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Metabolism of the Bilirubin and its Biochemistry Role

Nurgun Mehbaliyeva[1], Narmina Abdullayeva[2*], Nigar Huseynova[2]

Abstract. *Bilirubin is a tetrapyrrolic bile pigment that plays a crucial role in several vital metabolic pathways of the human body. It is a yellow-colored compound that circulates in the bloodstream and participates in various physiological processes. Bilirubin is predominantly generated through the catabolism of hemoglobin following the breakdown of erythrocytes, and its biosynthesis is primarily mediated by the liver. The homeostasis of bilirubin is intricately linked to multiple physiological and biochemical functions, and its precise regulation is essential for maintaining systemic health. Elevated serum bilirubin levels may serve as a clinical biomarker for a range of pathological conditions, including hepatic dysfunctions, hematological disorders, and cholestatic syndromes.*

Keywords: *bilirubin, free radicals, liver, Kupffer cells, cholesterol*

Introduction

Bilirubin metabolism affects various physiological and biochemical processes of the body, and its proper regulation is essential for maintaining health. Bilirubin exists in two major forms: conjugated and unconjugated bilirubin. Direct bilirubin is generated by the conjugation process in the liver and excreted from the body by being excreted as waste in the moist intestines. Conjugated bilirubin is formed in the liver through the conjugation process and is excreted into the intestines as a waste product, eventually being eliminated from the body. Unconjugated bilirubin, on the other hand, is produced as a result of erythrocyte degradation and is processed in the liver where it is converted into direct (conjugated) bilirubin. Disruptions in this metabolic pathway can lead to hyperbilirubinemia, a condition clinically manifested as jaundice. Notably, bilirubin is not merely a metabolic waste product; it also functions as a physiological antioxidant, helping to neutralize harmful free radicals in the body (Chen et al., 2018).

Materials and Methods

Thus, the liver serves as the central organ in the synthesis, excretion, and metabolism of bilirubin. Bilirubin originates from the degradation of erythrocytes, which have a lifespan of approximately 120 days, and its proper handling is essential for maintaining liver health. Hepatic metabolic processes—particularly the production and excretion of bilirubin—constitute key aspects of this function. The presence and concentration of bilirubin serve as important biomarkers for the early detection of liver and hematological disorders, providing a valuable basis for future clinical and molecular research (Agius, 2018).

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Hepatic Glucose Metabolism. Hepatocytes are the primary cell type involved in glucose metabolism within the liver. Circulating glucose enters hepatocytes via the GLUT2 transporter, which is embedded in the plasma membrane. The specific deletion of GLUT2 in hepatocytes abolishes hepatic glucose uptake. In addition, GLUT2 facilitates the release of glucose from the liver into the bloodstream. However, the absence of GLUT2 does not impair hepatic glucose production during fasting, suggesting that glucose may also be released via alternative transporters (e.g., GLUT1) or other mechanisms (Evans et al., 2013). Once inside the hepatocyte, glucose is phosphorylated by the enzyme glucokinase into glucose-6-phosphate (G6P). This reaction reduces intracellular free glucose concentrations, thereby facilitating continued glucose uptake. Since G6P cannot be transported out of the cell, it remains within hepatocytes. In the fed state, G6P serves as a key precursor for glycogen synthesis. Additionally, G6P is metabolized to pyruvate via glycolysis. Pyruvate then enters the mitochondria and is fully oxidized through the tricarboxylic acid (TCA) cycle and oxidative phosphorylation, leading to ATP production (Fig. 1).

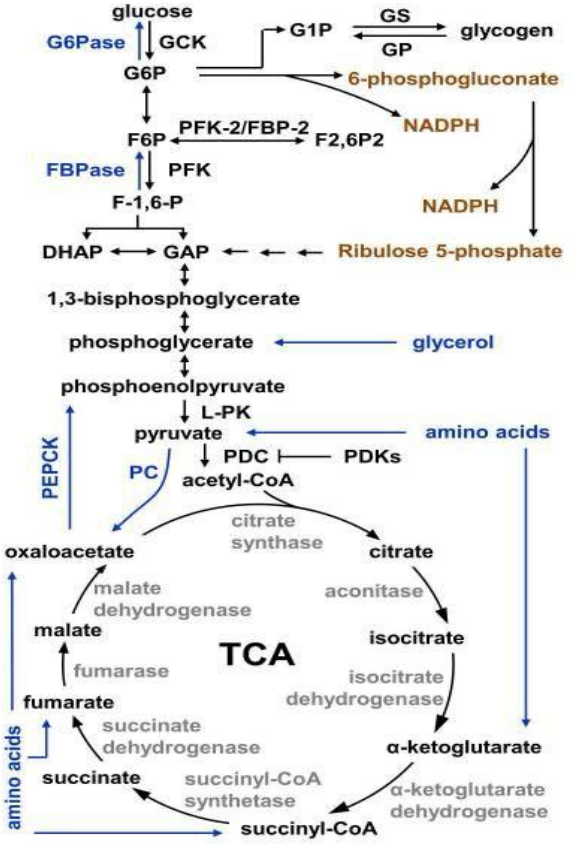

Figure 1. Glycogen metabolizm

In the fed state, glucose enters hepatocytes via GLUT2, is phosphorylated by glucokinase, and subsequently utilized by glycogen synthase for glycogen synthesis. During fasting, glycogen is hydrolyzed by glycogen phosphorylase to release glucose through glycogenolysis (Chew et al., 2023). The liver is considered the central regulatory organ responsible for maintaining whole-body cholesterol homeostasis (Fig. 2).

