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Ultrasound Technology in the Diagnosis and Prognosis of Mastitis in Dairy Cattle: Advancements, Applications, and Future Directions

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ABSTRACT

The review article examines the pivotal importance of ultrasound technology in the diagnosis and prognosis of mastitis in dairy cattle, a prominent obstacle in the dairy business. Mastitis, a condition characterized by inflammation of the mammary gland, carries significant economic and animal welfare consequences, underscoring the importance of prompt and precise care. Ultrasound, being a non-invasive and adaptable imaging technology, has become a potent diagnostic and prognostic aid. The article discusses mastitis, its financial ramifications, and the imperative nature of timely detection. The text explores the evolution of ultrasonic technology, examines its utilization in veterinary care, and emphasizes its advantages over conventional techniques. Furthermore, it explores the prognostic elements, namely in forecasting milk production and udder-related ailments. This text provides an explanation of how mastitis can be assessed using digital image analysis, numerical pixel values, and pixel heterogeneity. The article discusses the utilization of real-time monitoring technology and the incorporation of artificial intelligence in the analysis of ultrasound data. The statement recognizes the difficulties in using ultrasonography on a large scale and supports further investigation and practical application of this technology. In essence, it sees ultrasound as a highly promising instrument for enhancing the health and productivity of dairy cattle.

INTRODUCTION

The dairy business is of great global significance and has a crucial role in guaranteeing food security, promoting economic growth, and safeguarding animal welfare (Alonso et al., 2018; Appleby and Mitchell, 2018; Chang and Chen, 2022; Marabelli and Caporale, 2003; Qureshi et al., 2015). Dairy products, including milk, cheese, and yoghurt, are fundamental components of the human diet, supplying vital nutrients to individuals across the globe. These items are abundant in protein, calcium, and vitamins, which help maintain balanced and varied diets (Chandan, 2015; Comerford et al., 2021; Panghal et al., 2018). The dairy industry's importance extends beyond its function in providing sustenance, embracing diverse factors that have an impact on both developed and developing nations (Floros et al., 2010; Steinfeld, 2006).
From an economic standpoint, the dairy sector is a dominant force within the agriculture business. The dairy industry provides significant income, fosters employment, and sustains the livelihoods of numerous individuals engaged in various aspects of dairy production, including farmers, processors, distributors, and retailers (Hoang et al., 2021; Kumar et al., 2019; Mwangi, 2021; Orasmaa, 2017; van der Lee et al., 2014; Verburg et al., 2022; Yilma et al., 2011; Younas, 2013). The economic impact extends beyond a single step of the dairy supply chain and has a ripple effect on the overall economy, fostering growth in interconnected industries (Devaux et al., 2018; Gallaud and Laperche, 2016; Hartwich and Negro, 2010; Siems et al., 2021; Talukder et al., 2021).
The significance of livestock welfare is another critical aspect of the dairy sector. Prioritising the welfare of dairy animals, namely cows and goats, is not only morally right but also essential for sustaining optimal milk production

(Wolf et al., 2016). The industry consistently improves animal husbandry techniques to maximize productivity while giving utmost importance to the ethical treatment of animals (Adamczyk, 2018; Ventura et al., 2015; Weary and Von Keyserlingk, 2017).

The global economy is significantly influenced by the worldwide commerce of dairy products. Several nations participate in the export and import of dairy products, leading to significant foreign currency revenues and contributing to economic growth (Barkema et al., 2015; Chandio et al., 2017; Herrero et al., 2013; Upton, 2004). The worldwide relevance of the dairy industry is further emphasized by the widespread demand for dairy products, which drives international trade in this sector (Singh and Kumari, 2017; Wankar et al., 2021).

