REVIEW ARTICLE

CONTENTS

Digital dentistry in action: Analysis of clinical outcomes of computer-aided design and manufacturing, three-dimensional printing, and artificial intelligence in tooth defect rehabilitation

Inessa I. Yakubova[1], Nataliya M. Krupnyk[2], Anna-Sofiya A. Krupnyk[2], Volodymyr I. Ostrianko[3]

[1] DONETSK NATIONAL MEDICAL UNIVERSITY, KROPYVNYTSKYI, UKRAINE

[2] DANYLO HALYTSKY LVIV NATIONAL MEDICAL UNIVERSITY, LVIV, UKRAINE

[3] SHUPYK NATIONAL HEALTHCARE UNIVERSITY OF UKRAINE, KYIV, UKRAINE

ABSTRACT

Aim: To systematically evaluate the clinical outcomes of digital dentistry technologies - computer-aided design and manufacturing (CAD/CAM), three-dimensional (3D) printing, and artificial intelligence (AI) - in the rehabilitation of tooth defects, compared to conventional techniques.

Materials and Methods: A systematic search of PubMed, Scopus, Web of Science, and the Cochrane Library (up to mid-2025) identified clinical studies on CAD/CAM, 3D-printed dental prostheses, and AI in tooth restoration. Studies reporting survival, complications, patient outcomes, and diagnostic accuracy were included. Thirty-two studies (≈1580 patients) met inclusion criteria; 25 were included in quantitative synthesis. The five-year survival of CAD/CAM restorations was ~90%, comparable to conventional crowns. Milled and 3D-printed dentures showed similar satisfaction, with milled types offering better fit and fewer adjustments. Digital workflows shortened production time and reduced costs. AI models detected caries with ~85% sensitivity and ~90% specificity, and AI-based implant planning matched expert accuracy while cutting planning time (≈10 min vs 30 min). No safety issues were reported.

Conclusions: Digital dentistry (CAD/CAM, 3D printing) achieves high-quality, durable restorations (~90% five-year survival) with greater efficiency and lower cost than conventional methods. AI tools show strong potential for accurate, time-saving diagnostics and treatment planning. Overall, digital methods are safe, effective, and suitable for clinical integration. Further long-term studies, especially on AI-driven workflows and 3D-printed materials, are recommended to confirm sustained outcomes and establish evidence-based standards.

KEY WORDS: dental prosthesis; three-dimensional printing; artificial intelligence

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INTRODUCTION

Digital dentistry has revolutionized modern dental practice by introducing advanced technologies for designing restorations, diagnosis, and treatment planning. Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) technology–the use of computer-based design and manufacturing for dental prostheses–offers several advantages over traditional laboratory methods. Notably, it enables faster production, improved convenience, consistent high quality, and the elimination of interim steps such as temporary crowns.

With chairside CAD/CAM systems, for example, a prepared tooth can be digitally scanned and restored with a permanent ceramic crown in a single appointment, streamlining the workflow. Clinical studies have shown that these same-day CAD/CAM restorations can eliminate the need for provisional crowns and additional visits.

Similarly, 3D printing is transforming prosthodontics and other fields by enabling the precise, customized fabrication of devices–from dentures to surgical guides–with high accuracy and reproducibility. Additive manufacturing can reduce material waste and labour, although current challenges (equipment cost, material properties, post-processing) have tempered its universal adoption. Nonetheless, the trend is toward increasing use of 3D-printed solutions as materials improve [1].

In parallel, artificial intelligence (AI) has rapidly emerged as a valuable tool in dentistry. AI refers to computer algorithms (often based on machine learning) that perform tasks requiring human-like intelligence. In dental applications, AI systems can analyse radiographs or photographs to aid in detecting diseases (e.g., caries or periapical pathology) and assist in treatment planning (such as optimal implant positioning). By learning from large datasets of expert decisions, AI can support clinicians with diagnostic suggestions and decision-making.

All major dental disciplines–restorative, prosthodontics, orthodontics, and oral surgery–are beginning to adopt AI-driven solutions for improved efficiency and accuracy. For example, AI-based image analysis can highlight incipient lesions on bitewing X-rays that a human might overlook, and predictive models can forecast the long-term success of a treatment for a given patient profile [2].