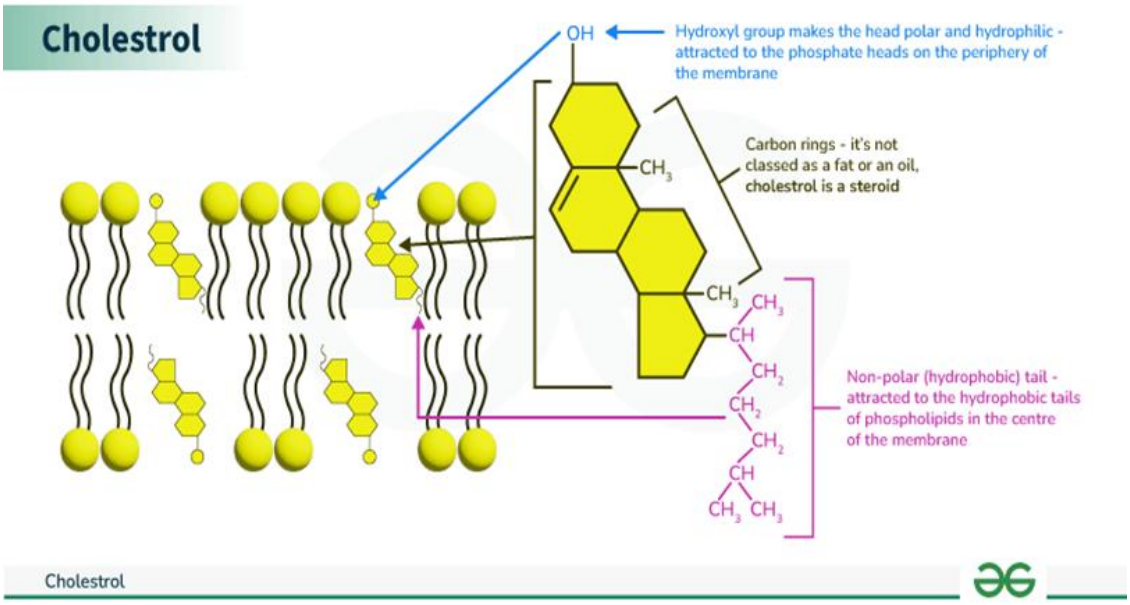

Figure 2. Structure of cholesterol

It serves as the primary site for de novo cholesterol biosynthesis, facilitates the clearance of cholesterol-containing chylomicron remnants and low-density lipoprotein (LDL) particles from the plasma, and makes a major contribution to the formation of high-density lipoproteins (HDL) (Zhang et al., 2023). Approximately 4 mg/kg of bilirubin is produced daily. Heme is a tetrapyrrolic macrocycle consisting of four pyrrole rings interconnected by carbon bridges, with a central iron atom. Bilirubin is primarily generated through a two-step sequential enzymatic degradation of heme within the reticuloendothelial system, particularly in the spleen. Other contributing cells include phagocytes and Kupffer cells of the liver. Once released into the plasma, bilirubin binds to albumin, the main transport protein in the bloodstream (Pirone et al., 2009).

The active transport of unconjugated bilirubin is mediated by carrier proteins, although the exact identity and mechanism of these transporters remain poorly understood (Fig. 3) (Blumgart et al., 2017). Albumin has a very high binding affinity for bilirubin, and under physiological conditions, unbound (free) unconjugated bilirubin is virtually undetectable in the plasma (Chew et al., 2023). Bilirubin is taken up by hepatocytes from the hepatic sinusoids via two distinct mechanisms: passive diffusion and receptor-mediated endocytosis. Passive diffusion does not require energy and occurs along the concentration gradient, resulting in a bidirectional flow.

