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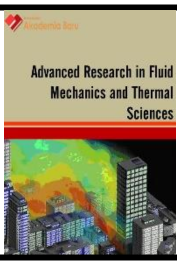

Hydrodynamics of Bluefin Tuna – A Review

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ABSTRACT

In the recent years, the study of unconventional fish-like bodies has been growing with the purpose of developing more efficient under-water vehicles; inspiration from nature to emulate these life forms to understand their propulsion system and to attain superior manoeuvring has given birth to the field of aquatic Biomimetics. Because of their remarkable capabilities, fish have shown extraordinary adaptation towards underwater locomotion which naturally has led to the sense of curiosity among engineers. A limited number of works has been published on bluefin tuna which is considered the largest Tuna species and the largest bony fish in ocean, weighing over 540 kilograms with length reaching over 3.05 meters and with a lifespan of 30 years. This fish has evolved overtime in terms of high-speed (reaching 75-100 km/hour), making it one of the fastest fish that swims in pelagic zone of oceans. Their torpedo shaped body is the most hydrodynamically efficient shape possible, making them the ultimate fish. This paper presents an overview of literature studies done exclusively and relevant to bluefin tuna. The review is divided into following sections: (I) Introduction (to swimming classification), (II) Thunniform Locomotion, (III) Undulatory Motion and Propulsion, (IV) Energy Efficiency and Energy Extraction, and (V) Computational Studies. The review highlights that this riveting fish is not only fastest but also, warm-blooded unlike any other fish that dives in pelagic zone and how that contributes to its high-speed. This paper aims to show that thunniform locomotion, with an emphasis on the lunate tail propulsion, is the most efficient locomotion only attained by super-advanced fish, and highlights the propulsive efficiency of thunniform motion which reaches about 70%, and the energy saving techniques adopted by bluefin tuna to make it the most efficient engine created by nature.

1. Introduction

Fish locomotion became a subject of utmost importance as earlier as fourth century B.C.; Aristotle wrote down his observations about how fish swim but failed to understand the undulatory motion which till date remains the primary method of swimming among fish. In his bid to understand the mechanism of fish locomotion, he tried to outline a similarity between motion of a snake and the

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walking of quadrupeds (animals with four feet). Through his work, he determined and strongly believed that paired fins become the main locomotory organs of fish as they are aligned on the sides during swimming. Consequently, the first attempt at mechanical analysis of fish locomotion was done by Borelli, a disciple of Galileo, who in the year 1680 published a diagram of fish swimming by sweeping its caudal fin and peduncle side-to-side in an arc (image reproduced in Gray, 1968). He dismissed the concept of Aristotle and further outlined the role of the gas bladder in controlling the specific gravity and hence, the position of the fish in the water. It was not until 1926, when Breder was able to classify and categorize fish locomotion correctly [1]. He built a boat which swam forward by utilizing an earlier version of boat propeller system that is known as oscillating vane propulsion system. This helped him understand the motion of fish and its applications. His line of work was further expanded by Lindsey in 1978. Her work, eventually, became the foundation for the study of classification of fish locomotion [2].

After Breder and Lindsey, other notable contributions in the physiology of fish locomotion were done by Blake [3] followed by Webb [4]; their contribution will be elucidated shortly. Numerous authors at that point had described fish swimming movements, but Gray showed clearly how it can be understood as a combination of two-wave like phenomena [5]. The most modern, comprehensive, and latest review in this field remains by Videler whose work is derived and inspired from Gray's. Videler's work covered a wide variety of very complex and intricate subjects regarding fish swimming which included physics and hydrodynamics, muscle physiology, kinematics of movements, energy and ecological study [6].

Furthering Breder's work, based on the body shape and the locomotory organs, Webb categorized fish locomotion into three: (I) BCF Periodic - Body and caudal fin, (II) BCF Transient - Fast starts and turns, and (III) MPF - Median and paired fin swimmers. BCF propulsion is used for high speed thrust, while MPF for slow speeds [4]. It has been seen that MPF swimmers can also employ BCF propulsion in response to stimuli indicative of danger which initiates an escape motion known as an escape reaction or an escape response [6]. The above propulsion classification involves different mechanical fundamentals and principles including ones by Blake [3], Videler [6]and Lighthill [7].