Despite the enthusiasm for these digital technologies, it is crucial to evaluate them based on evidence from clinical studies. Key questions remain: Do CAD/CAM restorations and 3D-printed prostheses last as long and fit as well as conventionally fabricated ones? Can they improve patient outcomes or clinical efficiency? Likewise, can AI tangibly enhance diagnostic accuracy or treatment outcomes compared with standard practice?

Previous research has addressed parts of these questions–for example, systematic reviews comparing digital and conventional dentures or assessing AI accuracy in detecting dental diseases–but a comprehensive synthesis encompassing CAD/CAM, 3D printing, and AI in tooth defect rehabilitation is still lacking [2].

AIM

To systematically evaluate the clinical outcomes of digital dentistry technologies - computer-aided design and manufacturing (CAD/CAM), three-dimensional (3D) printing, and artificial intelligence (AI) - in the rehabilitation of tooth defects, compared to conventional techniques.

MATERIALS AND METHODS

A total of 912 unique articles were identified in PubMed, Scopus, Web of Science, and the Cochrane Library. After duplicates were removed and abstracts were reviewed, 76 papers were selected for full-text screening. Finally, 32 studies published between 2010 and 2025 met the inclusion criteria, and 25 of these were included in the quantitative analysis.

The included research covered three main topics: (1) comparisons between CAD/CAM and conventional dental prostheses; (2) evaluations of 3D-printed and conventional prostheses; and (3) the use of artificial intelligence in dental diagnostics and treatment planning [3].

The studies consisted of randomised controlled trials, cohort studies, case series, and diagnostic accuracy studies. The median follow-up period for prosthetic outcomes was approximately two years, while most AI-related research was cross-sectional and assessed diagnostic accuracy at a single time point.

An exhaustive literature search (last updated August 2025) was performed in MEDLINE (PubMed), Scopus, Web of Science, and the Cochrane Library. We used combinations of keywords and MeSH terms related to digital dentistry and tooth restoration. For example, search terms included *"CAD/CAM"* OR *"computer-aided design"* OR *"digital fabrication"* combined with *"dental prosthesis"* OR *"crown"* OR *"denture"*; *"3D printing"* OR *"three-dimensional printing"* combined with *"dentistry";* and *"artificial intelligence"* OR *"machine learning"* combined with *"dentistry"* OR *"tooth"*. We also included outcome-related terms such as *"survival," "complications," "accuracy,"* and *"patient satisfaction"* to focus on clinical results.

No language restrictions were applied (studies were included if an English abstract was available). Reference lists of relevant articles were manually screened to identify any additional studies [4].

INCLUSION CRITERIA

We included studies meeting all of the following: (1) Population: Patients requiring restoration of tooth defects (due to caries, fracture, edentulism, etc.), in any clinical setting; (2) Interventions: Use of CAD/CAM milling or 3D printing to fabricate a restorative dental prosthesis (inlay/onlay, crown, fixed partial denture/bridge, complete denture, implant abutment, etc.), or use of an AI algorithm in diagnosis or treatment planning related to tooth rehabilitation; (3) Comparators: Ideally a conventional technique group (e.g. traditional lab-fabricated prosthesis, conventional diagnostic method) for comparison, though studies without a control group were included if they reported relevant outcomes for a digital technique; (4) Outcomes: At least one clinical outcome measure, such as restoration survival/failure rate, complication incidence, prosthesis fit (e.g. marginal gap), patient satisfaction or quality of life scores, number of appointments, or diagnostic accuracy metrics (sensitivity/specificity for AI) [5].

DATA EXTRACTION

Two reviewers independently screened titles/abstracts for eligibility, then evaluated full texts of potentially relevant articles. From each included study, data were extracted using a standardized form. Extracted data included: study design, sample size and patient characteristics, details of the digital technique (type of CAD/CAM system or printer and materials; type of AI algorithm and its training data if applicable), details of any conventional comparator, follow-up duration, and all reported outcomes of interest. For CAD/CAM and 3D-printed prosthesis studies, we recorded the number and type of restorations, follow-up period, any reported survival or success rates, failure or complication counts (and causes, such as secondary caries or fracture), measures of fit or accuracy (e.g. mean marginal gap in microns), patient satisfaction or functional scores, number of adjustment visits, and any cost or time data provided. For AI studies, we extracted performance metrics (sensitivity, specificity, accuracy, area under ROC curve) and any comparisons to clinician performance or conventional diagnostic methods. Discrepancies in data extraction were resolved by consensus or by involving a third reviewer.

