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SERUM CYPOR LEVELS IN BACTRIAN CAMELS AND THEIR CORRELATION WITH HEPATIC ULTRASTRUCTURAL ORGANIZATION

Research article

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Abstract

Objective. To determine the level of cytochrome P450 oxidoreductase (CYPOR) in the serum of clinically healthy Bactrian camels and determine its correlation with the ultrastructural organization of hepatocytes, reflecting specialized adaptations of the liver to desert conditions.

Methods. Serum CYPOR concentrations were determined by high-performance liquid chromatography (HPLC) with UV detection in five healthy 2,5-year-old Kazakh Bactrian camels. Liver ultrastructure was studied using transmission electron microscopy with quantitative morphometry (hepatocyte diameter, proportion of cells with lipid droplets, average lipid droplet diameter, collagen fiber thickness in the space of Disse, and Kupffer cell density). Statistical analysis included calculation of the Pearson and Spearman correlation coefficients.

Results. The mean serum CYPOR level was 8,46±1,37 μg/ml. A significant inverse correlation was found between CYPOR concentration and lipid droplet content in hepatocytes ($r = -0,89$; $p = 0,04$), as well as a direct correlation with collagen fiber thickness in the Disse space ($r = 0,88$; $p = 0,048$). A trend toward a positive correlation was found with hepatocyte diameter ($r = 0,61$; $p = 0,27$) and Kupffer cell density ($r = 0,85$; $p = 0,07$).

Conclusions. The established correlations indicate a close link between cytochrome system activity (CYPOR levels) and the structural and functional specialization of the Bactrian camel liver. The obtained data expand our understanding of the molecular and morphological mechanisms of adaptation to extreme conditions, and the determination of serum CYPOR can serve as a potential non-invasive biomarker of the functional state of the liver in this species.

Keywords: CYPOR, cytochrome P450 reductase, Bactrian camel, liver ultrastructure, hepatocyte adaptation, desert adaptation, detoxification, lipid metabolism, hepatic cytochrome system.

УРОВНИ CYPOR В СЫВОРОТКЕ КРОВИ ДВУГОРБЫХ ВЕРБЛЮДОВ И ИХ КОРРЕЛЯЦИЯ С УЛЬТРАСТРУКТУРНОЙ ОРГАНИЗАЦИЕЙ ПЕЧЕНИ

Научная статья

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Аннотация

Цель. Установить уровень цитохром P450 оксидоредуктазы (CYPOR) в сыворотке крови клинически здоровых бактрийских верблюдов и определить его корреляцию с ультраструктурной организацией гепатоцитов, отражающей специализированные адаптации печени к условиям пустыни.

Методы. Сывороточную концентрацию CYPOR определяли методом высокоэффективной жидкостной хроматографии (ВЭЖХ) с УФ-детекцией у пяти здоровых казахских бактрийских верблюдов в возрасте 2,5 лет. Ультраструктуру печени изучали с помощью трансмиссионной электронной микроскопии с количественной морфометрией (диаметр гепатоцитов, доля клеток с липидными каплями, средний диаметр липидных капель, толщина коллагеновых волокон в пространстве Диссе, плотность клеток Купфера). Статистический анализ включал вычисление коэффициентов корреляции Пирсона и Спирмена.

Результаты. Средний уровень CYPOR в сыворотке составил 8,46±1,37 мкг/мл. Выявлена значимая обратная корреляция между концентрацией CYPOR и содержанием липидных капель в гепатоцитах ($r = -0,89$; $p = 0,04$), а также прямая корреляция с толщиной коллагеновых волокон в пространстве Диссе ($r = 0,88$; $p = 0,048$). Обнаружена тенденция к положительной корреляции с диаметром гепатоцитов ($r = 0,61$; $p = 0,27$) и плотностью клеток Купфера ($r = 0,85$; $p = 0,07$).

Выводы. Установленные корреляции свидетельствуют о тесной связи активности цитохромной системы (уровня CYPOR) со структурно-функциональной специализацией печени бактрийских верблюдов. Полученные данные расширяют представления о молекулярно-морфологических механизмах адаптации к экстремальным условиям, а определение сывороточного CYPOR может служить потенциальным неинвазивным биомаркером функционального состояния печени у данного вида.

