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Fuzzy Logic as a Bridge to Human-like Artificial Intelligence in Orthodontics: A New Perspective

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Review

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ABSTRACT

Applications of artificial intelligence (AI) are increasingly becoming an indispensable component of orthodontic practices. The number of AI studies focused on orthodontics is growing rapidly. The fundamental operations of the AI algorithms utilized in these studies typically rely on binary logic (black or white, or 0 or 1). However, binary logic does not fully reflect the complexities of real life. Reality is more nuanced, with shades of gray and irregularities. Therefore, fuzzy logic-based AI systems, which mimic human-like reasoning, may facilitate more optimal and realistic decision-making in the healthcare and orthodontics fields. This review focuses on the clinical relevance of fuzzy logic in orthodontics, emphasizing how fuzzy logic can support orthodontists in making more flexible and realistic treatment decisions—especially in areas such as aesthetic evaluation, extraction planning, and functional orthopedic treatment. By bridging the gap between rigid binary decision-making and the complex variability seen in clinical practice, fuzzy logic offers a promising framework for improving patient communication and treatment outcomes.

Keywords: Fuzzy logic, artificial intelligence, orthodontics

İnsan Düşünme Biçimini Taklit Eden Saçaklı Mantığın Ortodontideki Yeri: Yeni Bir Bakış Açısı

Derleme

Süreç

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ÖZ

Yapay zekâ (YZ) uygulamaları, ortodonti pratiğinin vazgeçilmez bir bileşeni haline gelmektedir. Ortodontiye odaklanan YZ çalışmaları hızla artmaktadır. Bu çalışmalarda kullanılan YZ algoritmalarının temel işlemleri genellikle ikili mantığa (siyah veya beyaz, veya 0 veya 1) dayanmaktadır. Bununla birlikte, ikili mantık gerçek hayatın karmaşıklığını tam olarak yansıtmaz. Gerçeklik daha inceliklidir, gri tonları ve düzensizlikler içerir. Bu nedenle, insan benzeri akıl yürütmeyi taklit eden bulanık mantık tabanlı YZ sistemleri, sağlık ve ortodonti alanlarında daha optimal ve gerçekçi karar vermeyi kolaylaştırabilir. Bu inceleme, bulanık mantığın ortodontideki klinik önemine odaklanmakta ve bulanık mantığın ortodontistlerin özellikle estetik değerlendirme, çekim planlaması ve fonksiyonel ortopedik tedavi gibi alanlarda daha esnek ve gerçekçi tedavi kararları almalarına nasıl destek olabileceğini vurgulamaktadır. Katı ikili karar verme ile klinik uygulamada görülen karmaşık değişkenlik arasındaki boşluğu kapatarak, bulanık mantık hasta iletişimi ve tedavi sonuçlarını iyileştirmek için umut vadeden bir çerçeve sunmaktadır.

Anahtar Kelimeler: Saçaklı mantık, yapay zeka, ortodonti

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Literature Search Strategy of Current Article

Although this article is a narrative review rather than a systematic one, the following strategy was applied for the selection of references: Publications from 1945 to 2025 were searched in the PubMed and Google Scholar databases using the keywords “fuzzy logic,” “artificial intelligence,” “orthodontics,” “clinical decision-making,” and “AI in dentistry.” The author selected relevant references that elucidate the differences between fuzzy logic and Aristotelian logic, highlight the distinctions between traditional and fuzzy artificial intelligence, and report studies conducted in orthodontics using either traditional AI or fuzzy AI. These selected references formed the basis of this review. In addition, a glossary table has been prepared to facilitate understanding and tracking of the key terms used throughout the text (Table 1).