Blake categorized undulatory propulsion in steady (periodic) continuous swimming into four groups: anguilliform, sub-carangiform, carangiform and thunniform [3]. This work was a modification of Lindsey's classification. The thunniform locomotion, found in faster moving and stiffer fish, is a type of BCF periodic propulsion. In this type of locomotion, undulations are limited to posterior part of the body (characterized by the caudal fin). The thrust is attained by sending alternating waves towards the caudal fin that creates sinusoidal oscillating waves which in turn creates a jet in the wake of the body of the fish, hence resulting in the thrust [8]. It is the generation of reaction forces that move the body forward. Also, the highly oscillating lunate and homocercal (the upper and lower portions of fish tail are symmetrical) tails with streamlined bodies helps them to attain high swimming speeds [8]. This type of fish locomotion involves tails of high aspect ratio with smaller lateral oscillation of the body [9]. This mode of swimming is found in the family of Scombrid such as Atlantic and Pacific bluefin tuna whose anatomy for further understanding is shown in the Figure 1 below.

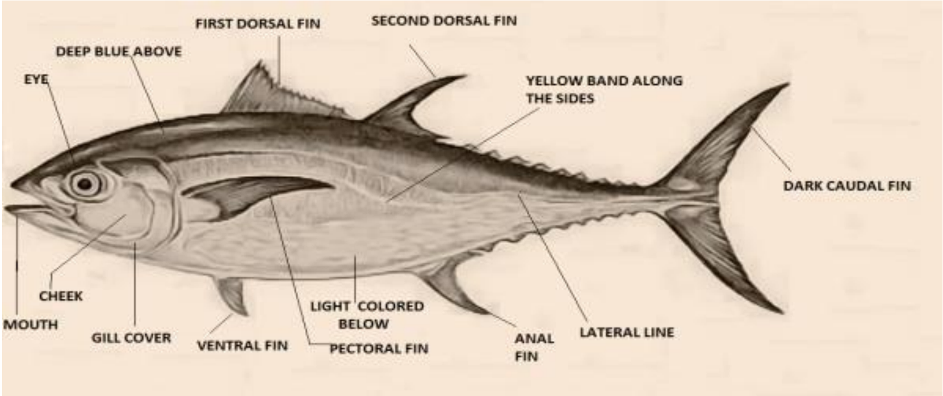

Fig. 1. Anatomy of Atlantic bluefin tuna

It remains unexplored and unknown whether the shapes of thunniform swimmers have evolved predominantly to enhance and optimize the locomotion. The convergent evolution process is believed to be responsible for the classes of vertebrate fish to adopt most superlative 'thunniform' design. Regarding the swimming performance, energetics and muscle physiology of tuna, recent studies contradict some of the predictions of hydro-mechanical models when a comparison between Carangiform and thunniform was done [10]. It is noteworthy that there is ample research available on comparison of Carangiform vs. Anguilliform [11] but a limited comparison work on Carangiform vs. Thunniform. This calls for an elaborate study of thunniform locomotion. Additionally, Thunniform swimmers have inspired the thrust generation of the tailed boat [12].

In order to understand the concept of endurance in fish, Beamish classified speeds and fatigue of fish into three major categories: sustained, prolonged, and burst swimming. Sustained swimming has speeds that can be maintained for longer periods (>200min) without muscular fatigue [13]. Prolonged swimming (20s to 20mins) ends in fatigue. Burst swimming ends in fatigue in < 20s. The maximum velocity that a fish can maintain for a precise time period is called critical swimming speed whose concept was put forth by Brett [14]. A study of maximum swimming speeds of juvenile bluefin tuna was found out to be 4.2 ± 1.8 SL/s [15]. The giant bluefin tuna showed continuously sustained swimming speeds between 1.2 - 3.2 m/s, or 86-260 km/day, or up to 94,608 km/year [16]. It is worth noting that the distance around the Earth's equator is 40,074 km, and two bluefin tuna's (estimated weight = 225 kg and 170 kg) tagged in the Gulf of Mexico were re-caught 118 and 119 days later, respectively, near Norway having swum 7778 km at a speed of 2.74 km/h, 0-76 m/s^2, or no more than 0.3 L/s [17]. This gives us a peek into the exceptional endurance and high-speed world of bluefin tuna.