ETHICS

This review article is based entirely on publicly available scientific data published in peer-reviewed journals, clinical guidelines, and established databases. No patient-identifiable information was used, and approval from an ethics committee was not required because the study did not involve new clinical interventions or the primary collection of patient data.

The authors adhered to the ethical principles of the World Medical Association's Declaration of Helsinki and to international standards for medical journal publications, including the recommendations of the International Committee of Medical Journal Editors (ICMJE).

No part of this work contains plagiarism or data fabrication. All sources of information are properly cited and appropriately referenced.

REVIEW AND DISCUSSION

This review analyzed evidence from clinical studies comparing digital and conventional methods in dental prosthetics and evaluating artificial intelligence applications in dentistry. Sample sizes across studies ranged from approximately 20 to 250 participants [6].

Most investigations on CAD/CAM systems, particularly chairside milling units such as CEREC, focused on the fabrication of ceramic (lithium disilicate, zirconia) or composite restorations. 3D-printing studies primarily employed stereolithography or digital light processing to produce denture bases or interim restorations. In contrast, conventional approaches relied on the lost-wax technique, heat-polymerized acrylic, or metal-ceramic fabrication methods.

AI-related studies covered diverse diagnostic and planning applications, including radiographic caries detection through deep learning, automated intraoral image analysis, cephalometric landmark identification, and AI-assisted implant planning. Most algorithms–predominantly convolutional neural networks–were trained on large image datasets and compared with expert evaluations using standard metrics such as sensitivity, specificity, and overall diagnostic accuracy [7].

Among the eight randomised controlled trials, five were rated as low risk of bias, while three were assessed as having some risk due to the practical impossibility of blinding. Non-randomised studies were of moderate quality, mainly limited by shorter follow-up periods and potential selection bias. AI diagnostic studies generally demonstrated a low risk of bias, though several lacked independent verifications of reference standards. Funnel plot analysis for the five-year survival of CAD/CAM crowns revealed no significant publication bias. Overall, the quality of evidence was high for short-term outcomes (≤5 years) and diagnostic accuracy, and moderate for long-term results owing to methodological heterogeneity and limited follow-up beyond five years.

Across longitudinal research, CAD/CAM restorations consistently achieved survival rates comparable to conventional methods. The pooled five-year survival of CAD/CAM crowns was approximately 90%, while ten-year survival for all-ceramic bridges ranged between 80% and 82%, aligning with traditional benchmarks. A large six-year retrospective analysis involving around 500 crowns reported no significant survival difference between CAD/CAM and conventionally fabricated crowns (overall 96%). The most frequent causes of failure were secondary caries and ceramic fracture–similar to conventional outcomes–while monolithic zirconia restorations exhibited fewer veneer chippings [8].

Digital workflows demonstrated equal or superior marginal fit and precision. Mean marginal gaps typically ranged from 50 to 100 μm, with lower variability in CAD/CAM restorations. Improved adaptation helps reduce plaque accumulation and secondary caries, thereby extending prosthesis longevity. In complete denture trials, patient satisfaction and oral health–related quality of life were similar between digital and conventional dentures. However, milled dentures provided a better fit, required fewer post-insertion adjustments, and offered greater material strength due to reduced porosity [9].

Studies assessing clinical efficiency consistently showed time and cost benefits of digital fabrication. Chairside, single-visit crowns eliminated the need for temporary restorations and additional appointments. For complete dentures, digital workflows shortened total production time by 20–30% and reduced laboratory labour costs, offsetting higher material expenses. These improvements resulted from automation, fewer remakes, and streamlined appointments, rendering CAD/CAM workflows economically advantageous, especially in high-volume clinical settings.

Patients generally reported high satisfaction with digital restorations, emphasising improved comfort during intraoral scanning and shorter treatment durations. Functional outcomes and Oral Health Impact Profile (OHIP) scores were comparable between digital and conventional groups, although convenience and patient preference clearly favoured digital methods. Complication rates were similar across fabrication types: common issues such as veneer chipping, secondary caries, and endodontic problems occurred at comparable frequencies. Monolithic CAD/CAM crowns and milled denture bases demonstrated lower fracture rates, and no new or unique complications were identified, confirming the safety and clinical reliability of digital techniques.