Dietary diversity has a crucial role in determining one's overall health, and the inclusion of dairy products contributes to this diversity (Gillespie and van den Bold, 2017; Organization, 2022; Raholiarimanana et al., 2023). The dairy industry's prosperity relies heavily on research and development. Consistent allocation of resources towards research and development (R&D) results in advancements in the quality of milk, refinement of processing methods, and the innovation of unique dairy-derived products. These advancements provide advantages not only to the sector but also to consumers who are looking for healthier and more varied food choices. Regions where dairy is a fundamental component of the diet have greater access to a wider variety of vital nutrients, which enhances nutritional intake and promotes overall health and wellness. Furthermore, advancements in the dairy business have resulted in the creation of value-added products, which enhance the variety of dietary options available (Krivonos and Kuhn, 2019; Ortega-Requena and Rebouillat, 2015; Rushton and Bruce, 2017; Singh and Datta, 2010).

The dairy sector has been transformed by technological developments and innovation, leading to a revolution in milk production. These developments encompass enhanced breeding procedures and cutting-edge processing processes, facilitating the creation of dairy products that are both safer and of superior quality. The dairy industry has experienced increased efficiency, sustainability, and competitiveness as a result of technological advancements (Ivanov and Tikhomirov, 2020; Kozina and Semkiv, 2020; Onteru et al., 2010; Thornton, 2010).

Dairy farming is intricately linked to rural development, as it frequently flourishes in rural regions. Dairy production enhances rural development through the enhancement of infrastructure, transportation, and market accessibility (Ali, 2007; Steinfeld and Mack, 1995; Vázquez-López et al., 2021). Small-scale dairy production in numerous developing nations serves as a means to escape poverty, empowering communities and fostering economic expansion (Mohapatra et al., 2012; Raja and Sehgal, 2015). Dairy farming has income generating and poverty reduction prospects for small-scale farmers in emerging nations. The sale of milk and dairy products can offer a dependable source of revenue, enhancing living conditions and promoting economic stability in susceptible communities. The dairy business also contributes to climate resilience (Cradock-Henry, 2021; Singh et al., 2023). Agroforestry and responsible land management, which are sustainable practises, help to store carbon and decrease the release of greenhouse gases (Recha et al., 2014). These practises are in line with worldwide initiatives to address climate change (Chiriacò and Valentini, 2021; Manual, 2019).

To summarize, the global dairy sector plays a crucial role in various aspects such as nutrition, economics, animal welfare, international trade, dietary diversity, technology, rural development, climate resilience, poverty alleviation, and innovation. This review article explores a particular component of the dairy industry, specifically the economic impact of mastitis in dairy cattle. It emphasizes the need to solve this difficulty in order to maintain the industry's ongoing success.

Mastitis in Dairy Cattle: Definition and Types

Mastitis, a common ailment in dairy cows, consists of two main forms: clinical and sub-clinical mastitis. Clinical mastitis is distinguished by evident and severe symptoms, such as swelling, redness, pain, and changes in milk quality, such as the presence of clots, pus, or blood (Ibrahim, 2017; Kibebew, 2017; Sharun et al., 2021). Cows suffering from clinical mastitis frequently displays systemic indications of disease. Conversely, sub-clinical mastitis is characterized by subtle or absent symptoms, such as no apparent indicators or minor alterations in milk quality. However, it is identified by observing increased somatic cell counts (SCC) in milk. Gaining a clear understanding of these differences is essential for fully grasping the economic consequences of mastitis on dairy cows (Bhosale et al., 2014; Giesecke et al., 1974; Samad, 2022).

Impact on Milk Production and Quality

Mastitis has a substantial impact on both the quantity and quality of milk in dairy animals. The presence of clinical mastitis results in a swift and significant decline in milk yield as a consequence of the pain and discomfort caused by the infection. In severe instances, the damaged udders may completely halt milk production, leading to immediate and conspicuous decreases in the amount of milk produced each day (Harjanti and Sambodho, 2020; Maréchal and Loir, 2011). Sub-clinical mastitis, while less conspicuous, still leads to gradual decline in milk yield, resulting in significant long-term financial losses for dairy farmers. In addition, mastitis decreases the quality of milk (Lescourret and Coulon, 1994). The presence of clinical mastitis in cow's results in milk that is unfit for human consumption and unsuitable for processing into dairy products due to the presence of visible pollutants and sensory alterations. Sub-clinical mastitis, which is detected by elevated somatic cell count (SCC), negatively affects the quality of milk by decreasing its shelf life and potentially leading to reduced pricing for producers (Auldist and Hubble, 1998; Bobbo et al., 2017; Poławska et al., 2012).