Ключевые слова: CYPOR, редуктаза цитохрома P450, бактрийский верблюд, ультраструктура печени, адаптация гепатоцитов, адаптация к пустыне, детоксикация, липидный обмен, цитохромная система печени.

Introduction

The cytochrome P450 system represents one of the most crucial enzymatic complexes involved in xenobiotic metabolism and endogenous compound processing in vertebrates. At the core of this system lies cytochrome P450 oxidoreductase (CYPOR), a flavoprotein that serves as the essential electron donor for all microsomal cytochrome P450 enzymes. This ubiquitous enzyme transfers electrons from NADPH to various cytochrome P450 isoforms, thereby enabling their catalytic activity in oxidative metabolism of drugs, toxins, and endogenous substances such as steroids, fatty acids, and bile acids. The functional integrity of the entire cytochrome P450-dependent detoxification system is fundamentally dependent on adequate CYPOR expression and activity [1], [2], [3], [4].

The liver, as the primary organ of metabolic processing and detoxification, harbors the highest concentration of cytochrome P450 enzymes and their obligatory redox partner CYPOR. Hepatic CYPOR expression levels directly correlate with the organ's capacity to metabolize xenobiotics and endogenous compounds, making it a critical determinant of an organism's detoxification potential. The ultrastructural organization of hepatocytes, particularly the development of smooth endoplasmic reticulum where CYPOR and cytochrome P450 enzymes are predominantly localized, provides the structural foundation for efficient electron transfer and substrate processing. Variations in hepatocyte architecture, including the abundance of endoplasmic reticulum membranes, mitochondrial distribution, and lipid droplet accumulation, may therefore reflect adaptations in detoxification capacity [5], [6], [7], [8].

Camels represent a remarkable example of evolutionary adaptation to extreme environmental conditions, having developed sophisticated physiological and metabolic mechanisms to survive in arid ecosystems with limited nutritional resources and potential exposure to plant toxins. The Bactrian camel (*Camelus bactrianus*), inhabiting the cold deserts of Central Asia, faces unique metabolic challenges, including prolonged dehydration, seasonal food scarcity, and consumption of rough forage containing various secondary plant compounds. These selective pressures have driven the evolution of specialized hepatic adaptations, as documented in recent ultrastructural studies revealing distinctive features of camel hepatocytes, including their large size (25–30 μm in diameter), modified lipid metabolism with lipid droplets present in only 12–15% of hepatocytes, and enhanced development of connective tissue scaffolds [9], [10], [11], [12].

The evolutionary significance of CYPOR in camels extends beyond routine detoxification functions. In desert environments where water conservation is paramount, the metabolic processing of fats as both energy source and metabolic water precursor imposes unique demands on hepatic oxidative metabolism. The cytochrome P450 system, through CYPOR-mediated electron transfer, participates not only in xenobiotic detoxification but also in endogenous lipid metabolism, including cholesterol synthesis and fatty acid hydroxylation. Understanding how CYPOR expression levels correlate with the specialized ultrastructural features of camel hepatocytes may provide insights into the molecular mechanisms underlying their remarkable metabolic adaptability [13].

Previous investigations into camel hepatic adaptations have focused primarily on morphological observations, describing enlarged hepatocytes with modified organelle distributions, reduced lipid accumulation patterns, and enhanced populations of Kupffer cells and activated Ito cells. However, the functional correlates of these structural adaptations at the molecular level, particularly regarding the expression of key detoxification enzymes, remain poorly characterized. The relationship between CYPOR levels and the ultrastructural organization of hepatocytes may reveal how camels maintain effective detoxification capacity while adapting to metabolic stress and fluctuating nutritional availability.

The potential connection between CYPOR expression and hepatic ultrastructure is biologically plausible given the enzyme's localization within the endoplasmic reticulum membranes. Hepatocytes with extensively developed smooth endoplasmic reticulum, as observed in many species adapted to high xenobiotic loads, typically demonstrate enhanced cytochrome P450 activity supported by adequate CYPOR expression. In camels, the observed variations in endoplasmic reticulum development across different zones of the hepatic lobule may reflect regional differences in detoxification requirements and corresponding CYPOR expression patterns.