Beyond diagnostics, AI has shown promise in treatment planning and predictive analytics. In one comparative study, AI-generated dental implant plans differed from expert plans by less than 1 mm in position and 2° in angulation, while requiring one-third of the planning time. Surgical guides printed from AI- and human-derived plans achieved equally precise implant placement, indicating clinical reliability. Emerging predictive models for caries risk, prosthesis failure, and endodontic success suggest that AI can aid personalised treatment planning, although validation remains limited [10].

AI applications also extended to orthodontic and radiologic analysis. Systems for cephalometric landmark detection achieved localization errors under 2 mm and correlation coefficients above 0.9 with expert measurements. Models assessing periodontal bone loss or interpreting cone-beam CT scans reached accuracies of 85–90%. Experimental AI-driven crown design tools produced anatomically realistic 3D models, foreshadowing integration of AI into CAD/CAM workflows to automate design steps and enhance efficiency [11].

In summary, digital dentistry–encompassing CAD/CAM, 3D printing, and AI–achieves clinical effectiveness and safety comparable to, or exceeding, conventional techniques, with notable benefits in precision, efficiency, and standardisation. Limitations remain in the availability of long-term follow-up data and the need for continued clinical validation of AI systems [12].

This comprehensive analysis evaluated how digital dentistry technologies–CAD/CAM milling, 3D printing, and AI–are impacting clinical outcomes in the restoration of tooth defects. Across a broad range of studies, the findings consistently show that these innovations either match or improve upon traditional methods on multiple fronts. These results carry important implications for dental practitioners considering the adoption of digital workflows [13, 14].

CAD/CAM and 3D Printing – Proven Performance. One of the clearest messages from our review is that CAD/CAM-fabricated restorations perform at least as well clinically as conventionally fabricated ones. Earlier concerns that the convenience of digital fabrication might come at the expense of restoration longevity or quality are not supported by the evidence. On the contrary, the precision of CAD/CAM often leads to an equal or better fit, which is a cornerstone of restoration success.

Even a decade ago, studies were hinting at parity between CAD/CAM and traditional crowns. For example, Sailer et al. [15] found similar five-year survival rates for all-ceramic CAD/CAM crowns and conventional metal–ceramic crowns. Now, with improved high-strength ceramic materials and refined milling techniques, the performance gap has essentially closed. Our pooled estimates showed approximately 90% five-year survival for CAD/CAM single crowns, which is virtually identical to established benchmarks for traditional crowns. Additionally, CAD/CAM crowns exhibit similar failure patterns (mostly caries and fractures) to traditional ones, indicating no new vulnerabilities introduced by the digital process.

In the realm of complete dentures - once thought to be too complex for full digital fabrication - digital techniques have rapidly caught up. The fact that patient satisfaction with digital dentures is comparable to conventional dentures means that, from the patient's perspective, the end-product of either workflow is acceptable given competent execution. However, the advantages of digital dentures manifest in efficiency and certain clinical outcomes: reduced adjustment visits and faster turnaround are significant benefits, especially for elderly edentulous patients who may have difficulty with multiple appointments. Our findings, supported by others, show that milled dentures often require fewer post-delivery adjustments and have better initial fit than conventional dentures [11]. This is a win-win scenario: fewer sore spots for patients and less chairside time for clinicians. Furthermore, the cost savings in lab fabrication for digital dentures (as demonstrated by Lo Russo et al. [13] and other studies) suggest that digital workflows can be more economical in the long run, especially as the digital infrastructure (software, mills, printers) becomes more common and amortized.

It should be noted that 3D printing in prosthodontics is a slightly newer approach than CAD/CAM milling. The current evidence for 3D-printed dentures is promising - clinical outcomes (fit, satisfaction) appear similar to conventional dentures - but printed dentures did not yet outperform conventional ones in measured parameters except for reduced material waste and inventory (digital libraries of tooth shapes, etc.). This is understandable. The layer-by-layer photopolymerization used in 3D printing can introduce fine layer interfaces or slight inaccuracies that milled dentures (carved from a homogeneous puck) avoid. Milled dentures at present have an edge in terms of material properties (density, strength) and fit. However, constant improvements in printable resins and printer resolution are narrowing the gap. It is foreseeable that as new printable high-impact acrylics or even printable ceramics emerge, 3D printing will become equally competitive or even preferable due to its flexibility for complex geometries and automated production.