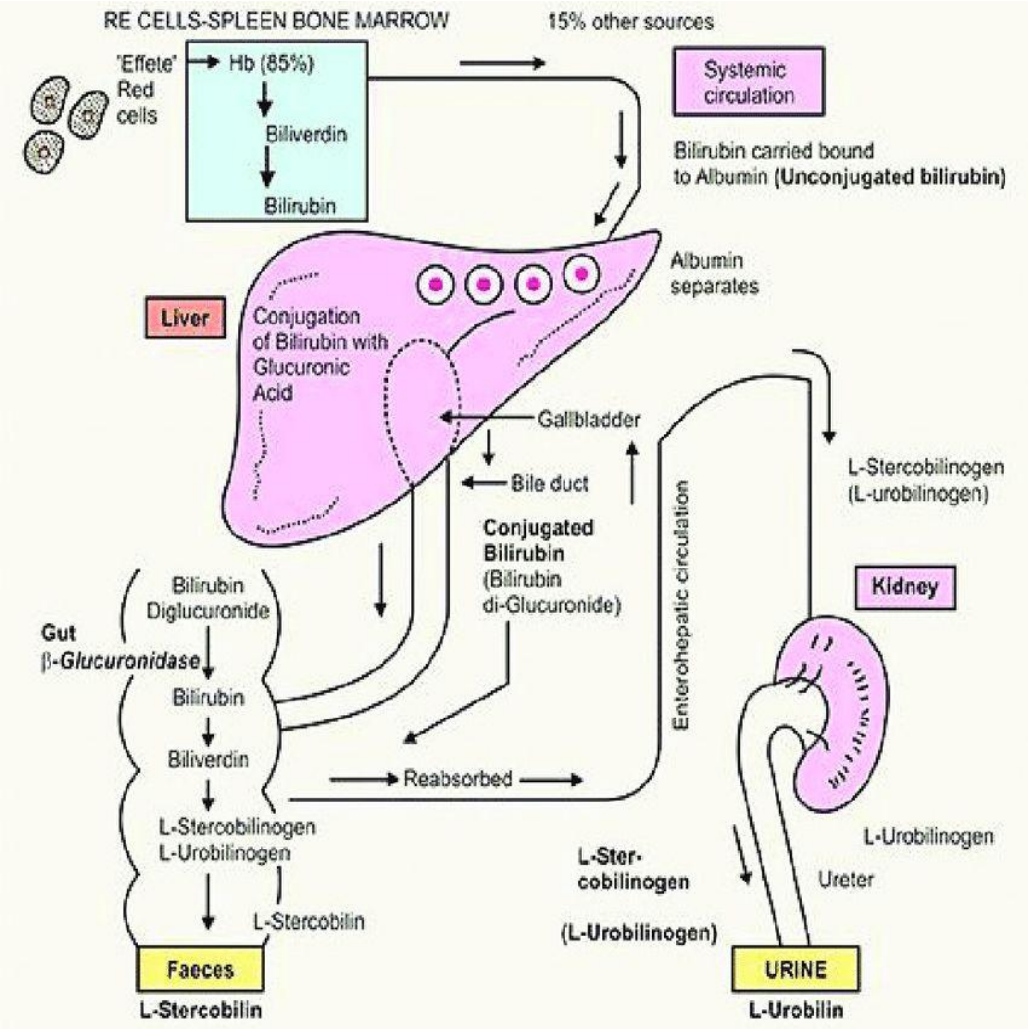

Figure 3. Bilirubin synthesis in the liver

Results and Discussion

The study demonstrated, that bilirubin is an important metabolite of heme (ferroprotoporphyrin IX), a coordination complex that links iron in various proteins. It is a potentially toxic substance. However, the body has developed mechanisms for its safe detoxification and excretion. Bilirubin and its metabolites also provide a distinctive yellow color of bile and feces and, to a lesser extent, urine. This topic summarizes the mechanism of heme metabolism and bilirubin synthesis (Bauer & Kämper, 2016). Bilirubin is formed by a 2-stage sequential catalytic degradation reaction that occurs primarily in the cells of the reticuloendothelial system, specifically in the spleen. Other cells include phagocytes and Kupfer cells of the liver. Receiving Heme these cells receive heme and the enzyme heme oxygenase acts on them. The enzyme releases chelated iron by catalyzing the oxidation of the alpha-carbon bridge. This reaction produces equimolar amounts of carbon monoxide, which is excreted by the lungs and leads to the formation of the green pigment biliverdin (Chisari & Ferrari, 2018). Bilirubin, insoluble in aqueous solution, binds in circulation to albumin, which is a reversible and covalent type of binding.

Metabolism of bilirubin. Albumin binding: after bilirubin is released into plasma, it is taken up by albumin, a carrier throughout the body. The binding affinity of albumin to bilirubin is quite high, and under ideal conditions, free (non-albumin-bound) unconjugated bilirubin does not appear in plasma. To a lesser extent, especially in cases of hypoalbuminemia, binding with high- density lipoproteins