Economic Consequences and Animal Welfare Concerns

The economic ramifications of mastitis are significant. Both symptomatic and asymptomatic mastitis result in economic losses for dairy farmers. The occurrence of clinical mastitis leads to quick decreases in milk supply, treatment expenses, and the necessity to dispose of milk. On the other hand, sub-clinical mastitis causes prolonged decreases in both milk quantity and quality (Hogeveen et al., 2011; Nielsen, 2009). Furthermore, the management of mastitis cases results in a rise in operational expenses. In addition to its economic implications, mastitis gives rise to significant animal welfare concerns (Oltenacu and Broom, 2010). Afflicted cows experience pain, discomfort, and anguish, with clinical mastitis resulting in observable indicators of suffering. Elevated somatic cell count (SCC) levels suggest discomfort even in sub-clinical instances. Chronic mastitis, whether it manifests as clinical or sub-clinical, has enduring welfare ramifications, with the ability to impact the health, lifespan, and productivity of cows (Langford and Stott, 2012; Wells et al., 1998). Implementing preventive measures, such as practising good hygiene and administering vaccinations, is crucial for reducing the economic and welfare consequences of mastitis (Ventura et al., 2015).

To summarise, mastitis in dairy cattle consists of two types: clinical and sub-clinical. Each form has its own economic implications and raises issues about animal welfare. This condition significantly hampers the production and quality of milk, resulting in financial losses for farmers and endangering the welfare of animals. Implementing efficient mastitis control protocols is crucial for tackling these complex difficulties and guaranteeing the long-term viability and humane treatment of dairy cattle in the sector (Mainau et al., 2014).

Historical Development and Origins of Ultrasound

The beginnings of ultrasound technology can be traced back to the discovery of the piezoelectric effect by Pierre and Jacques Curie in 1880 (Newman and Rozycki, 1998). This groundbreaking finding facilitated the production and detection of sound waves with a high frequency, ultimately resulting in the advancement of ultrasound technology. Ultrasound technology experienced significant progress throughout both World War I and World War II, since it was utilized in military equipment such as Sonar and Radars. These devices played a crucial role in navigation, communication, and the detection of submarines (Friedlander, 1967; Graff, 2012; Muir and Bradley, 2016). Following the war, there was ongoing advancement in ultrasound technology, leading to its utilization in many industrial and scientific domains. With the passage of time, ultrasound technology has evolved to become smaller, more inexpensive, and of superior quality, enabling its integration into the field of veterinary medicine. The historical context emphasizes the significant influence of wartime applications on the development of current ultrasound technology (Mahalle et al., 2021; Nicolson and Fleming, 2013; Szabo, 2004).

Advancements in Ultrasound Technology

The diagnostic capabilities of ultrasound technology have been greatly enhanced by recent breakthroughs. Significant advancements have been made in the field of medical imaging, specifically in the incorporation of three-dimensional (3D) and four-dimensional (4D) imaging techniques (Goddard, 2000; Rantanen and Ewing III, 1981). These cutting-edge methods provide complete and dynamic views, which are particularly beneficial in the field of obstetrics. Contemporary ultrasound equipment provide sophisticated imaging techniques including Doppler ultrasound and contrast-enhanced ultrasonography (CEUS), which allow for the observation of blood circulation and improve the precision of diagnoses (Hagen et al., 2011; KOCHAR, 2011; Meinecke-Tillmann, 2017; Wells, 2006). Portable ultrasound devices have significantly transformed point-of-care diagnostics, finding utility in emergency medicine and rural healthcare settings (Jagannathan et al., 2009; Leighton, 2007; Leong et al., 2011; Uchino, 1998). Artificial intelligence (AI) integration improves the interpretation of images, automates measurements, and enables early detection of problems. The integration of elastography, wireless networking, cloud-based storage, enhanced transducers, contrast agents, and telemedicine has revolutionised ultrasound technology.