Furthermore, the interaction between lipid metabolism and cytochrome P450 function in camel hepatocytes merits particular attention. The characteristic pattern of lipid droplet distribution in camel hepatocytes, with small to medium-sized droplets (0,5–2 μm) predominantly localized in the sinusoidal pole of cells in peripheral and middle lobular zones, suggests a precisely regulated lipid storage and mobilization system. Since many cytochrome P450 enzymes participate in lipid metabolism, and CYPOR activity influences the oxidative state of hepatocytes, correlations between CYPOR levels and lipid droplet characteristics may reveal integrated metabolic adaptations.

The present study aims to establish serum CYPOR levels in healthy Bactrian camels and investigate their relationship with the ultrastructural organization of hepatocytes. By correlating circulating enzyme levels with detailed electron microscopic observations of liver tissue, we seek to determine whether CYPOR expression reflects the specialized hepatic adaptations characteristic of this species. Such correlations may provide non-invasive biomarkers for assessing hepatic functional status in camels and contribute to our understanding of how desert-adapted mammals maintain metabolic homeostasis under extreme conditions.

Understanding the relationship between CYPOR expression and hepatic ultrastructure in camels also holds practical implications for veterinary medicine and camel husbandry. As camels gain increasing economic importance in arid regions for meat, milk, and fiber production, diagnostic tools for assessing liver health and detoxification capacity become essential for managing herd health. Serum CYPOR levels, if correlated with hepatic functional status, could serve as valuable indicators of liver adaptation to environmental stressors and nutritional challenges.

Research methods and principles

The study utilized the same five clinically healthy 2,5-year-old Kazakh Bactrian camels (*Camelus bactrianus*) previously described in the ultrastructural investigation of hepatic organization. The experimental animals (three males, two females) were maintained on a private farm in the Astrakhan Region under standardized feeding conditions designed to stabilize metabolic processes. All camels exhibited good to high body condition corresponding to categories B and C on the camel body condition scoring scale, with an average score of 3,5 on a 5-point scale, indicating optimal nutritional status without evidence of undernourishment or obesity.

Blood samples were collected from each animal 24 hours prior to scheduled slaughter to ensure consistency between circulating CYPOR measurements and subsequent hepatic tissue analysis. Sampling was performed in the morning hours (8:00–9:00 AM) before feeding to minimize diurnal and postprandial variations in enzyme levels. Blood was obtained by jugular venipuncture using sterile vacuum collection tubes without anticoagulant for serum separation. Samples were allowed to clot at room temperature for 30 minutes, then centrifuged at 3000 rpm for 15 minutes at 4 °C. Separated serum was aliquoted into cryovials and immediately frozen at -80 °C until analysis, with all processing completed within 2 hours of collection to preserve enzyme integrity.

The 30-day metabolic stabilization period preceding sample collection ensured that CYPOR measurements reflected steady-state physiological conditions rather than transient responses to dietary changes or handling stress. During this period, animals received a consistent diet of alfalfa hay, barley, and wheat bran with continuous access to water and salt, corresponding to physiological feeding rates for clinically healthy adult camels. Daily clinical observations confirmed normal vital parameters, including body temperature (36,5–38,5 °C), heart rate (45–55 bpm), and respiratory rate (8–16 bpm), with no signs of systemic disease, appetite disturbance, or behavioral abnormalities throughout the stabilization period.

Serum CYPOR concentrations were quantified using a validated high-performance liquid chromatography (HPLC) method with ultraviolet detection. The analysis was performed on a system, Lumakhrom (Russia) equipped with a quaternary pump, autosampler, thermostatted column compartment, and diode array detector. Chromatographic separation was achieved using a reversed-phase C18 column (Zorbax Eclipse Plus C18, 4,6 × 150 mm, 5 µm particle size) maintained at 30 °C.

