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Review Article

3D printing in forensic medicine and crime-solving: integrative literature review

Impressão 3D na medicina legal e resolução de crimes: revisão integrativa da literatura

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ABSTRACT: 3D printing technology provided opportunities for explorations in new biological areas, such as Forensic Medicine, helping to solve crimes. Considering the use of this technology in Criminal Forensics, this work consists of a literary review that aims to report the contribution of 3D printing in solving criminal acts. The main 3D impressions used, their advantages and disadvantages were reported. As an adjunct, molecular techniques were also presented in 3D printing that can assist in solving crimes. Data analysis revealed that the use of 3D printing collaborated in the expert reports that elucidated investigations conducted in the criminal area. Technology was presented as an option to reduce costs, deadlines and invasive impacts on the body, in forensic contexts. It was concluded that it is necessary to plan the construction of the object taking into account technical restrictions of 3D printers, mainly the digitization process. In addition, determining which computational method to combine to obtain the best results in Forensic Medicine are critical steps in the printing process.

Keywords: Forensic science; 3d printer; Criminal expertise, Rapid prototyping.

RESUMO: A tecnologia de impressão 3D oportunizou explorações em novas áreas biológicas, como na Medicina Legal, auxiliando na resolução de crimes. Considerando o uso dessa tecnologia na Perícia Criminal, este trabalho consiste em uma revisão literária que visa relatar a contribuição da impressão 3D na solução de atos criminosos. Foram relatadas as principais impressões 3D utilizadas, suas vantagens e desvantagens. Como adjuvante, foram apresentadas ainda as técnicas moleculares em impressões 3D que podem auxiliar na resolução de crimes. A análise dos dados revelou que o uso da tecnologia de impressão 3D colaborou nos laudos periciais que elucidaram investigações conduzidas na área criminal. A tecnologia apresentou-se como opção por reduzir custos, prazos e impactos invasivos sobre o corpo em contextos forenses. Concluiu-se que é preciso planejar a construção do objeto levando em conta restrições técnicas das impressoras 3D, principalmente o processo de digitalização. Além disso, determinar qual método computacional combinar para se obter os melhores resultados na Medicina Legal é passo crítico no processo de impressão.

Palavras-chave: Ciência forense; Impressora 3D; Perícia criminal; Prototipagem rápida.

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INTRODUCTION

Legal Medicine has become an essential tool in a criminal investigation, aiding in such fields as Genetics, Anthropology, Anatomy, and others[1]. However, in the digital era we live in, criminals have developed intelligent and innovative methods for achieving their goals. Goodman (2015), the founder of *the Future Crimes Institute* – an institution dedicated to reuniting specialists to discuss the implications of new technologies – denoting 3D printers will play an enormous role in the criminal scenario[2].

Three-dimensional printing (3D), or rapid prototyping, was introduced in the 1980s[3]. Although its commercial application is relatively new, specialists can construct physical objects based on computerized aided concepts or digital reproduction of a real-life object[4].

Generally speaking, manufacturing these objects consists of a complex process starting from computerized scanning of an item being manufactured; after that, it is digitally sliced into various thin layers. Finally, those geometric data are utilized by manufacturing equipment to build each layer sequentially until the desired three-dimensional product is completed[5,6].

The first applications in medical and morphological disciplines introduced 3D printers as efficient products for manufacturing anatomic elements[7,8], valuable pieces exhibited in museums, and rare paleoanthropological fossils[9,11]. This technology has gradually been adopted in clinical fields – while producing surgical prostheses in ophthalmology[12], maxillofacial surgery[13,14], traumatology[15], and cardiology[16].

Abramov proposed applications in the forensic scenario for the first time in 1998[17]. Based on that, there have been some investigations using 3D printing to elucidate crimes and decrease the number of closed cases due to missing evidence. These investigators and forensic examiners use 3D printing to reconstruct accidents, replicate crime scene evidence, and unidentified skeletal remains[18]. Many service-providing companies offer such services in the United States, for example, Lazarus 3D, Houston, TX or 3D Printed Evidence, Jacksonville, FL[19].

3D modeling hardware, software, and prototype technology has developed rapidly in the last few years, providing users a multitude of options for combining hardware, software, and production materials for rapid prototyping. The challenge focuses on determining which combinations to use to achieve the best results, as it is a booming methodology[20].