Application of Ultrasound in Veterinary Medicine

The application of ultrasound in veterinary medicine is varied and necessary. Originally designed for medicinal applications in humans, ultrasonography rapidly became widely utilised in the veterinary domain. The practice of early pregnancy identification in animals, particularly in cattle, sheep, and horses, originated because to its non-invasive and safe characteristics (Houghton and Turlington, 1992). The veterinary practice has greatly profited from recent improvements in ultrasonography technology. It is crucial in managing reproductive health by assisting in determining the stage of pregnancy, assessing the viability of the foetus, and monitoring reproductive health in different animal species (Jones and Beal, 2003; Kähn and Volkmann, 2004; Mali, 2015; Medan and Abd El-Aty, 2010; Smith et al., 2014). Ultrasound is a highly effective diagnostic tool that can be used to analyse soft tissue structures, identify and evaluate anomalies, and provide guidance for therapies. Its wide-ranging significance in animal healthcare across various species and healthcare contexts is demonstrated by its uses in musculoskeletal imaging(Boström et al., 2022; Kofler, 2009), cardiology (Boon, 2011; John and Durham Jr, 2017), exotic animal medicine(Hildebrandt and Saragusty, 2015; Meomartino et al., 2021), emergency treatment (Creedon and Davis, 2023; Rajamahendran et al., 1994), teaching (Wichtel et al., 2022; Wood et al., 2000), research (Ginther, 2014; Pierson et al., 1988), and telemedicine (Lisciandro, 2021; Mun and Turner, 1999; Wilson, 1992).

Diagnostic Role of Ultrasound in Mastitis-Ultrasonographic Examination of Mammary Glands

The ultrasonographic evaluation of mammary glands is a specialized technique commonly employed in veterinary medicine, particularly in dairy cattle and other livestock (Barbagianni and Gouletsou, 2023; Molik et al.; Tommasoni et al., 2023). It fulfils multiple essential functions. Veterinarians utilize it to evaluate the condition of mammary glands, identifying initial indications of mastitis that are vital for prompt intervention and treatment in order to uphold milk output and quality (Bonelli et al., 2020; Fasulkov, 2012; Paul, 2022; Schwarz et al., 2020; Tommasoni et al., 2023). This examination also aids in assessing udder structures, including the teat canal, teat wall, teat cistern, and gland cisterns, with the purpose of identifying anomalies (Esselburn, 2012; Martin et al., 2018; Paul, 2022). Furthermore, it assists in evaluating disruptions in milk flow and obtaining accurate measurements of teat characteristics, offering valuable information about the factors that affect teat health (Ambord and Bruckmaier, 2010; Celik et al., 2008; Martin, 2020; Venkatesan et al., 2017; Weiss et al., 2004). In addition to its therapeutic applications, ultrasonography is also utilized for research and educational purposes in the field of veterinary medicine.

Detection of Hematomas, Abscesses, Inflammation, and Tissue Growth

Ultrasound technology is essential for identifying and evaluating different illnesses in animals, such as hematomas, abscesses, inflammation, and tissue growth (Abouelnasr et al., 2016; Crilly et al., 2017; Streeter and Step, 2007). It offers vets the ability to correctly visualise these diseases in real-time through imaging. Ultrasound can accurately identify and describe hematomas, which are blood accumulations outside of blood vessels caused by injury. This also pertains to abscesses, which are localised accumulations of pus caused by infection. Ultrasound is capable of identifying regions of inflammation that might arise from many sources, and it can aid in tracking the effectiveness of treatment. Moreover, it is proficient in detecting anomalous tissue proliferation, such as neoplasms or cysts, facilitating diagnosis, and directing therapy alternatives such as biopsies for laboratory examination (Dos Santos et al., 2016; Franz et al., 2009; Szencziová and Strapák, 2012).