PATIENT AND CLINICIAN ACCEPTANCE

Another important point is the excellent acceptance of digital methods by both patients and clinicians in the studies. Patients appreciate shorter treatment times and often comment on the increased comfort of digital impressions (no gag-inducing impression trays). Clinicians, on their side, appreciate the predictability and repeatability that CAD/CAM provides - a digital workflow can reduce variability caused by differing technical skill levels among dental lab technicians. For instance, one study concluded that digital dentures were clinically effective and also more cost-efficient than traditional ones, highlighting that investment in digital can pay off in improved efficiency without harming quality. Of course, transitioning to digital dentistry requires initial investment in equipment and training. The learning curve for using CAD/CAM design software or for interpreting AI outputs should not be underestimated. Many early-adopter studies were done in academic or specialist centers with enthusiasts in digital dentistry. A broader implementation in general practice might face practical issues like the cost of acquiring technology, the need for technical support, and modifications to clinic workflow. Nonetheless, the strong evidence of clinical equivalence (and in some cases superiority) should encourage practitioners that these investments likely yield returns in more efficient patient care. Over time, as costs come down and new graduates enter the workforce already trained in digital methods, these hurdles will continue to diminish.

In treatment planning scenarios, the positive results–such as AI planning matching expert implant plans–point towards a future in which routine planning tasks could be offloaded to AI for greater efficiency. Importantly, in the implant planning study [8], AI did not introduce new errors, and each plan still underwent the surgeon's approval. Rather than making clinicians obsolete, AI in this role could help standardise care, reduce planning oversights (such as missing vital anatomical considerations), and ensure that even novice clinicians can achieve safe and consistent treatment plans by starting from AI-generated suggestions.

In the busy environment of dental practice, AI could free up clinicians' time to focus on complex decision-making and patient communication by handling the heavy lifting of data analysis and initial planning. One can imagine future AI-based recommendations for restorative treatment–for example, given a large lesion, an AI might recommend either a crown or an onlay based on learned success rates in similar cases–which the clinician can then evaluate alongside their own judgement [9]

LIMITATIONS OF CURRENT EVIDENCE

Despite generally positive findings, there are limitations and areas where evidence is still maturing. Many studies have relatively short follow-ups. While 3-5 year data for CAD/CAM crowns are solid, 10-year data (though promising in isolated studies) come from fewer sources. Long-term performance, especially of newer materials like some 3D-printed resins, remains to be verified. It's possible that certain complications or late failures could emerge over a decade (for example, will the bond at the tooth-restoration interface of a resin-printed crown hold up over 10+ years?). Therefore, continued surveillance and more long-term cohort studies or RCTs are needed to monitor outcomes over time [10].

Heterogeneity within the "digital dentistry" umbrella is another important consideration–there are many different CAD/CAM machines, printer types, and AI algorithms. Not all systems produce identical outputs; results achieved by a skilled operator with one system might not generalize precisely to another system or to an average user [11]. However, the consistency of positive outcomes across multiple systems in our included studies provides reassurance that the beneficial effects are general features of the technology class rather than characteristics of a single brand [12].

For AI, a key limitation is that many tools evaluated remain proprietary or are not yet widely available commercially. The performance observed in research settings might not immediately translate to every dental practice unless those specific algorithms become both accessible and user-friendly. Moreover, AI systems require large volumes of high-quality data for training; therefore, for uncommon conditions or atypical presentations, the AI may be less reliable. For example, most caries-detection algorithms are trained on thousands of common bitewing radiographs, but how would they perform when faced with an unusual artifact or a rare lesion? The clinician's expertise thus remains crucial as the final arbiter [12-13].

Ethical and practical considerations also accompany the adoption of AI. Some practitioners have raised liability concerns: if an AI misses a diagnosis, the dentist is still responsible; conversely, if an AI suggests an aggressive treatment that turns out to be unnecessary, who is accountable? Professional guidelines will need to evolve to address these questions, and informed consent might need to include disclosure of AI assistance in care (analogous to informing patients when a trainee is involved in their treatment). Transparent reporting of AI's role and ensuring that AI tools meet regulatory and safety standards will be important as they integrate into clinical practice [14-15].

FUTURE DIRECTIONS

The trajectory of digital dentistry appears overwhelmingly positive, and our analysis substantiates that it is not just an experimental trend but a fundamental improvement in many aspects of care. Going forward, improvements in materials for both CAD/CAM and 3D printing will likely address the few remaining gaps (such as the slightly lower strength of some printed resins). We anticipate more hybrid workflows - for instance, printing an interim prosthesis to verify fit and occlusion, then milling the final version for ultimate strength and accuracy. This kind of dual approach is already being tested to harness the advantages of both methods (speed and low cost of printing, with the robust properties of milled acrylic or ceramic) [16-17].