also occurs. Albumin binding limits the outflow of bilirubin from the vascular cavity, minimizes glomerular filtration and prevents its deposition and deposition in tissues (de Sauvage et al., 2011). Bilirubin is taken from hepatic sinusoids into hepatocytes by two different mechanisms: passive diffusion and Receptor-Mediated Endocytosis. The passive diffusion process does not consume energy and, as a result, proceeds with a concentration gradient, making the flow bidirectional. Active transporter intake of unconjugated bilirubin from hepatic sinusoids is carried out through carrier proteins that are not well understood. Part of the conjugated and unconjugated bilirubin within the hepatocyte is transported back into the sinusoidal space, and this fraction is again transported downstream of the sinusoidal flow. Conjugation is mandatory to dissolve bilirubin in water and facilitate its secretion through the canalicular membrane and excretion with bile. Bilirubin binds to glucuronic acid in the hepatocyte by a family of enzymes called uridine-diphosphoglucuronic glucuronosyltransferase (UDPGT) (Sedlak et al., 2017). The process of glucuronidation is one of the many important detoxification mechanisms of the human body. Under normal conditions, bilirubin is the main molecule from which diglucuronide is synthesized. However, if the conjugation system fails under conditions of excessive bilirubin synthesis, most of the bilirubin may be conjugated as bilirubin monoglucuronide. The combination of bilirubin into a water-soluble form involves breaking hydrogen bonds, an important process for its excretion by the liver and kidneys. This is achieved by glucuronic acid, which binds the side chains of propionic acid of bilirubin (Liu et al., 2008).

Conclusion

In summary, the liver is the central organ involved in the synthesis, excretion, and metabolism of bilirubin. Bilirubin is generated from the degradation of erythrocytes, which have a lifespan of approximately 120 days, and its proper processing is essential for maintaining hepatic function. The metabolic activities of the liver - particularly those related to bilirubin production and elimination - constitute critical aspects of its physiological role. The plasma concentration of bilirubin serves as a valuable biomarker for the early detection of both hepatic and hematologic disorders. Bilirubin metabolism affects various biochemical processes, and its regulation is essential for maintaining health, and it provides a foundation for diagnostic research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Study of Diagnostic Methods and Control Measures For Listerosis Disease Among Big-Horned Animals in the Ganja-Gazakh Zone

Ayten Agayeva[1*], Rahila Farmanli[1]

Abstract. *The purpose of the research is to study the diagnostic methods and control measures for listeriosis among cattle in farms of the Ganja-Gazakh zone. The research was conducted in various farms located in Shamkir, Samukh and Goygol districts, in the laboratory of the Department of "Episootology, Microbiology and Parasitology" of the Faculty of "Veterinary Medicine" of the Azerbaijan State Agrarian University of Veterinary Medicine. Depending on the immune status of the organism and the virulence of the pathogen, the disease manifests itself in acute, and subacute forms among animals. Based on the high efficiency of their application in combination with sulfagin, gentomycin and oxytetracycline for the specific treatment of the disease, we recommend their use for the prevention of listeriosis before vaccination. In case of listeriosis, along with specific treatment, we carried out symptomatic treatment. We carried out disinfection, disinsection and deratization works in livestock farms in an organized manner.*

Keywords: *cattle, disease, listeriosis, bacteriological examination, morphological, cultural, biochemical, antigenic, pathogenic properties*

Introduction

Listeriosis is an infectious disease of animals and humans caused by the bacteria Listeria monocytogenes and is characterized by nervous system disorders, septic conditions, puerperal disease and mastitis. An asymptomatic (latent) form of the disease is also observed. Many species of domestic and wild mammals, birds and humans are affected. It can occur as a secondary or mixed infection in a number of infectious diseases in pigs and birds. The disease has been recorded in Azerbaijan (Shirinov, 2002; Eyubov, 2005).

Many scientists have determined that the occurrence of listeriosis in various types of animals and birds depends on the amount of precipitation, the nature of the feed, pH, the degree of contamination of the soil with the causative agent of the disease, the presence of antagonistic microflora in the soil and the degree of virulence of the causative agent of listeriosis. P. R. Lazarev, V. I. Gershun and I.I.Guslavskaya show that incompleteness of the feed ration due to cold and soluble protein, as well as changes in the pH of silage, reduce the overall resistance of animals and increase their susceptibility to listeriosis (Kalinin, 1987).

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Listeriosis causes a decrease in animal productivity, causes metritis during calving, and causes great economic damage. At the same time, it causes a certain amount of financial resources to be spent on various health measures (Mammadli, 2015).

Listeriosis is a zoonotic disease of animals and humans, characterized by polymorphism of clinical signs or asymptomatic carriage and high mortality. M.M. Halimbayov, A.A. Annaghiyev, M.G. Ganiyev, A.M. Khalilov, A. Khankishiyev, H.A. Rahimova, Y. Ahmadov, C.N. Mammadova, A.G. Abbasov, F.M. Gulubayov played a special role in studying the epizootology, pathogenesis and specific prophylaxis of listeriosis in various types of agricultural animals in the Republic of Azerbaijan. In our country, the first vaccine against listeriosis of agricultural animals in world veterinary practice was developed and this preparation was used in the specific prophylaxis of listeriosis of sheep in 1965–1978. In 1980, a colored antigen was prepared for the diagnosis of listeriosis of agricultural animals with AR (A.A. Annaghiyyev, E.A. Aliyev, F.M. Gulubeyov), an author's certificate was obtained for the diagnostic, and it is currently used in both veterinary and medical practice (Aliyev, 2013; Mammadli, 2020).