2. Thunniform Locomotion

In thunniform swimmers, the thrust is generated exclusively by a highly stiff caudal fin mounted on an extremely narrow peduncle. The undulation is confined mostly to the caudal fin. The undulations are limited to 1/3 rear of the body and reaches maximum amplitude at the end of the tail peduncle [18, 19]. Literally speaking, the term 'thunniform' means to swim like a tuna. The bluefin tuna has a shape suggestive of the thunniform swimmers [20]. The caudal fin remains the main propulsive device driven by tail peduncle as it oscillates in these swimmers [21-22]. In tuna's, the high-speed, rapid, and powerful strokes of the caudal fin can be comprehended from the quick and high-pitched sound made by it during its death-throes on the deck of a boat [23]. There are certain dangers to a fish swimming at such a high speed. It has been researched that the structure of bluefin tuna ears has a material in the ear cavity that is denser than other fish species known to mankind.

Interestingly, this not only offers it a protection during high accelerations but also, enables it to see during high-speed turns [24].

Posteriorly speaking, in these swimmers the propulsive force is delivered from the massive body muscles to the caudal fin by a system of tendons which run like pulleys past two joints towards the end of vertebral column. A study aimed at understanding the flow features and vorticity structures by investigating the hydrodynamic performance of the caudal fin and the wake generation showed that front parts do not move while as the posterior parts move to induce oscillation which generated thrust [25]. They have on an average 7 to 10 finlets running from curved dorsal and anal fin to the peduncle of caudal fin, and similarly have lesser number of finlets following the anal fin which starts short after the second dorsal fin. The finlets contribute very little to the propulsive force, but they serve by deviating the water along the peduncle to prevent separation of the boundary layer which leads to reduced overall drag; this is similar to the wing-tip slots used in aircrafts. Bluefin tuna, also, have horizontal keels on either side of caudal fin base which are converging towards the posterior part of the Tuna. These keels direct a jet successively reducing the cross flow and boundary layer separation [26]. The body of bluefin tuna is wide, heavy and streamlined similar to a torpedo, anteriorly. The first dorsal fin reduces flinching and recoil while as the second dorsal fin has similar hydrodynamic function as that of the finlets.

3. Undulatory Motion and Propulsion

The most inherently common technique of swimming implemented by the most aquatic animals is the formation of a transverse wave moving along the body from head to tail known as undulatory motion. The extraordinary performance of some cetaceans (like dolphins, whales, etc.) and some recreational fish (like tuna, marlin, swordfish etc.) are due to undulatory mode; these fish are known to have strong and stiff caudal fins of large aspect ratio. The bluefin tuna uses a propulsive wave of low amplitude and high frequency [27]. Undulatory mode of swimming is commonly used for a swifter routine swimming and extended sprints [4, 7] while as, at lower swimming speeds, fish transition to finned propulsion, either by oscillating or undulating their fins [28, 29]. It is worth mentioning that large cetaceans such as whales having lengths from 2 to 30 m can swim at a cruising speed from 6 to 10 m/s [30], while as Tuna can swim at 20 to 27 m/s.

From a biomechanical point of view, when it comes to undulatory motion, its crucial to understand interaction between muscle contractions and the body wave, and the interaction between body wave and water, respectively, in order to generate propulsive forces. The process of converting muscle forces into propulsive force consists of three steps: 1) the muscles generate forces, 2) the muscle forces are disseminated to propulsive structures, such as the tail (caudal fin); and 3) propulsive structures push against the water. These steps are synonymous to the three main components of any propulsion system which include motor, transmission and propeller [31]. The extent of functional integration is linked to the distribution of the propellers (fins) along fishes' bodies. In undulatory swimmers with wide amplitude envelope, most of the body contributes to generating thrust [32] whereas fish with narrower amplitude envelope generate thrust mainly with their posterior body; in some extreme cases, only the tail acts as a propeller [33]. The latter is the case of bluefin tuna.

In the last two decades, several new techniques have been used to understand relationship between axial muscles and swimming power. From Electromyographic (EMG) studies [34-35] to mathematical modelling [6] to kinematic studies including experimental and computational flow study [36].