The Transition from Aristotelian Logic to Fuzzy Logic in the History of Science

According to Isaac Newton's Principia (1687), the universe operates as a definite system, with particles moving in accordance with specific physical laws[1]. When Newton stated that nothing in the universe is uncertain, vague, or unclear, he was essentially adhering to Aristotelian logic.[2] Aristotelian logic does not accommodate ambiguity; it dictates that something must either be true or false, black or white, 0 or 1. In this framework, Newtonian or classical physics represents a binary world where the principles of linear (Aristotelian) logic apply[3]. During this period, scientific concepts were viewed in absolute terms—either true or false, like black or white. The notion that something could be both true and false was simply unacceptable. For instance, it was believed that light could only be either a particle or a wave.[4] The idea that light could exhibit properties of both a particle and a wave was dismissed as nonsensical.

Table 1. Glossary of key terms

Term	Definition	Notes
Traditional AI	AI systems based on strict binary (0 or 1) logic, with rigid decision-making rules.	Often used in pattern recognition and rule-based models.
Binary logic	Classical logic where propositions are either true or false (0 or 1), with no intermediate states.	Foundation of traditional AI models.
Fuzzy logic AI	AI systems utilizing fuzzy set theory allowing intermediate values between 0 and 1, handling uncertainty.	Mimics human reasoning with shades of gray.
Human-like reasoning	Cognitive process characterized by flexible, context-aware decision-making with uncertainty.	Often approximated by fuzzy logic in AI applications.

In the Age of Enlightenment, following Newton, observation, experimentation, and measurement became fundamental to scientific inquiry in determining truths. Furthermore, it was believed that the results derived from experiments, which focused on a specific portion of a system, could definitively explain the whole. However, the whole is not always composed of strictly binary components. While certain parts of the whole can be clearly distinguished as black or white, the 'whole' often possesses a more granular, nuanced structure.[5]

In the 1920s, with the advances in quantum physics, the ‘0 or 1’ logic of Aristotle’s philosophy began to be questioned.[6] This new physics (quantum physics), which replaced classical physics, deeply challenged the established understanding of the scientific world. Unlike the ‘black and white’ Newtonian physics, the new physics was dominated by probability, rather than certainty.[7] ‘Nothing is certain, nothing is impossible’ became the foundational principle of quantum physics[8]. Consequently, the electron could simultaneously exhibit both particle and wave properties. This ‘A’ situation of the new physics, where ‘A’ is both A and not A, gave rise to fuzzy or multivariable logic[2]. For many years, computers operated on a binary system, using 0 or 1 in software. However, modern computer software no longer adheres to the linear 0 or 1 system of Aristotelian logic, but instead works with ‘both 0 and 1,’ that is, fuzzy logic.[7]

The concept of fuzzy logic was first introduced in an article by Lotfi Zadeh in 1962.[9] Later, fuzzy logic began to be incorporated into the software of technological devices by engineers to enhance the machine intelligence quotient (IQ) of hundreds of products and systems, ranging from computers to vacuum cleaners. In fact, a concept known as 'Fuzzy Engineering' was introduced to the literature by Bart Kosko in the 1990s.[10] Bart Kosko, who has authored numerous articles in the field of fuzzy logic, summarized the reason for the 'fuzzy revolution' in the technology world at that time, stating, "The binary logic of modern computers often falls short when describing the vagueness of the real world. Fuzzy logic offers more graceful alternatives" in one of his articles.[11]

"When it comes to human biology, individual differences such as age, gender, race, stage of growth and development, and nutritional habits prevent definite results in any health application. This is closely related to the saying, 'there is no disease, there is a patient.' Therefore, in human health and the treatment protocols applied to them, fuzzy logic often plays a role, rather than binary logic. So, how can fuzzy logic be applied in orthodontic practice? (Figure 1 and Table 2) This relationship can be explained under various subheadings as follows:

Fuzzy Logic in Aesthetic Evaluation

Orthodontic treatment is primarily aimed at improving two aspects: aesthetics and/or function. When addressing ‘function,’ binary Aristotelian logic can be employed. In other words, the airway is either narrow or not; the patient is either a mouth breather or not. However, when it comes to aesthetics, fuzzy logic comes into play. Aesthetic expectations and norms can vary depending on the era, geography, society, and individual preferences.[12,13] Many orthodontic studies have demonstrated that the aesthetic expectations of orthodontists, dentists, and laypeople may not align[14]. In fact, the results of numerous studies have shown that when it comes to smile or facial aesthetics, sharp boundaries such as 'aesthetic' or 'unaesthetic,' as seen in Aristotelian linear logic, may be misleading. For instance, what an orthodontist considers an unaesthetic smile may be viewed as aesthetic by the patient. In other words, that smile can be both aesthetic and unaesthetic. For example, are crooked teeth aesthetic? Can the answer to this question be both yes and no? According to most orthodontists and the general population, crooked teeth are not considered aesthetic. However, in some Asian countries, crooked teeth may be regarded as more aesthetically pleasing.[15] While this is an unusual example, it powerfully illustrates the gray, nuanced nature of the concept of aesthetics. For instance, an illustrative hypothetical case scenario to enhance understanding of the topic: A 24-year-old patient presented with a mild 2 mm deviation of the upper and lower dental midlines. In conventional binary assessment systems, such a deviation is typically classified as an “aesthetic problem requiring correction.” However, the patient exhibited overall balanced facial symmetry and reported that the midline deviation did not constitute an aesthetic concern for himself or his social environment. The fuzzy logic approach considers both the patient's subjective perception and facial anatomical features to evaluate the aesthetic impact of the midline shift, thereby avoiding its classification as an unequivocal problem necessitating intervention. Consequently, corrective treatment is only proposed in cases where the midline deviation is perceptibly significant. This approach minimizes unnecessary interventions and enhances patient satisfaction.

Clinical Benefit

When it comes to functional aspects and situations that directly impact the patient's quality of life, binary logic can be employed when informing the patient about the need for treatment. However, when it comes to aesthetics, the patient's aesthetic concerns and expectations should be prioritized over the physician's own aesthetic norms and perceptions. The nuanced, gray nature of aesthetic appearance should be taken into account.

Fuzzy Logic in the Decision of Treatment with or without Extraction

Making the decision regarding tooth extraction is one of the critical stages in orthodontic treatment planning. Permanent tooth extraction is generally undesirable for patients and their legal guardians. Today, an acceptable occlusion can often be achieved without tooth extraction by utilizing alternative methods and materials such as distalization, advanced self-ligating bracket systems, and wide arch wires. In other words, although not applicable to all cases, for certain situations, instead of adhering to the binary Aristotelian logic of "treatment with or without extraction," fuzzy logic allows for the consideration of both extraction and non-extraction treatment options. For instance, an illustrative case scenario for enhanced understanding of the topic is as follows: A 14-year-old male patient presents with moderate dental crowding and a mild skeletal Class II malocclusion. Orthodontist A recommends extraction therapy, whereas Orthodontist B proposes a non-extraction approach employing advanced distalization appliances and arch expansion techniques. While a binary AI model classifies these treatment options simply as "extraction required" or "extraction unnecessary," a fuzzy logic-based model assesses and communicates the advantages and disadvantages of both alternatives to the patient and their family. Consequently, a collaborative decision is made by taking into account factors such as treatment duration, cost, aesthetic outcomes, and relapse risk, thereby enabling the patient to make a more informed and individualized choice.

Clinical Benefit

When patients and their families hear that permanent tooth extraction is recommended by an orthodontist, they often seek a second opinion from another orthodontist to verify the accuracy of the decision. If the second or third orthodontist suggests that treatment can be performed without extraction, patients may become confused. This is because orthodontic treatment planning often follows a fuzzy logic structure. Rather than presenting a strict black-and-white position, such as "You cannot be treated without tooth extraction," it is more beneficial to explain that both extraction and non-extraction treatment options can be valid. However, there may be differences between the two methods regarding treatment duration, recurrence probability, ideal aesthetics, and cost.