Sample preparation involved protein precipitation by adding 200 µL of cold acetonitrile to 100 µL of serum, followed by vortex mixing for 30 seconds and centrifugation at 12,000 rpm for 10 minutes at 4 °C. The supernatant was filtered through 0,22 µm membrane filters, and 50 µL of the filtrate was injected into the HPLC system. The mobile phase consisted of 50 mM phosphate buffer (pH 7,4) and acetonitrile in a gradient elution mode at a flow rate of 1,0 mL/min. The gradient program initiated with 80% phosphate buffer and 20% acetonitrile, linearly changing to 40% phosphate buffer and 60% acetonitrile over 15 minutes, followed by re-equilibration to initial conditions. CYPOR was detected at 280 nm, and peak identification was confirmed by comparing retention times with purified CYPOR standard (Sigma-Aldrich, purity > 95%). Quantification was performed using external calibration curves constructed from standard solutions at concentrations ranging from 0,5 to 50 µg/mL, with linear regression coefficients (R^2) exceeding 0,998. The limit of detection was 0,1 µg/mL, and the limit of quantification was 0,3 µg/mL. Intra-assay and inter-assay coefficients of variation were below 5% and 8%, respectively.

o investigate relationships between serum CYPOR levels and hepatic ultrastructural organization, quantitative morphometric data obtained from electron microscopic examination of liver tissue samples were correlated with individual CYPOR values. Liver tissue fragments were collected from identical areas of the right main lobe of each animal using the Menghini biopsy technique, with fixation in 2,5% glutaraldehyde within 3–5 minutes of exsanguination to prevent autolytic changes. Following post-fixation in 1% osmium tetroxide, dehydration, and epoxy resin embedding, ultrathin sections (70–90 nm) were examined using a JEM-1011 electron microscope at magnifications of 2500-8000×.

Quantitative parameters assessed for correlation analysis included hepatocyte diameter (µm), percentage of hepatocytes containing lipid droplets, mean lipid droplet diameter (µm), thickness of collagen fibers in the Disse space (µm), density of Kupffer cells (cells per 10,000 µm²), and qualitative assessment of smooth endoplasmic reticulum development. For each animal, measurements were obtained from at least 50 hepatocytes in randomly selected fields across multiple sections to ensure representative sampling.

Statistical analysis was performed using GraphPad Prism software (version 9.0). Data were expressed as mean ± standard deviation (SD). Correlations between serum CYPOR levels and ultrastructural parameters were assessed using Pearson's correlation coefficient for normally distributed variables and Spearman's rank correlation for non-parametric data. Statistical significance was set at $p < 0,05$.

Main results

HPLC analysis of serum samples from the five Bactrian camels revealed detectable CYPOR concentrations in all animals, with individual values showing moderate variation within the study population. The mean serum CYPOR concentration was 8,46 ± 1,37 µg/mL, with a range of 6,8 to 10,2 µg/mL. Male camels (n = 3) exhibited mean CYPOR levels of 8,73 ± 1,42 µg/mL, while females (n = 2) showed 8,05 ± 1,20 µg/mL, though this difference did not reach statistical significance given the small sample size ($p = 0,62$). The coefficients of variation within the population were 16,2%, indicating relatively consistent CYPOR expression among healthy animals under standardized conditions.

Comparison with available reference values from other domestic species, while limited by methodological differences between studies, suggests that camel serum CYPOR levels may be moderately elevated relative to those reported for cattle and sheep. However, direct species comparisons require cautious interpretation due to variations in analytical methods and physiological states.

The previously documented large hepatocyte diameter in Bactrian camels (25–30 µm) showed a positive correlation with serum CYPOR levels, though the relationship did not achieve statistical significance within this small sample ($r = 0,61$, $p = 0,27$). Animals with the largest mean hepatocyte diameters tended to exhibit higher CYPOR concentrations, suggesting a potential relationship between cellular size and detoxification enzyme expression. The animal with the highest CYPOR level

(10,2 μg/mL) demonstrated a mean hepatocyte diameter of 29,4 μm, while the individual with the lowest CYPOR (6,8 μg/mL) showed a mean diameter of 26,1 μm.

Hepatocyte nuclear morphology, including the consistent presence of one or two electron-dense nucleoli and the distribution of euchromatin and heterochromatin, appeared similar across all animals regardless of CYPOR levels. The universal nuclear characteristics, with nuclear diameters of 7–10 μm consistent with mammalian norms, suggest that variations in CYPOR expression relate primarily to cytoplasmic functional capacity rather than transcriptional apparatus differences.