In order to understand the mechanics of swimming: thrust, drag and hydrodynamic efficiency, it is of importance to understand the two important dimensionless numbers: Reynolds number and Strouhal number. These concepts can help us to build a model of undulatory motion. While one explains steady motion of the hydrofoil which is the bluefin tuna in our case, and the latter explains the flapping motion (oscillation). Reynolds number shows the relative importance of inertial forces and viscous forces. It is worth noting that water is 800 times denser than air, and 20 times less viscous.

$$Re = \frac{\rho U L}{\eta} \tag{1}$$

where ρ is fluid density, U is forward speed, L is length of the fish and ŋ is the dynamic viscosity

$$St = \frac{fA}{U} \tag{2}$$

where f is the flapping frequency, A is the flapping amplitude, and U is the forward velocity.

The value of Re for most cetaceans is 108, for migrating fish (in our case: bluefin tuna) 106, for tadpoles 102 [37]. It is of importance to understand the significance of Reynolds number which covers the entire range of interest known to hydrodynamicists. For large Reynolds number as is the case of bluefin tuna, the inertial effect is more important than viscosity because inertial effect creates an irrotational flow outside thin boundary layer while as viscosity only plays an important role in creating skin friction. The highest mean Reynolds number for sustained swimming (6.3 x 105), observed for bluefin tuna over 200 cm long, is just above the range over which flow would be expected to be laminar over a rigid streamlined body [4].

The Strouhal number describes the wake of the flapping foil (flap-ping fish) but not the foil alone (fish) [38]. It defines how fast the tail is flapping as compared to speed. The most efficient fishes seem to flap with a Strouhal number between a range of 0.25 to 0.35 [38]. Thrust and efficiency are strongly related to Strouhal number [39]. It important to the avoid critical Strouhal numbers; when the flapping body starts to lose thrust, it gives us with the value of upper critical Strouhal number, while as, when the body is losing both its thrust as well its capability to use vorticity control and manipulation, it gives us the value of lower critical Strouhal number[11]. A study rendered thunniform locomotion as inefficient at lower speeds [36]. Also, it is used as an indicator for formation of shedding vortex; higher the value of St, the more shed vortices and more aggressive vortices are produced around the body [40]. Despite the fact that the importance of the Strouhal number at higher speed is undeniable; in reality it doesn't help capture the complexities of swimming efficiency in fish at slower speeds [39]. This leads us to a conclusion that a thorough study is further required in order to understand this further and to come up with a solution for this problem.

The undulations in the body of the fish generate hydrodynamic forces that act on the body which can be divided into two components: one along mean path of motion and one perpendicular to mean path of motion. The component along the mean path of motion is the sum of thrust and drag. The fish can control thrust by regulating the speed with which the body travels down the body [20]. If the wave speed is higher than the swimming speed, the fish generates thrust; however, if the wave speed is lower than the swimming speed, the drag decelerates [21]. As long as the total of thrust and drag balance the duration of one complete tail beat, the fish continues to swim steadily over following successive tail beat cycles.

A few researches and investigations done on the oscillating lunate-tail, also known as crescent-moon shaped tail, as exhibited by bluefin tuna have been done by using methods such as large-amplitude elongated body theory as engaged by Lighthill [7]. He was the first to apply a two-dimensional oscillating-airfoil theory on lunate tail which appears to be of an important value in hydro-dynamics of fish as a first mathematical understanding towards propulsion of lunate tails [20] as exhibited in our case by buefin tuna [19] which has caudal fin of high aspect ratio.

Lighthill elucidated the relationship between mass of water (called it the virtual mass) and fish body movements. He showed how difference in velocities (according to Bernoulli's theorem) between rapid water near tail and still water at some distance creates a pressure difference which creates the propulsive force. Through other methods like Videler's hydrofoil approach of finding lift force and drag force, it can be seen that lift force makes a positive contribution and drag makes a negative contribution to the propulsive force [6]. Based on the conservation of energy, an important correlation between undulatory mode of propulsion and large Reynolds numbers was found; it was done by calculating waving motion of a 2D flexible plate [41]. These results till date stand significant showing that the undulatory motion is desirable.