Explaining that neither option is definitively right or wrong can be challenging for orthodontists. For patients, understanding the relative advantages and disadvantages of each treatment option can be difficult, which can sometimes lead orthodontists to resort to binary logic when communicating with patients. Ideally, the decision for extraction or non-extraction treatment should be made collaboratively with the patient and their family, after ensuring they are adequately informed.

Of course, it is not feasible for fuzzy logic to be applied to all cases in orthodontics. There are situations where binary logic is necessary (i.e., tooth extraction is unavoidable). A similar fuzzy logic approach can also be applied when making decisions about orthodontic surgery.

Functional Orthopedics Treatment and Fuzzy Logic

Mandibular advancement is performed using devices such as twinblock, monoblock, or bionator in skeletal Class II patients characterized by mandibular retrognathia.[16] The ideal treatment period for this therapy is typically considered to be during the pubertal growth spurt (MP3cap period).[17] However, when patients seek orthodontic treatment, they sometimes present in the post-pubertal stage (DP3u, PP3u, or MP3u). It is at this point that the success of the treatment shifts from a black-and-white structure to a gray, or fuzzy, structure. It would be inaccurate to claim that functional orthopedic treatment performed during the post-pubertal period is always unsuccessful, but it would also be wrong to state that it is guaranteed to succeed. For example, Manni et al. demonstrated the possibility of mandibular advancement using the mini-screw-supported Herbst appliance in the post-pubertal period.[18] Similarly, Coşkun and Esenlik argued that mandibular advancement can be effectively performed during both the adolescent and post-adolescent periods.[19] Therefore, the approach that successful results can be achieved in some post-pubertal patients but not in others reflects the use of fuzzy logic by orthodontists. For instance, an illustrative hypothetical case scenario to enhance understanding of the topic: A 16-year-old adolescent patient presented seeking functional orthopedic treatment for mandibular retrognathia. She had reached the end of her pubertal growth spurt (MP3u stage). While a traditional binary AI model attempts to predict treatment outcomes as either "successful" or "unsuccessful" with certainty, a fuzzy logic approach estimates the probability of success to be approximately 60%. The orthodontist explains this probabilistic prognosis to the patient and her family, also presenting alternative surgical treatment options. The patient and family decide to proceed with functional orthopedic therapy, understanding the risk-benefit balance. Throughout the treatment process, the probability of success is periodically reassessed, allowing for flexible decision-making based on clinical progress.

Clinical Benefit

Rather than providing a 100% success rate, orthodontists can explain the likelihood of successful treatment to patients and/or their legal guardians when they present for treatment during the post-pubertal period. The potential for a successful outcome should be highlighted, as it may avoid more invasive procedures, such as orthognathic surgery, while providing improved facial aesthetics and occlusion. This approach facilitates a more collaborative decision-making process with the patient and/or legal guardians. It will also help them better understand alternative treatment options (such as dental compensation or orthognathic surgery) if mandibular advancement proves unsuccessful. Presenting the option of direct surgery without exploring these possibilities may prevent the consideration of non-invasive treatments, such as functional orthopedic therapy.

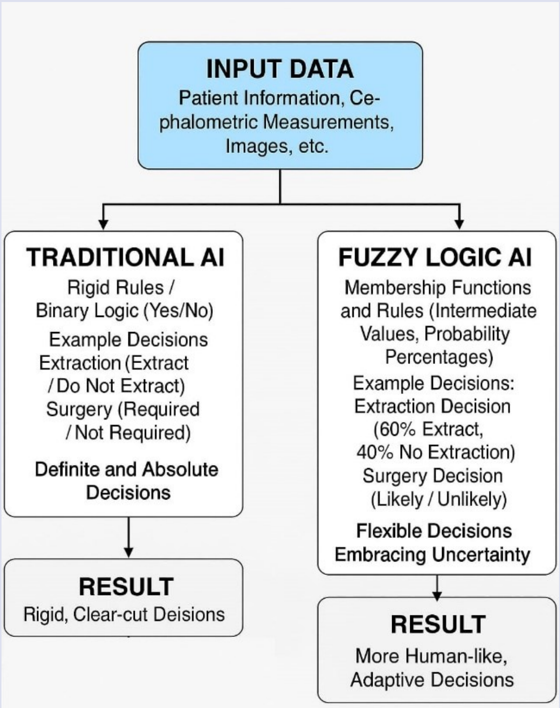

Figure 1. Comparison of traditional AI and fuzzy logic AI workflows in an orthodontic case.