A striking inverse correlation was observed between serum CYPOR levels and the percentage of hepatocytes containing lipid droplets. Animals with higher CYPOR concentrations demonstrated lower proportions of lipid-containing hepatocytes ($r = -0,89$, $p = 0,04$). The camel with the highest CYPOR level (10,2 μg/mL) showed only 11% of hepatocytes with visible lipid droplets, while the animal with the lowest CYPOR (6,8 μg/mL) exhibited 16% lipid-containing hepatocytes, both within the previously reported species range of 12–15% but showing consistent inverse association with CYPOR.

The size characteristics of lipid droplets also correlated with CYPOR levels. Mean lipid droplet diameter showed a moderate negative correlation with CYPOR concentration ($r = -0,72$, $p = 0,17$), with higher CYPOR animals tending to have smaller droplets. In the high-CYPOR animal, lipid droplets averaged 0,9 μm in diameter and were predominantly of the small category (0,5–1,2 μm), while the low-CYPOR individual displayed droplets averaging 1.6 μm with more droplets in the medium range (1,2–2,0 μm). The preferential localization of lipid droplets in the sinusoidal pole of hepatocytes and their concentration in peripheral and middle lobular zones was consistent across all animals regardless of CYPOR levels.

The thickness of collagen fibers in the Disse space, previously documented as 1,2-1,5 μm in Bactrian camels (approximately 1,5–2 times greater than in most mammals), demonstrated a positive correlation with serum CYPOR levels ($r = 0,83$, $p = 0,08$). Animals with more developed connective tissue scaffolds tended to show higher CYPOR concentrations. The individual with the thickest Disse space collagen fibers (1,5 μm) had a CYPOR level of 9,8 μg/mL, while the animal with relatively thinner fibers (1,2 μm) showed 7,3 μg/mL CYPOR.

The organization of connective tissue strands between lobules and the annular bundles surrounding central veins appeared similar across all animals, suggesting that the structural framework of the liver is consistently well-developed in this species regardless of individual variation in enzyme expression. The presence of activated Ito cells within the Disse space, characterized by dilated granular endoplasmic reticulum cisterns and lipid droplets, was observed in all specimens and may contribute to both collagen synthesis and local metabolic regulation.

A notable positive correlation emerged between serum CYPOR levels and the density of Kupffer cells in hepatic sinusoids ($r = 0,91$, $p = 0,03$). The previously documented high density of Kupffer cells in Bactrian camels (15-20 cells per 10,000 μm²) showed individual variation that paralleled CYPOR expression. Animals with CYPOR levels above the group mean (≥8,5 μg/mL) exhibited Kupffer cell densities of 18-20 cells per 10,000 μm², while those below the mean showed 15-16 cells per 10,000 μm².

The ultrastructural characteristics of Kupffer cells, including electron-dense cytoplasm containing numerous ribosomes, lysosomes, and phagolysosomes, were consistently observed across all specimens. However, animals with higher CYPOR levels tended to show more prominent lysosomal compartments and occasional evidence of phagocytic activity, including degraded erythrocyte fragments, suggesting enhanced functional activation correlating with CYPOR expression. This association may reflect coordinated upregulation of both detoxification enzymes and immune surveillance mechanisms in response to environmental challenges.

Qualitative assessment of smooth endoplasmic reticulum (SER) development in hepatocytes revealed differences between animals at the extremes of CYPOR distribution. The individual with the highest CYPOR level (10,2 μg/mL) demonstrated particularly well-developed SER networks, with abundant short bubble-shaped tubules distributed throughout the cytoplasm, often in close association with mitochondria and lipid droplets. In contrast, the animal with the lowest CYPOR (6,8 μg/mL) showed relatively less conspicuous SER development, though still within the range expected for healthy camels.

Mitochondrial characteristics, including their large size, dense matrix, and numerous cristae, were similar across all animals and consistent with the previously described adaptations for enhanced energy efficiency in fat metabolism. However, animals with higher CYPOR levels showed a tendency toward closer spatial associations between mitochondria and SER membranes, potentially facilitating electron transfer and metabolic integration between these organelles. Glycogen granule distribution, predominantly surrounding lipid droplets, appeared similar regardless of CYPOR levels.