A study modelled undulatory swimming found in aquatic vertebrates, and concluded that undulatory swimming is the most effective means of locomotion among fish and proved that caudal fin of large aspect ratio and large sweepback angle result in larger cruising speeds [36] and these results are in consistence with the previous study that established that bluefin tuna are known to have an efficient propulsive technique during cruising [42]. The three-dimensional wing theory was improvised from Lighthill's 2D method [43] and later on, lifting surface theory to calculate thrust on different wings [44]. The above methods as well as the lifting line established a fact that lunate-tail achieves better hydrodynamic performance in terms of propulsion efficiency as compared to the rectangle flapping foil [45].

In addition to above, a modern theory called three-dimensional waving plate theory showed that three-dimensional effects can be greatly reduced by undulatory motion, proving further the importance of undulatory motion [46]. A study on propulsive mechanism of rigid and flexible oscillating tuna-tails whose results showed that rigid tail produces higher propulsive efficiency when the hydrodynamic load is less while as flexible tail produces much better propulsive efficiency when the load is high which provides an insight into the hydrodynamic performance of the tail of the tuna [22]. This was backed by another research which proved propulsive efficiency of rigid caudal fin of tuna is high but at the price of mechanical rigidity [29]. Another significant research compared the hydrodynamic performance of caudal fins of tuna, dolphin and whale by using a 3-D potential flow method, and they concluded that tuna caudal fin has largest propulsive efficiency [37]. This can be shown in the graph below. To back this up, it has been elucidated that bluefin tuna have swimming efficiencies ranging from 62-72 % [21].

Consequently, the above researches show us an efficient and outstanding propulsive performance of bluefin tuna. The experimental records show the amplitude of tuna’s tip to be between 0.15 - 0.2 of the total body length which has been proven to be the highest mean propulsive efficiency [47].

4. Energy Efficiency and Energy Extraction

Hydrodynamics of swimming is only a small portion of the whole problem. From the bioengineering point of view, the entire process begins with the biochemical energy stored in the swimming creatures, which can be converted into mechanical energy for maintaining the body motion; the latter is in turn transformed into hydrodynamic energy for swimming. A part of the hydrodynamic energy is spent as the useful work done by the thrust, which balances the work done by frictional drag, and the remaining part becomes the energy lost, or dissipated, in the flow wake.

It is a well-known fact that the shape of Tuna helps decrease energy consumption [48]. There are other ways which makes it an efficient energy saving hydrobiont capable of travelling long distances. A study postulated that Pacific bluefin tuna (PBT) dive during the day for food scavenging. The study showed that the diving depths of PBT increased during North Pacific Sea migration [49]. This type of movement is known as glide and upward (GAU) swimming which is exhibited by scombrid fish [21]. On calculating the Kinetic energy of GAU swimming movements, it was reported that compared to the horizontal swimming mode, or continuous swimming mode, the GAU mode enables the scombrid fish to save energy [35]. Therefore, these studies proved that GAU is the most efficient energy saving mode of swimming.

Another study calculated the energy-saving techniques of Pacific bluefin tuna and computed that smaller glide angle results in longer horizontal distance during the gliding phase which saves energy during migration [50]. This is in consistence with previous results.

Tunas are heavier than water; they possess negative buoyancy. Their respiration system is adapted to continuous swimming to achieve high velocities and have blood system which maintains their body temperatures above the water [27]. Hence, they are considered warm blooded unlike other fish that dives in pelagic zones (the cold desert of the ocean) and it has proven to contribute to their high swim speed [14]. Being endothermic or homoeothermic in nature, they use a system of retiamirabile which acts at a counter-current heat exchanger in the blood circulation and blocks the transportation of heat to gills [17]. Bluefin are able to maintain high stomach temperatures and a maximum muscle temperature of 28 ^{o}C in 7 ^{o}C [50]. This makes them an active predator with evolved heat conservation systems that elevate their body temperatures [51]. While this strategy may help Tunas for maximizing their swimming speed, it is accompanied by a potential flaw as well. A device that gets warm as it functions faster and vice-versa creates a potential thermal runaway. It is a known fact that in a struggle to free itself from a forceful capture, the Tuna is capable of cooking itself to death during the struggle. They are still the creatures of immaculate existence that specialize in energy speculation.