For AI, as data accumulates and algorithms become more sophisticated, we might see AI contributing beyond assistance to more autonomous predictions and decisions (with oversight). One interesting area is AI in preventive dentistry: imagine AI models that sift through patient data (clinical history, diet, genetic markers) and predict which patients are at high risk of developing tooth defects (caries or cracks) so that preventive measures can be intensified for those individuals. This could personalize preventive care schedules in a way that current risk assessment tools only approximate [18-19].

To fully realize the benefits of digital dentistry, integration is key. Currently, many dental offices use a mix of digital and analog systems. In the near future, we expect a more unified digital ecosystem where a patient's intraoral scan flows seamlessly into AI analysis, then into CAD design software, and finally to a fabrication device - all the while updating the electronic health record. Such integration can create efficiencies and reduce manual data re-entry or errors. This also raises the possibility of "big data" analyses in dentistry: aggregated outcomes from thousands of digitally documented cases could be analyzed (likely with the help of AI) to continually refine best practices - a concept known as a learning health system [20-21].

CLINICAL SIGNIFICANCE

For practicing dentists and specialists, the results of this analysis should build confidence that investing in digital technologies can improve practice efficiency without compromising patient outcomes. A dentist can comfortably tell a patient that a CAD/CAM crown will serve them as well as a traditional lab-fabricated crown - with the added bonus of getting it done faster. Prosthodontists managing edentulous patients can embrace digital denture workflows knowing that patient outcomes (comfort, function) will not be worse than conventional techniques, and that certain clinical steps (like border molding or multiple trial fittings) might be streamlined or eliminated. The positive evidence may also encourage dental educators to incorporate more digital training in curricula, ensuring new graduates are proficient in these tools from day one [22].

LIMITATIONS OF THIS REVIEW

We acknowledge some limitations in our own review process. First, despite exhaustive search efforts, it is possible some relevant very recent studies (especially those published in late 2025) were not yet indexed or available to us and thus were missed. Second, due to the breadth of the topic, some of our subgroup analyses included relatively few studies (for example, only a handful directly compared printed vs milled dentures). Therefore, conclusions in those sub-areas should be interpreted with caution until more data emerges. Third, when pooling data, we sometimes had to combine outcomes reported in slightly different ways by different authors (e.g. one study's definition of "success" might differ from another's). We tried to harmonize definitions (for instance, treating "survival without complication" as equivalent to "success" in another study) to make pooling valid. Nevertheless, some statistical heterogeneity was present in a few analyses, reflecting clinical and methodological diversity across studies. We used random-effects models to account for between-study variability, but any residual heterogeneity means the pooled result is an average effect and individual patient outcomes may vary case by case [22].

CONCLUSIONS

Within the limitations of the available evidence, this analysis supports the conclusion that digital dentistry technologies deliver clinical outcomes comparable to–and, in certain aspects, superior to–those achieved with conventional dental techniques for tooth defect rehabilitation. CAD/CAM and 3D printing enable clinicians and dental technicians to fabricate restorations and prostheses with high precision and predictability, yielding survival rates and patient satisfaction comparable to traditional methods.

Patients benefit from the streamlined workflows of digital processes–such as single-visit crowns and faster denture deliveries–without compromising quality of care. In particular, CAD/CAM-milled prostheses have demonstrated excellent fit and durability (five-year survival around 90%), while 3D-printed prostheses are rapidly advancing and offer unique advantages, including design flexibility and reduced material waste.

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CONFLICT OF INTEREST
The Authors declare no conflict of interest

CORRESPONDING AUTHOR
Inessa I. Yakubova
Donetsk National Medical University
1 Velyka Perspektyvna St., 25015 Kropyvnytskyi, Ukraine
e-mail: yakubova.inessa@gmail.com

ORCID AND CONTRIBUTIONSHIP
Inessa I. Yakubova: 0000-0003-2780-2460 A D E F
Volodymyr I. Ostrianko: 0000-0003-2780-2460 A B D E
Nataliya M. Krupnyk: 0009-0002-6863-5224 B E F
Anna-Sofiya A. Krupnyk: 0000-0001-9859-5417 B E F

A – Work concept and design, B – Data collection and analysis, C – Responsibility for statistical analysis, D – Writing the article, E – Critical review, F – Final approval of the article

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