Listeriosis is an infectious disease characterized by meningoencephalitis, balanitis, metritis, mastitis, septicemia. The incubation period lasts from one week to 1 month. Listeriosis occurs in septic, nervous, genital and atypical forms. Factor (0.3-0.5 and 0.5-2.0 μm) is a bacterium located singly, in pairs or in clusters. In some cases, bacteria occur in polymorphic rod, cocci, vibrio forms. Bacteria stain positively with all aniline dyes and the Gram method. Microbes do not form capsula and spores. In fresh (4-6 hours) broth culture, bacteria are motile. On meat-peptone agar-agar, bacteria form thin, fleshy colonies similar to Pasteurella, with a diameter of 1-1.5 mm (Lysak, 2007).

When studying culture strains obtained from various sources by I.A. Bakulov, O.V. Krivonosov, I.V. Gershun, it was determined that there are both virulent and weakly virulent variants of listeria. In addition, various literature data show that external environmental factors play an important role in the occurrence and course of listeriosis (Bessarabov, 2007).

The disease has a mortality rate of up to 40%, and causes considerable damage to agriculture as a result of reduced productivity and calving in animals. In addition, a system of various health measures is used, which leads to the expenditure of a certain amount of financial resources (Gadimov, 1990).

Materials and Methods

To achieve the set goal, we selected 26 sick animals related to the red desert and local breeds, divided them into 6 groups of 4 animals in each group, and conducted scientific research on them. The research work was carried out in various cattle farms of the Ganja-Gazakh zone (Shamkir, Samukh and Goygol), at the Department of Epizootology, Microbiology and Parasitology of the Azerbaijan State Agricultural University. In recent years, the climate in the Republic of Azerbaijan has changed dramatically, the amount of precipitation has decreased and drought has increased. As a result, the composition of feed in many regions has changed, its quality has deteriorated, and the number of insects and rodents has increased. As we know, the main source of infection is various wild and domestic animals, especially rodents, birds and insects, which carry the causative agent of the disease. The microbe enters the body through the mucous membranes (nose, conjunctiva, mouth) through water, feed, air, dust, etc. It is assumed that infection also occurs through blood-sucking insects, especially ticks.

As a result of all these factors, listeriosis was recorded among cattle in various farms of Shamkir, Samukh and Goygol regions. Based on the appeal of the heads of these farms, employees of the Department of Epizootology, Microbiology and Parasitology of the ASAU were engaged in studying the occurrence, course, treatment and many other issues of the disease.

It turned out that the farms mentioned were healthy due to listeriosis and had no contact with unhealthy farms. Listeriosis infection was recorded in August-October 2022. The disease was mainly observed in 18-28-month-old heifers, and infection was not detected in the causative bulls. The incubation period of the disease is 7-30 days. In addition to fever, general weakness, and loss of appetite, some animals showed signs of central nervous system dysfunction, including loss of balance, convulsions, severe nervous excitability, paralysis of some muscle groups, neck flexion, and conjunctivitis. In a group of sick animals, blindness, stomatitis, anemia of visible mucous membranes, and comatose state were noted.

Listeriosis mainly has an acute, subacute, and chronic course. Listeriosis occurs in several clinical forms: nervous, septic, mixed, latent-asymptomatic, with damage to the reproductive system (parturition, delayed ejaculation, endometritis, and metritis) and udder (mastitis). In large horned animals, the CNS is more affected. The disease begins with weakness and loss of appetite. Serous-mucous discharge occurs from the nasal cavity, and abundant mucus is secreted from the mouth. After 3-7 days, uncontrolled movements, convulsions, fits of excitement, paresis of individual muscle groups, loss of vision, conjunctivitis, stomatitis are observed. Body temperature rises at the beginning of the disease or remains within the normal range. Listeriosis in calves proceeds in the form of septicemia, sometimes accompanied by damage to the CNS.

Results and Discussion

From the research work we conducted, it became clear that the pathological-anatomical changes in large horned animals were mainly sharp changes in the brain, especially the engorgement of cerebral blood vessels, blood leakages were observed on the brain and cerebellum. In the cranial cavities and ventricles of the brain, a cloudy fluid mixed with pus was seen. To diagnose listeriosis, we took into account its epizootological characteristics, clinical signs and pathological-anatomical changes, used blood culture, bacteriological examination and serological reactions. While the animal was alive, we used the blood of the sick animal (5-10 ml), the discharged pupa, pupal discharge, pupal membrane, nasal passages, conjunctival fluid, and milk taken from the inflamed scrotum. We also sent the brain and spinal cord to the laboratory for examination.

We examined the pathological samples received in the laboratory based on the bacteriological scheme. Bacteriological examinations play an important role in the diagnosis of listeriosis. During microscopy, we prepared a smear from the pathological material and stained it using the Gram method. During microscopy, listeria were found singly or in pairs. In some cases, we determined that listeria were observed in coccus-like, diplobacteria, rod-shaped, and chain-like forms.