The equipment is relatively inexpensive, portable, and requires a shorter time for data acquisition and enabling observation and studying structures involved in the crime scene, making it unnecessary to damage the body in forensic contexts. The application of these technologies also makes it possible to collect data with minimal degradation and reduced human errors[21,22].

The purpose of this research scenario has been to identify studies dealing with the use of 3D Printing in Legal Medicine and solving crimes. It has also sought to verify the leading 3D printers used, including their advantages and drawbacks. Finally, we considered molecular techniques in 3D printing to aid in solving crimes.

METHODOLOGY

The research work was prepared based on qualitative research, from April to November 2019, applying the integrative literature review approach methodology. The purpose was to gather and systematize the study results related to this theme. The review's framework was based on articles found in the Pubmed database (a service provided by the *U. S. National Library of Medicine*) and *Science Direct*, due to the scarcity of reports on the Latin American scope and mostly the Brazilian. The selection criteria focused its most significant relevance on (i) the inclusion of the expressions "forensic science and 3D printing", "3D printing and forensic analysis" and "crime diagnosis by 3D printing"; (ii) published in the ten years (2009 to 2019) and (iii) published in the scientific article format.

RESULTS AND DISCUSSION

After performing the literature review research, information analysis proceeded. Twenty-one articles were found, thirteen from the Pubmed database and eight from *Science Direct*. After reading the article titles and abstracts, we noticed that some were repeated in different databases, and others did not adhere to the study's purpose. Thus, as stated above, eleven articles were selected that comply with the initially proposed criteria, and those were completely read. Ten of those came from Pubmed and one from *Science Direct*, as shown in Table 1.

The research was predominately focused on printing skull lesions in the selected articles, where the primary purpose was a submission in courts. Generally, the study considers articles that display 3D printing as an object for reflection, given its overall importance in criminal analysis.

We understand the relationship between using 3D Printing in Criminal Forensics, and the study was divided into four sections. First, we showed submitted 3D printing to Legal Medicine for solving crimes. Second, we described what the leading 3D printed models utilized in Criminal Forensics are. Third, we commented on what the advantages and disadvantages are of 3D printed models in Criminal Forensics. Finally, the fourth addresses applications of molecular techniques in 3D printing for solving crimes.

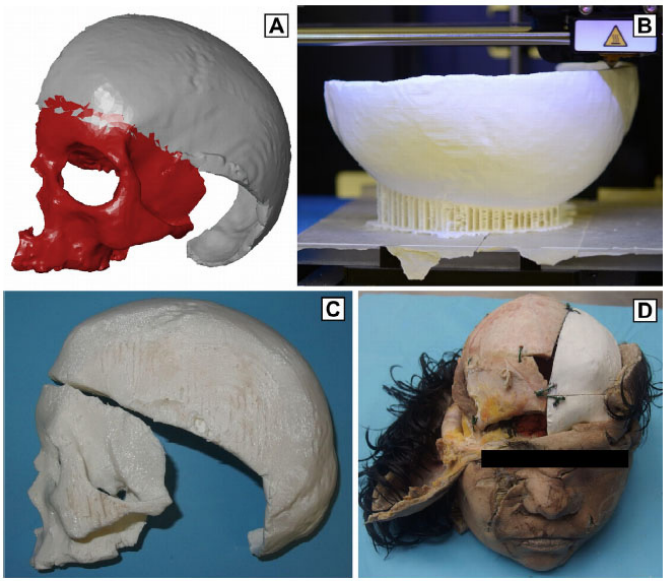
Table 1. Articles selected from the search in the Pubmed and *Science Direct* databases

AUTHOR	TITLE	YEAR	DATABASE
Woźniak et al.[18]	Weapon identification using antemortem computed tomography with virtual 3D and rapid prototype modeling-A report in a case of blunt force head injury.	2012	Pubmed
Ventola[47]	Medical Applications for 3D Printing: Current and Projected Uses.	2014	Pubmed
Kettner et al.[35]	Reverse Engineering-Rapid Prototyping of the Skull in Forensic Trauma Analysis.	2011	Pubmed
Urbanová et al.[4]	The virtual approach to the assessment of skeletal injuries in human skeletal remains of forensic importance.	2017	Pubmed
Urbanová et al.[17]	Applying 3D Prints to Reconstructing Postmortem Craniofacial Features Damaged by Devastating Head Injuries.	2018	Pubmed
Baier et al.[19]	Introducing 3D Printed Models as Demonstrative Evidence at Criminal Trials.	2017	Pubmed
Ebert et al.[38]	Getting in touch-3D printing in Forensic Imaging.	2011	Pubmed
Edwards; Rogers[20]	The Accuracy and Applicability of 3D Modeling and Printing Blunt Force Cranial Injuries.	2017	Pubmed
Carew; Errickson[37]	Imaging in Forensic Science: Five Years On.	2019	Science Direct
Byagathvalli et al.[41]	A 3D-printed hand-powered centrifuge for molecular biology.	2019	Pubmed
Chan et al.[40]	Low-Cost 3D Printers Enable High-Quality and Automated Sample Preparation and Molecular Detection.	2016	Pubmed