Table 2. Summary of selected key studies related to AI and fuzzy logic in orthodontics

Author(s)	Year	Focus area	Methodology	Key findings
Evangelista et al.[24]	2022	AI in tooth extraction decisions	Systematic review, meta-analysis	AI shows good accuracy but uses binary logic.
Camcı & Salmanpour[21]	2024	Predicting patient cooperation using AI	Voice analysis vs photos + machine learning	Voice-based AI models showed higher prediction success.
Coşkun & Esenlik[19]	2020	Post-adolescent functional ortho treatment	3dMD + cephalometry in prospective trial	Functional treatment can succeed post-puberty in selected cases.
Manni et al.[18]	2024	Mandibular advancement post-puberty	Case report, STM4 appliance	Skeletal changes achieved with mini-screw-supported Herbst.
Zadeh[9]	1962	Introduction of fuzzy logic	Theoretical concept paper	Fuzzy logic allows modeling uncertainty and imprecision.
Kosko & Isaka[11]	1993	Applications of fuzzy logic	Review article	Fuzzy logic mimics human decision-making better than binary AI.

Methodological Limitations of Fuzzy Logic AI

Although fuzzy logic-based AI demonstrates superior capability in mimicking human-like reasoning compared to traditional AI, it encounters several methodological challenges in practical applications. For instance, the development of fuzzy logic algorithms necessitates complex mathematical modeling, which must be formulated under the guidance of domain experts to accurately define the underlying rules. Furthermore, unlike traditional AI models that benefit from established universal standards for validation and comparison, no such standardized framework currently exists for fuzzy logic AI models. The inherent flexibility of fuzzy logic in interpreting outputs may also introduce uncertainties under certain circumstances. These limitations underscore the need for further research aimed at establishing standardized validation protocols and enhancing algorithmic transparency to facilitate the reliable integration of fuzzy logic AI into orthodontic practice.

Is Fuzzy Logic Only Valid for Borderline Cases?

Based on the topics discussed thus far, some readers might assume that the "fuzzy logic" described in this article is only relevant to borderline cases in orthodontics. In our view, stating that fuzzy logic is limited to borderline cases reflects a binary logic mindset, which is incorrect. As previously discussed in various contexts—especially in the realm of aesthetics—fuzzy logic is not confined to borderline cases but is applicable in numerous aspects of orthodontic practice. This is because fuzzy logic mirrors the complex nature of biological systems and adopts a probabilistic rather than deterministic approach, particularly in relation to the response of living organisms to treatments.

Conclusions

When diagnosing or planning treatment in orthodontics, especially when considering aesthetic factors, making decisions collaboratively with the patient—i.e., employing "fuzzy logic"—can lead to more accurate and nuanced outcomes. In orthodontic education, especially for residents, incorporating fuzzy logic helps prevent them from being constrained by the narrow boundaries of binary logic in certain cases. Embracing fuzzy logic can encourage more flexible thinking among current orthodontists and help avoid rigid approaches.

It is also important to note that claiming fuzzy logic applies to every case would be an example of Aristotelian logic. Orthodontics is a discipline where decisions must sometimes be made using Aristotelian logic but, more often than not, requires the application of fuzzy logic. With the rapid advancements in artificial intelligence, the integration of fuzzy logic into orthodontics will bridge the gap between machine intelligence and human-like reasoning, enabling more personalized, accurate, and efficient decision-making through artificial intelligence.

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Conflicts of Interest Statement

The authors declare no conflict of interest.

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