We obtained a pure culture of the factor by inoculating the blood of sick animals from the parenchymatous organs of dead animals into various nutrient media, prepared smears on glass slides, examined them under a microscope, and used biological tests. After obtaining a pure culture of the listeriosis pathogen, it was examined for its morphological, cultural, tinctorial, and biochemical properties, and its pathogenicity was determined. It turned out that the pathogen forms a precipitate in liquid nutrient media and, when shaken, rises up like a hair, resembling small, transparent dewdrops in solid nutrient media.

Table 1.
Treatment of cattle with listeriosis

Treatments	Injection method	Dose (once)	Number of patients	Conclusion	
				Survived quantity	%
Sulfagin and gentomis	Perosal and intramuscular	25 g+2.5 ml	4	4	100
Sulfagin and oxytetracycline	Peros	25 g+2.5 ml	4	4	100
Gentomycin	Intramuscular	2.5 ml	4	3	75
Oxytetracycline	Intramuscular	2.5 ml	4	3	75
Sulfagin	Peros	25 g	4	2	50
Control	–	–	4	4	–

As can be seen from Table 1, while sulfagin in combination with gentomycin and oxytetracycline achieves 100% recovery, only 50-75% of animals recover from the use of these drugs alone. Based on the high efficiency of sulfagin in combination with gentomycin and oxytetracycline, we recommend their use for the prevention of listeriosis before vaccination. In the case of listeriosis, along with specific treatment, we carried out symptomatic treatment. The main goal of symptomatic treatment is to stimulate the functional activity of the cardiovascular system and the digestive system. In order to ensure the healthy and vigorous development of large-horned animals, and to prevent them from contracting listeriosis, we set ourselves the goal of timely implementation of preventive measures. One of such measures and the main one is timely and high-quality vaccination of animals with the appropriate vaccine.

According to researchers, individuals who have contracted listeriosis and recovered from it in natural conditions develop relative immunity. Precipitins, agglutinins, and complement-binding antibodies are detected in the blood serum of animals that have recovered from the disease naturally. However, the serum of convalescents does not have therapeutic properties. The first vaccine against the disease was prepared by A.A. Annagiyev from the “A” strain. A dry live vaccine prepared from the “AUF” strain was proposed in 1974 and is used based on the current instructions (Alasgarov, 2016).

We vaccinated all clinically healthy animals 10 days after treatment with a dry vaccine prepared from the AUF strain against listeriosis. We vaccinated 687 cattle on farms according to the instructions. We injected the vaccine intramuscularly twice with an interval of 10 days. We periodically sent samples to the laboratory to determine the quality indicators of feed and water. We applied the feed ration, which is important for feeding large horned animals. We implemented the solution of the following issues in disease prevention. In order to ensure the protection of healthy livestock farms from the disease due to listeriosis:

- We ensured that animals brought to farms were kept in quarantine for 30 days.
- We ensured the systematic elimination of rodents.
- We eliminated blood-sucking insects and ticks.
- Ensuring constant quality control of feeds (especially silage and mixed feed)
- We ensured the conduct of bacteriological examinations in accordance with the relevant requirements.
- In cases of abortion or stillbirth, we implemented a strict approach and sent pathological samples for examination.

We boiled milk from large horned animals (with a positive result in serological reactions) for 15 minutes. We banned the transportation of feed that had been in contact with sick animals. We carried out disinfection, disinfestation and deratization work in livestock farms in an organized manner. We

biothermally neutralized manure on the farm. We disinfected stables and farmyards. For this purpose, we used 3% sodium hydroxide, 2% chlorinated lime solution, and 6% creolin emulsion. We periodically carried out deratization measures on the farm. We lifted the restriction 2 months after the last patient recovered from the farm and after receiving a negative result during serological tests.

Conclusion

The results of the study showed that 100% recovery was achieved when sulfagin was used in combination with gentamicin or oxytetracycline for the treatment of sick animals in unhealthy farms due to listeriosis. During the research work we conducted, we vaccinated all animals susceptible to listeriosis in unhealthy farms with a dry vaccine prepared from the AUF strain according to the relevant instructions. For the prevention of listeriosis, animals should always be brought to the farm from healthy farms. We always monitored the quality of feed and fought against rodents. We used preventive measures when the disease was observed on the farm.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The Possibilities of Using the Nature of Semiconductors in Practical Life

Gunay Dadashzade

Abstract. *The transformation of the global automotive market with the increase in the production of electric vehicles in recent years has created an incredible demand for the development of electronic components based on SiC and GaN semiconductors with a wide band gap in the world, without which it is impossible to imagine the electronics of modern and future hybrid and electric vehicles, communication systems, mobile devices and space technology. This demand has led to a sharp increase in investment in the development and development of new technologies for SiC and GaN wafers of larger diameters in order to reduce the cost of manufacturing electronic products and continue to displace classic silicon components. Every year, semiconductor devices based on SiC and GaN are penetrating deeper into our lives. The past 2021 allowed them to make an impressive breakthrough and lay the foundation for growth in their consumption in the next five years and beyond. The main driver of this growth is the automotive market, or more precisely, hybrid and electric cars.*

Keywords: *electric vehicle, components, battery, power, semiconductors*

Introduction

Semiconductors are materials that can conduct electricity, but to a limited extent. Their unique feature is that their electrical conductivity can be controlled and modified by introducing appropriate dopants or by changing external conditions, such as temperature, pressure, or an electric field. Under normal conditions, semiconductors act as insulators, but under certain circumstances, they can conduct electricity, making them indispensable in the production of electronic components.