In addition to this, the flow control mechanism adopted by bluefin makes them the masters of energy extraction. A few numerical and experimental studies done on oscillating foils and biomimetic flows have shown that flow control, besides helping in energy extraction, also, helps in achieving turbulence reduction and separation elimination [19, 52-56]. This exploitation of vortex shedding has helped fish like bluefin tuna to minimize energy and maximize efficiency with a possible potential to improve the overall thrust [57-58]. This was backed up by earlier computational and numerical analysis addressed towards the study of the flow characterization and vorticity control mechanisms adopted by tuna which showed that the energy loss in upstream wake generation results in an increased swimming efficiency due to efficient thrust generation [37]. The wake recapturing and increased thrust are related to the shape of the caudal fin of bluefin; due to narrowed body near peduncle region and the sharp trailing edge of the said body [47]. This will further be elucidated in the section below. Based on the previous reviews on the state-of-the-art on the development of propulsive systems, a call for the study of viscous and separated flow processes is much needed [59].

5. Computational Studies

The interaction between fluid flow and flow structure can be studied through elaborate computational studies; besides helping to grow our understanding of the significance of vortex formations and turbulence on anatomical structures. The computational studies use Navier-stokes equations to solve the fluid problems whether inviscid or viscous in nature. A three-dimensional incompressible solver to compute the unsteady flow past a tuna with caudal fin oscillations was developed in the year 1996; it remained the first of its kind at the time [60]. After this followed a series of computational studies that accentuated the importance of vorticity control employed by fish during propulsion and manoeuvring to minimize the energy needed for locomotion [9, 37, 53, 61]. These studies confirmed the computational studies as a powerful and resourceful problem-solving tool.

One such work discusses the turbulence created by BCF swimmer; the results show that the increase in Reynolds number is proportional to vortex structure separation from the fin [62]. A reverse Karman vortex sheet is seen to be created in the tail wake resulting in an overall thrust of a tuna-like swimmer [25, 63]. In a report published by Naval undersea warfare division in USA, the experimental and computational study determined the location of transition to turbulence on tuna for various speeds and it was shown that the boundary layer remains laminar up to 3m/s [48]. In addition, this shows the limited work done in this field. It is rare to find studies that show the effect of turbulence on propulsive efficiency [64].

Till date no ideal hydrofoils have been created that exhibit the highest performance of swimming, shape and stiffness interaction [65]. It is already known that the fish like bluefin tuna have higher aspect ratio [5, 32, 66, 67, 68, 69] tend to have longer leading edges which helps in higher lift production and in turn remains an important aspect in creation of the hydrofoils. This application can be accomplished through the extensive CFD study of bluefin tuna.

The largely used models in computational software's are RANS, LES and DNS. DNS gives us the most accurate, detailed descriptions of turbulence but LES, or LES-RANS models remain widely and most practically used, which calls for major development in the study of turbulence in computing field. A major inhibition for their reliability and predictability remains the lack of a universal measure for LES resolution [70].

As an alternative to CFD, the study of juvenile Tuna fish is preferred and is much easier over the study of adult fish [71] adding to the list of impediments in the progress of this biomimetic studies.

It has been suggested, while accentuating the advancement in computational studies, the future work of studying hydrodynamics of fishlike bodies can be divided into three domains of research which go concurrently to provide us a complete outlook of biomimetic study of fishlike bodies: the effect of morphological difference, locomotion diversities and the boundaries conditions to the swimming performance of fishlike body [72].

6. Conclusions

This review wants to serve as an important binding key to both old and latest studies related to the importance of studying the bluefin tuna hydrodynamically, computationally and anatomically. It can be seen a limited number of researches has been done on this quintessentially designed fish. While the review has highlighted the significance of swimming efficiency of bluefin tuna which is nearly 80%, it has also shed light on the gaps that need to be worked on. Among them four most prominent ones remain: i) the limited development of computational fluid dynamic models of bluefin tuna, ii) a limited work on wake-vortex and turbulent flow studies, iii) the transition of boundary layer on a tuna swimming remains an open question and, iv) the hydrodynamic function of all the other fins (dorsal, anal, pectoral, ventral) of the bluefin tuna remains unexplored. The plan is to do a computational study of the function of all fins of Tuna in order to leave some groundwork for further study in this field which remains limited. This research has consequences in the design of autonomous underwater vehicles, submarines, propellers, hydrofoils and more.

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