Comparison with Traditional Diagnostic Methods

Ultrasound technology has numerous benefits compared to conventional diagnostic procedures in veterinary care. This technology is non-invasive, allowing for immediate imaging without the need for surgical interventions or anaesthesia (Barbagianni and Gouletsou, 2023; King, 2006; Prasad et al., 2021; Teller and Moberly, 2020). This method guarantees the well-being of both animals and operators. Ultrasound is highly advantageous for capturing real-time images, in contrast to the static techniques previously employed (Chowdhury et al.; Gorsi et al., 2019). Furthermore, it does not utilise ionising radiation, which increases its safety and enables many uses. The device's capacity to deliver high-resolution images with exceptional differentiation of soft tissues renders it highly useful in the detection of diverse disorders. Ultrasound is highly effective in providing guidance for minimally invasive operations, hence minimizing problems. Technological advancements have resulted in the development of portable and compact ultrasound machines, which have improved accessibility and reduced prices in comparison to certain conventional diagnostic equipment. To summarise, ultrasound's multifunctionality, non-intrusiveness, immediate imaging, safety, precision, and availability have transformed veterinary medicine, rendering it an essential instrument for diagnosing and treating diverse ailments in animals (Džermeikaitė et al., 2023; Kamaya et al., 2013; King, 2006; Rix et al., 2018).

Assessment of Udder Tissue Changes

Ultrasound is a good technique for evaluating changes in udder tissue in the context of mastitis. Veterinarians employ ultrasonography to observe the interior components of the udder, such as the mammary glands and surrounding tissues. Ultrasound can be used to detect particular changes related to mastitis, including inflammation, edoema (collection of fluid), abscess formation, and tissue necrosis. The magnitude and scope of these alterations offer vital data for predicting the outcome. For example, if ultrasound reveals extensive tissue destruction, it may suggest a less positive prognosis compared to a localised infection. The capacity to capture images in real-time allows veterinarians to make well-informed judgements on the management and treatment of mastitis (Themistokleous et al., 2023; Tommasoni et al., 2023).

Assessment of Udder Morphometry

Ultrasound plays a crucial role in evaluating udder morphometry, which entails measuring different factors associated with the physical attributes of the udder. The measurements encompass udder depth, teat length, and teat diameter. An evaluation of udder morphometry is crucial for assessing the health, functionality, and milk production capacity of the udder. Alterations in udder morphometry, such as the presence of oedema or an increase in tissue thickness, might serve as indications of mastitis or other problems related to the udder. Ultrasound enables accurate measurements and monitoring of these alterations over a period of time. This data facilitates the identification, therapy, and control of udder health problems in dairy cattle (Atigui et al., 2016; Martin et al., 2020; Martin, 2020; Paul, 2022; Pourlis, 2020).

Teat Morphometry

Ultrasound imaging offers precise visualisation of teat anatomy, encompassing the teat wall, teat cistern, and teat canal (Millier, 2013; Smolenski, 2018). Alterations in these anatomical formations may be linked to a range of teat-related problems, including injury, blockages, or infections(Franz et al., 2001; Franz et al., 2003; GH et al., 2016; Inn). Ultrasound-based evaluation of teat morphometry is a significant tool for diagnosing and comprehending issues linked to teats, as well as for informing treatment decisions. For instance, veterinarians can utilise this information to strategize teat operations or interventions aimed at enhancing milking efficiency. Visualising teat structures non-invasively and in real-time improves the precision of diagnosing and treating conditions related to the teat (Adam et al., 2017; Díaz et al., 2013).

Supramammary Lymph Node Assessment

The supramammary lymph nodes play a crucial role in the immune response system of the udder. Ultrasound can be utilised to evaluate the dimensions and visual characteristics of these lymph nodes. Enlarged or atypical lymph nodes may suggest an immunological response to infection or inflammation in the udder. Ultrasound is essential for assessing the health of lymph nodes, enabling veterinarians to detect possible problems or reactions to mastitis. Utilising ultrasonography tests to monitor alterations in supramammary lymph nodes enhances the thorough evaluation of udder health and facilitates informed treatment decisions (Bradley et al., 2001; Gupta et al.; Hussein et al., 2015; Risvanli et al., 2019; Tommasoni et al., 2023).