Natural semiconductors, such as pure silicon, do not have sufficient electrical properties for use in modern electronic devices. To increase their ability to conduct electricity, doping is used, which involves introducing small amounts of other chemical elements into the semiconductor structure. Depending on the type of dopant, two main types of doped semiconductors can be distinguished:
An n-type semiconductor is formed by doping a semiconductor with elements with a large number of electrons, such as phosphorus or arsenic. The introduction of these impurities creates an excess of electrons that can move freely within the material, increasing its conductivity. A p-type semiconductor is formed by doping a semiconductor with elements with a smaller number of electrons, such as boron or aluminum. These impurities form so-called electron holes, which act as positive charge carriers and also help improve the material's conductivity.

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The most common semiconductor materials are silicon (Si) and germanium (Ge), although many other compounds with semiconducting properties exist, such as gallium arsenide (GaAs) and indium phosphide (InP). These materials are used to manufacture semiconductor components such as diodes, transistors, and integrated circuits, which form the basis of modern technology. The share of hybrid and electric vehicle sales in the country reached 94.9%. Norway is actively building charging and service infrastructure, and numerous tax breaks for citizens buying electric vehicles are stimulating the transition away from internal combustion engine vehicles. Next-generation electric vehicles require power devices that can improve the efficiency of the vehicle (with a subsequent increase in the driving range) and the speed of battery charging. Figure 1 shows the key nodes of the vehicle where SiC and GaN electronic components can be used. SiC inverters have proven to be a key solution to meet these requirements. In addition to converting the input DC to AC, the inverter regulates the level of power supplied to the motor in accordance with driving needs (Challenges and Future Perspectives).

Methods

The progress of silicon carbide technology, in terms of increasing diameter, production volume, improving quality and decreasing cost of SiC, has reached the point where mass production of 150 mm wafers is based on the use of silicon carbide blanks, as shown in Fig. 1. The progress of silicon carbide technology, in terms of increasing diameter, production volume, improving quality and decreasing cost of SiC, has reached the point where mass production of 150mm wafers is based on the use of silicon carbide blanks, as shown in Fig. 1.

Figure 1. Production of 150 mm thick silicon carbide plate

Findings and Discussion

The role of the inverter is increasing as the electric vehicle industry gradually transitions from 400 to 800 V. The efficiency of transferring battery power to the motor in a traditional inverter is 97–98%, while the efficiency of a SiC inverter reaches 99%. Note that an increase in efficiency of one or two decimal places provides very significant benefits to the entire vehicle (Compound Semiconductor Quarterly Market Monitor, 2021).

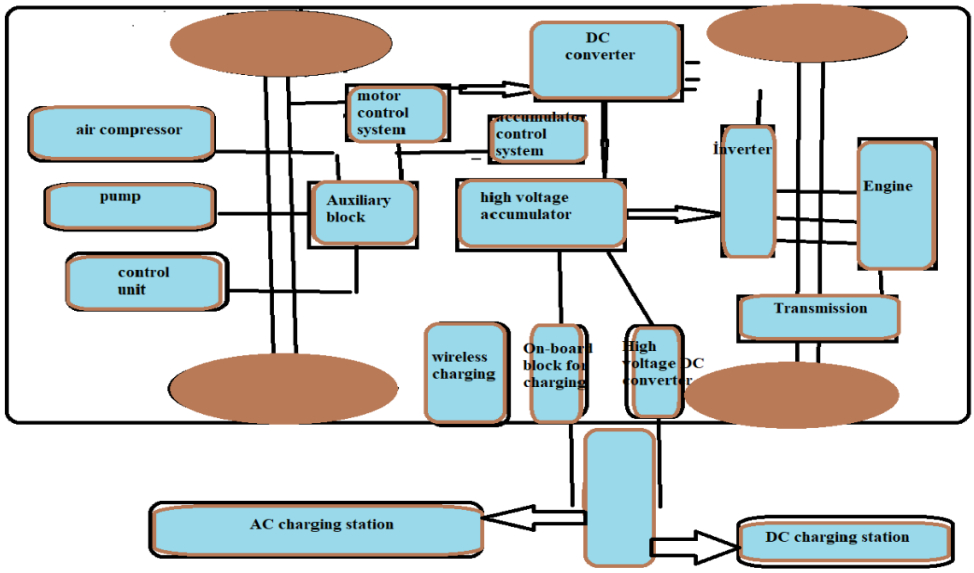

Figure 2. Key nodes for the application of SiC and GaN-based electronic components in an electric vehicle

SiC inverters are ideal for these applications because they can withstand high voltages and temperatures, allowing all other components to be smaller. With 800 V batteries, the required current is reduced and smaller cables can be used, reducing costs, vehicle weight, and electrical system assembly time. This not only improves the range of EVs, but also their efficiency. Charging times for 800 V batteries can be reduced to one-fifth of the time required for 400 V batteries by using powerful SiC DC/DC converters. The former's high efficiency allows the amount of energy delivered to the batteries to be maximized during charging with negligible power losses (SiC and GaN: A Tale of Two Semiconductors, 2021).

