained in those researches requires attention and suggests further research, always in the combination of physical and mathematical models and experiments on volunteers. It is the anisotropy of perceptual space, at least as far as this part of the vestibular apparatus is concerned, which requires a more general study and theory: the same angular force is perceived more intense with the head ahead by 30°, that is, with the excitement only of the lateral canals, compared to other positions. It’s known that the canals are not semi-toric, the simplistic diction ”semicircular canals” has prevailed. Modelling also has a long way to go to correct the obvious inaccuracy of approaching the canals as independent of each other. We showed physically that the consideration of ”crus commune” could help explain this anisotropy; a biophysical consideration of canals in their geometric reality and in particular

in their non-independence can open up boundless horizons of study and application.

We all know that semicircular canals are activated to reveal only angular forces, which can be physiological, and Coriolis forces that can be pathological even in very low doses. Angular forces can be well reproduced, the problem is how to orient them with respect to the canals, that is, with respect to the head. If the problem shifts from the position of the head with respect to the body to the position of the head in the space compared to any vector drag speeds, a review of the models of this part of the vestibular apparatus is required. First of all, it was necessary to study more rigorously the geometry and therefore the mechanical characteristics of these three canals with all their mutual dependencies, and also the not insignificant differences in size. This would have involved anatomical research, precision measurements, which is not the expertise of either a physicist or a biophysicist, and experiments on volunteers with specific assessments of the excitability of each pair of contralateral semicircular canals, starting with angular forces and then continuing possibly with Coriolis forces designed to prioritize the excitement of a pair of canals over the other two.

The problem arises as to whether this anisotropy stems from the fact that the canals are not independent of each other, as applies to the ”crus commune” in relation to the two vertical canals, i.e. the superior and posterior ones. In fact, for the same conditions, the mere fact that the two vertical canals have a common duct explains the lower sensitivity of these compared to the lateral canals. But it is one of the many partial answers we have for such questions. The demonstration, simple and basically intuitive, is in *Min. O.R.L.* , y. 30, no. 2, pp. 137-156, April-June 1980, and in *Otolarygonology*, y. 34, no. 4, pp. 1-5, July-August 1984. But above all, the canals are not ”semi”circular, we did an estimate of 2/3 for the two verticals, and do not depend only by the common duct, as all three canals flow into the utricle and communicate with other components of the vestibular apparatus. Modelling needs more anatomical adherence, which could mean a considerable complication. Hence, the need for experiments on human volunteers with absolutely special equipment precisely for the knowledge of this anisotropic perceptual space, which is, the different sensitivity of the canals. This is a condition for a significant evolution of physical and mathematical models, condition of the evolution of knowledge, and condition of more effective application.

Here is another difficulty-’. because excitement is always about pairs of canals; and moreover, the posterior canal of one side is on a plane roughly parallel to that of the superior contrateral canal, and vice versa. However, this means that we can experience anisotropy, but for plans and not for canals. We cannot compare the sensitivity between the superiors and the posteriors canals, but between a superior and the posterior counterlateral canal with that of the other pair of vertical canals at the two sides, and the sensitivity of each pair with the sensitivity of the pair of lateral canals.

A simple rotating chair can be used, in the most favorable hypotheses, for rough experimentation on the pair of lateral canals, not forgetting the dependencies mentioned above and the not negligible dynamics resulting in the endolymph. Each can imagine the acrobatics to be performed by sitting and fastening to the chair to make horizontal the two planes of the two pairs of vertical canals contralateral and (roughly) on the same plane. You might even succeed, but how to get the fixity of the head? Do not forget that even very small movements would give rise to Coriolis forces, which are also proportional to the angular drag speed, which would soon become high with the administration of constant angular accelerations above the threshold for a not short time and increasing steps. It was hypothesized at the time, but that research had to be abandoned.

Much more complex equipment would be needed, allowing the two planes of the vertical canals to be excited separately one at a time, as well as the plane of the two lateral canals, with the possibility of comparison. It takes, for example, a platform to ensure the head and the whole body reliably, and for the head, the best system remains the dental one; and can be oriented in such a way as to make each of the three pairs of planes horizontally, and then apply a series of steps of increasing angular forces, around a vertical axis that is perpendicular to that plane, within the subjective tolerability. The

subjective comparison data is not simple and can be altered by many disturbance factors, so some training on suitable subjects and a repetition of the tests with different sequences will be required. These data, together with the detection of the nystagmus at least two-dimensional, and with the medical evaluation of the various neurovegetative effects also considered in their relative intensity, should then be compared with the accurate geometric and weight studies that give us rigorous evaluations of the system. The models resulting from this evolution will allow a better application to situations of unusual arousal of the apparatus, and a more precise knowledge.

5 | CAN WE EXPERIENCE THIS WITH CORIOLIS' FORCES?

Theorycally, one might think of the similar cycle of experimentation with semicircular canals arousal on the three planes with Coriolis forces rather than with angular forces. There is no reason to assume that the anisotropy being researched has some difference in the perception of one force or the other. The same observations apply to the difficulty of orienting the head and holding it still in a rotating chair equipment, and about the need for a device that is considerably more complex in its mechanics. In addition, there is the difficulty because the head should not be fixed but moving in a constant direction, around a constant axis. In principle, it is not impossible to obtain a Coriolis force in a constant direction and therefore with respect to which to orient once each of the three planes: the direction is perpendicular to the axis of drag rotation and to the relative speed of the head on this non-inertial system. However, the motions of the head can only to a small extent be considered linear and for such to be reproduced, among other things with many approximations: usually the relative motions of the head are rotational motions, therefore with non-constant vector speed. Also, moving the head would be problematic to maintain a constant orientation of the other factor, which is, precisely the angular drag velocity. In short, it is possible, but in a rough way and with a supplement of difficulty. The difficulties are considerable for an experimental investigation only with angular forces.

6 | BROAD APPLICABILITY

Considerable advance in knowledge about this small but important human sensory apparatus could bring us a whole range of indications about the operation in situations of abnormal and pathological excitation.

These situations are increasingly occurring in a world like our in which man's head lies continuously in non-physiological movement and induced by the most varied machinery, even without mechanical propulsion. We had to deal with space flight, with air flight, with the car; we could talk alternately, for example, about children's (and not only) recreations based on abnormal excitement also of the vestibular apparatus, and there are many; we could continue with helicopters, with mobility 3D on the water and under the water, with air mobility also on passive instruments (delta plans, paragliders), or with exercises such as bungee jumping, and so on. But these are just examples. Think to skiing, not just the acrobatic one (hot dog), in the slalom, the angular accelerations and round-speed drags are, at times, very high, the relative movements of the head are abrupt and very varied. Think of the dancers or gymnasts who make pirouettes and know that in that drag how to move the head around its axis with two cautions, while it is much more difficult to tilt the head.

Even more pronounced is the phenomenon of dancing on roller skates, and the speed of drag rotation is even greater for ice skaters when they make accelerated pirouettes by bringing their arms closer to the body. It will not be a negligible fact to keep the head fixed by the ice speed skaters, save a barely anticipate the curves with a rotation of the head, once again, on an axis parallel to the drag rotation. The world record for 1000 meters of ice speed (Shani Davis) is 1m 6s 42/100 i.e. at a speed of 15,058m/s, while the world record of the 100 meters flat, all in straight, is 9s 58/100 (Usain Bolt) i.e. at a speed of 10,438m/s. Vestibular problems are today's problems that tend to become more relevant in a readable future perspective.

Biophysical studies can help in a very significant way.

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