Ultrasound in Dairy Cattle Management: Prognosis, Susceptibility, and Milk Yield

Ultrasound technology plays a versatile role in the management of dairy cattle. It allows veterinarians to participate in well-informed conversations with dairy farmers regarding the prognosis of mastitis, which can influence treatment decisions and expectations (Singh et al., 2021; Tommasoni et al., 2023). Moreover, ultrasound examination explores the correlation between udder characteristics and the vulnerability to mastitis, thereby assisting in customised treatment and genetic selection to reduce susceptibility (Bhakat et al., 2022). Furthermore, ultrasound is crucial in forecasting milk production by evaluating the condition of the udder and promptly detecting any udder-related ailments. The implementation of this comprehensive approach makes a significant contribution to the well-being of dairy cattle and the optimisation of milk production (Brandt et al., 2010; Rai and Bhateshwar, 2023; Sani et al., 2017).

Computer-Assisted Echotexture Analyses

The utilisation of computer-assisted echotexture analysis, which involves digital image processing, offers numerous applications and benefits for evaluating the udder, teat, and supramammary lymph nodes in dairy cattle. It facilitates accurate, unbiased, and instantaneous assessment, assisting in the supervision of dairy herds (Murawski et al., 2019; Ponco et al., 2021; Schwarz et al., 2020; Themistokleous et al., 2023; Themistokleous et al., 2022; Zhang et al., 2022).

Numerical Pixel Values (NPVs) and Pixel Heterogeneity (PSD)

Numerical Pixel Values (NPVs) and Pixel Heterogeneity (PSD) are essential components of digital image analysis as they accurately measure the information and texture present in images. NPVs correspond to the intensity of pixels, whereas PSD quantifies the variance in pixel values. These measurements have various applications in domains such as quality control and medical imaging. In the context of mastitis detection, there's a connection between NPVs, PSD, and tissue biochemical composition. Mastitis-induced changes in mammary tissue density and composition are reflected in ultrasound images, affecting NPVs and PSD (Gözütok, 2017; Molik et al.; Molik et al.; Murawski et al., 2019). These measurements serve as imaging biomarkers for diagnosing and monitoring mastitis. The utilisation of digital image analysis offers numerous advantages, such as unbiased quantification, enhanced productivity, data monitoring, timely intervention, and enhanced management of herd health. It improves the accuracy and efficiency of evaluating udder, teat, and lymph node conditions, which leads to improved performance of dairy herds.

Integration of Artificial Intelligence with Ultrasound Data

The amalgamation of artificial intelligence (AI) with ultrasound data holds great potential in the field of veterinary care. Artificial intelligence improves the precision of diagnoses, facilitates early identification, aids in making decisions based on data, and provides predictive analytics. Nevertheless, there exist obstacles pertaining to the quality of data, interoperability, ethical concerns, and regulatory issues that must be resolved (Hennessey et al., 2022; Kour et al., 2022; Min, 2023).

Future Prospects and Challenges

The utilisation of real-time monitoring technology in veterinary medicine holds the capacity to fundamentally transform illness identification and management, resulting in enhanced animal health, operational effectiveness, and research prospects. Nevertheless, there are other obstacles that need to be addressed in order to achieve successful implementation, including financial constraints, data accuracy, compatibility, privacy concerns, and the need for proper education (Bouhali et al., 2022; Gahungu et al., 2020; Lassau et al., 2019).

The extensive implementation of AI-driven ultrasound technology in veterinary medicine encounters multiple obstacles, such as expenses, data integrity, compatibility, data confidentiality, technical proficiency, validation, ethical concerns, reluctance to embrace change, diverse agricultural environments, limited proficiency, and ongoing maintenance. To tackle these issues, it is necessary to engage in collaboration and meticulous planning (Yitbarek and Dagnaw, 2022).

CONCLUSION

Ultrasound technology is essential for diagnosing and predicting the course of mastitis in dairy animals. It facilitates the timely identification of mastitis, allowing for precise observation of udder irregularities, and provides significant understanding of the potential effects on milk production and udder well-being. Swift intervention guided by ultrasound findings is crucial for limiting the spread of disease, minimising financial losses, and preserving the well-being of animals. The integration of modern technologies such as artificial intelligence is expected to greatly improve the accuracy and efficiency of ultrasound-based diagnostics and prognostics, leading to optimistic possibilities in the future. With the continuous progress of research and technology, the role of ultrasonography in enhancing the health and productivity of dairy cattle in combating mastitis is anticipated to expand.

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