The global growth of the BEV market, which meets modern standards for efficiency and CO2 emissions, requires the use of new semiconductor technologies in the drive inverter. The supply voltage of the BEV inverter is in the range of 400–900 V, depending on the drive power, battery type and the presence of a step-up converter. Since the drive inverter controls the motor, its operating frequency is usually less than 20 kHz. The advantage of using higher frequencies here is only to move away from the audible range of audio noise. Therefore, the main losses of the inverter are conduction losses, especially at low BEV loads (SiC and GaN: A tale of two semiconductors, 2021).

Typically, the choice in such cases is a silicon IGBT, but its inherent saturation threshold voltage (due to its "bipolar" structure) at low loads cannot be reduced, even when a large number of IGBTs are connected in parallel. Silicon carbide has an electric field strength 10 times higher (~3 MV/cm) than Si, so the unipolar SiC MOSFET structure is well suited for the implementation of 650, 900 and 1200 V power transistors due to the following main features:
SiC MOSFETs do not have a saturation voltage, unlike Si IGBTs; when paralleling SiC MOSFET chips, the on-resistance can be reduced to ≤ 1–2 mOhm;
SiC MOSFETs can conduct in the third quadrant (unlike Si IGBTs) by using a body diode during the dead time (Tdt is very short for SiC structures) and then turning on the SiC MOSFET channel in the third quadrant, which gives the same low losses in the reverse conduction state as in the forward conduction state. The combination of using a body diode during the dead time and synchronous rectification eliminates the need for an external antiparallel diode, which reduces the size and cost with minimal impact on efficiency at frequencies up to 50 kHz; using SiC MOSFETs can reduce inverter losses in a typical BEV EPA drive cycle by up to ~78%. The basic technology for developing

low-resistance SiC MOSFET power modules can be scaled from 650-900 V to 1200 V by simply modifying the epitaxial drift zone (blocking layer) and edge regions.

The topology remains the same for all devices in the specified voltage range, ensuring easy integration into power modules (GaN Systems listed on 2021 Deloitte Technology Fast 500*)*. Figure 3 illustrates the traditional method of connecting conductors using ultrasonic welding to the top contact surface using the third generation of SiC MOSFET crystals as an example. This technology can be used in 650, 900 or 1200 V modules with a slight change in the chip topology. 900 V crystals with low channel resistance (10 mOhm for the CPM3-0900-0010A) are already available. They were used in the development of a version of the 900 V modules, the static and dynamic losses of which have already been tested.

Conclusion

The rapid growth of the global automobile market with the gradual predominance of the production of hybrid and electric vehicles guarantees accelerated development and further reduction in the cost of semiconductor devices based on SiC and GaN. Assessing the good market prospects of SiC and GaN products, large foreign companies continue to increase investments in their production, as well as in the acquisition of companies developing these products and materials, including for the start of production of new areas of electronic components that were previously absent in these companies (GaN Systems' power transistor prices drop below $1, 2021*)*.

Figure 3. Chips Wolfspeed SiC MOSFET

The development of electronic components based on GaN is evolving from the creation of simpler power discrete components (transistors, diodes, etc.) and control microcircuits (drivers, controllers) to more complex integrated solutions with high energy efficiency, including for use in harsh space conditions. Increasing the diameter of SiC wafers to 200 mm, which will happen in 2022 despite technical difficulties, is the main means that will reduce the cost and price of production of silicon carbide ECs.

The first epitaxial GaN wafers on a silicon substrate with a diameter of 300 mm with high homogeneity and low defects, presented on the market in 2021, will further reduce the cost of production and prices of electronic GaN components. Evolution and progress in the industrial development of the technology of vertical GaN-on-GaN and GaN-on-Si structures for active components with low cost in the future will create competition not only for silicon IGBTs, but also for SiC transistors, diodes in the high-voltage range up to 10 kV.

Recently, much attention has been paid to the sintering technology of SiC chips, which allows eliminating the use of welded conductors during assembly. One of the main advantages is an increase in the so-called intermittent service life (IOL), since fatigue processes in welded conductor joints or crystal connections often cause failures. Other potential advantages include better (two-way) cooling, better heat distribution and higher short-circuit resistance (Quantum physics; Semiconductor; HyperPhysics; YOLE Intelligence).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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