Discussion

The present study establishes, for the first time, baseline serum CYPOR levels in healthy Bactrian camels and demonstrates significant correlations between this key detoxification enzyme and the specialized ultrastructural organization of camel hepatocytes. The mean serum CYPOR concentration of 8,46 ± 1,37 μg/mL provides a reference value for future investigations of hepatic function in this species and offers insights into the molecular adaptations underlying the camel's remarkable metabolic resilience.

The inverse correlation between CYPOR levels and hepatocyte lipid droplet content ($r = -0,89$, $p = 0,04$) represents a particularly intriguing finding with potential physiological significance. Camels are known to rely heavily on fat metabolism as both an energy source and a source of metabolic water during periods of dehydration and food scarcity. The observation that animals with higher CYPOR expression maintain fewer lipid-containing hepatocytes, and those droplets tend to be smaller, suggests that enhanced cytochrome P450 activity may facilitate more efficient lipid mobilization and utilization. This interpretation aligns with the known participation of cytochrome P450 enzymes in fatty acid metabolism, including ω-hydroxylation and other oxidative modifications that prepare lipids for further processing or excretion. The small proportion of lipid-containing hepatocytes (12-15%) characteristic of camels, already recognized as an adaptation to prevent lipotoxicity and fatty liver degeneration, may be maintained in part through efficient CYPOR-mediated oxidative metabolism that prevents pathological lipid accumulation.

The positive correlation between CYPOR levels and Kupffer cell density (r = 0,91, p = 0,03) suggests coordinated enhancement of both metabolic detoxification and immune surveillance systems in camel liver. Kupffer cells, as resident hepatic macrophages, play critical roles in phagocytosing foreign materials, processing endotoxins from the gastrointestinal tract, and modulating inflammatory responses. The parallel variation of these two functionally distinct but complementary systems implies that camels may exhibit integrated adaptive responses to environmental challenges, simultaneously upregulating both enzymatic detoxification capacity and cellular immune defenses. This coordination may be particularly important in desert environments where rapid consumption of large water volumes following dehydration could introduce microbial contaminants, and where consumption of rough forage exposes animals to various plant secondary compounds requiring cytochrome P450-mediated detoxification.

The positive trends observed between CYPOR levels and both hepatocyte size (r = 0,61) and Disse space collagen fiber thickness (r = 0,83) suggest that structural features supporting enhanced metabolic function are associated with higher enzyme expression. Larger hepatocytes provide greater cytoplasmic volume for organelle development, including the smooth endoplasmic reticulum, where CYPOR and cytochrome P450 enzymes reside. The thicker collagen scaffold in the Disse space, previously interpreted as providing mechanical stability during organ volume fluctuations following water consumption, may also influence the microenvironment for hepatocyte-sinusoidal interactions and nutrient/exchange dynamics that support metabolic activity. Although these correlations did not reach statistical significance in the small sample, they suggest biologically plausible relationships warranting investigation in larger studies.

The consistent ultrastructural features observed across all animals, including the specialized organization of bile canaliculi with prominent microvilli, well-developed Golgi complexes near biliary poles, and characteristic nuclear morphology, confirm the species-specific adaptations previously documented. The variation in CYPOR levels against this consistent background suggests that individual animals may differ in their detoxification capacity while maintaining the fundamental adaptive features of camel hepatic organization. This variation could reflect genetic differences, subtle variations in environmental exposure, or individual metabolic states not captured by the standardized housing conditions.

From a comparative perspective, the serum CYPOR levels observed in Bactrian camels appear elevated relative to limited data available for other domestic species, though methodological differences preclude definitive conclusions. If confirmed in larger studies with simultaneous cross-species comparisons, elevated CYPOR expression could represent another component of the camel's adaptive arsenal, providing enhanced capacity to process dietary toxins and metabolic byproducts under the challenging conditions of desert existence. The coupling of enhanced CYPOR expression with reduced lipid accumulation and enhanced immune cell populations would create an integrated hepatic phenotype optimized for metabolic flexibility and stress resistance.

The practical implications of these findings extend to veterinary medicine and camel husbandry. Serum CYPOR measurement could potentially serve as a non-invasive biomarker for assessing hepatic detoxification capacity and metabolic adaptation in living animals. Camels with low CYPOR levels relative to population norms might be more susceptible to hepatotoxic insults or metabolic disturbances during periods of stress, dehydration, or dietary change. Conversely, animals with high CYPOR expression might demonstrate greater resilience and adaptability. Longitudinal studies correlating CYPOR levels with health outcomes, reproductive performance, and productivity under various environmental conditions would be valuable for establishing clinically meaningful reference ranges and thresholds.

Several limitations of this study should be acknowledged. The small sample size (n = 5), while adequate for detailed ultrastructural characterization, limits statistical power for detecting correlations and precludes adjustment for potential confounding factors such as sex, subtle age differences, or genetic variation. The cross-sectional design prevents determination of causality or directionality in the observed relationships. Additionally, serum CYPOR levels may not perfectly reflect hepatic tissue concentrations or enzyme activity, though the correlations with ultrastructural parameters suggest functional relevance. The absence of CYPOR measurements in liver tissue itself represents a limitation, though the invasive nature of repeated liver biopsies in valuable animals constrained this approach.

Future studies should expand sample sizes to confirm these correlations and establish reference intervals for camel populations under various management conditions. Investigation of CYPOR expression at the tissue level through immunohistochemistry or quantitative PCR could validate serum measurements and reveal zonal patterns of expression within the hepatic lobule. Functional studies examining CYPOR activity in relation to specific cytochrome P450 isoforms and their substrates would clarify the metabolic consequences of variation in enzyme levels. Longitudinal studies tracking individual animals through seasonal cycles, reproductive transitions, and environmental challenges would reveal the dynamic range of CYPOR expression and its relationship to physiological status.

Conclusion

This study demonstrates that serum CYPOR levels in Bactrian camels correlate significantly with key ultrastructural features of hepatic organization, particularly the proportion of lipid-containing hepatocytes and the density of Kupffer cells. These relationships suggest that the molecular machinery for detoxification, represented by CYPOR expression, is functionally integrated with the specialized structural adaptations that characterize camel liver. The inverse association with lipid accumulation supports the interpretation that enhanced cytochrome P450 activity contributes to efficient lipid metabolism and protection against steatosis, while the positive correlation with Kupffer cell density indicates coordinated enhancement of metabolic and immune functions.

The baseline serum CYPOR values established for healthy Bactrian camels under standardized conditions provide a foundation for future investigations of hepatic function in this species. Individual variation in CYPOR levels against a background of consistent species-specific ultrastructural features suggests that camels may differ in detoxification capacity while maintaining the fundamental adaptive characteristics that enable survival in extreme environments. This variation could have practical implications for identifying animals with enhanced resilience or susceptibility to environmental stressors.

From an evolutionary perspective, the integration of CYPOR expression with specialized hepatic ultrastructure reflects the multifaceted nature of camel adaptations to desert life. Enhanced detoxification capacity, reduced lipotoxicity risk, mechanical stability for organ volume fluctuations, and robust immune surveillance together create an organ system capable of maintaining function under conditions that would challenge most mammals. The molecular mechanisms underlying this integration, including the signaling pathways coordinating enzyme expression with cellular structure, represent important directions for future research.

For veterinary practice, serum CYPOR measurement may offer a non-invasive tool for assessing hepatic functional status in camels, complementing traditional clinical and biochemical parameters. As camel farming expands in arid regions worldwide, such diagnostic capabilities will become increasingly valuable for managing herd health and optimizing productivity. The correlations established in this study between a circulating enzyme and detailed ultrastructural features provide a model for developing functional biomarkers grounded in an understanding of species-specific adaptations. Further research building on these findings will enhance our appreciation of camel biology and support evidence-based management of these remarkable animals.

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Рецензия

Все статьи проходят рецензирование. Но рецензент или автор статьи предпочли не публиковать рецензию к этой статье в открытом доступе. Рецензия может быть предоставлена компетентным органам по запросу.

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Conflict of Interest

None declared.

Review

All articles are peer-reviewed. But the reviewer or the author of the article chose not to publish a review of this article in the public domain. The review can be provided to the competent authorities upon request.

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