The contribution of 3D printing in legal medicine and crime solving

The presentation of physical models as evidence in court is a routine practice. However, there are many ethical and legal concerns involved in the transfer, transport, and submission of mortal remains, which prevent investigators from presenting any physical evidence originating from human beings. The judicial system depends wholly on photographs as evidence, which does not always supply the exact quantity of information that a three-dimensional structure can prove[23]. Furthermore, the handling of bones and human remains by several people and different surroundings can bring about degradation of evidence[24]. It possesses the capability of creating three-dimensional replicas of human remains; 3d printing has revolutionized Legal Medicine, enabling the materialization of diverse evidence from human sources, precisely supplying all the information relevant to the court and the jury[25].

Computed tomography data from the clinical exam enables the 3D reconstruction of fractures, as observed in Figure 1. The broken bone's physical model can demonstrate the nature of the lesions to people who are not endowed with medical training and/or are not specialized in interpreting anatomical images[18].



Source: Urbanová et. al.[17]

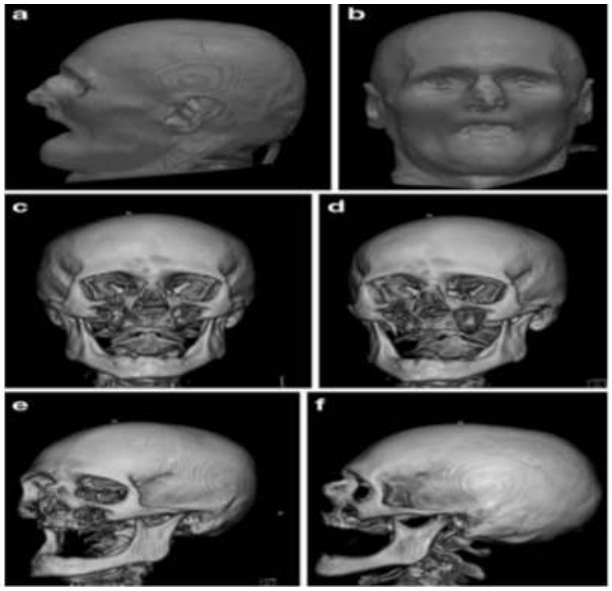
Figure 1. Reconstructive image of 3D objects utilized in criminal investigation A) Polygonal models of the skull. B) 3D printing process 3D. C) Two parts of the 3D printing. D) Reconstruction of the victim's head

The transportation of human remains is also strictly controlled by laws, by which the authorities from different fields cannot be granted access to such evidence[24]. 3D printing can be applied in this scenario, and the printed matter can be transported to all forensic sectors, even for elucidating the crime. They were thereby preventing rapid loss of information and preservation of the biological matter.

Main 3D printed models using in criminal forensics

The articles report that the most effective application of 3D printing in Forensic Sciences is in Medicine and Dentistry. The postmortem forensic exams can reconstruct targeted investigation objects in 3D by diverse imaging acquisition modalities, such as computed tomography (CT), demonstrated in Figure 2. There are even variants of computed tomography - CT using multi-detectors (MDCT) or CT with a conical beam (CBCT)[26]; angio-CT[27]; and magnetic resonance imaging (MRI)[28,29]. Besides, there are various software programs can produce 3D models of bones that can be rotated, measured, and analyzed for evaluating parameters like age, gender, and pathology[30].

Nevertheless, clinical data must be considered in the successful determination of the lesion mechanism in cases of death that occurs long after the generating event. In cases of bite marks, footprint analysis, labial, and digital impressions, the matter can be 3D scanned and printed immediately afterward to reduce the loss of information and preserve in three dimension[31].

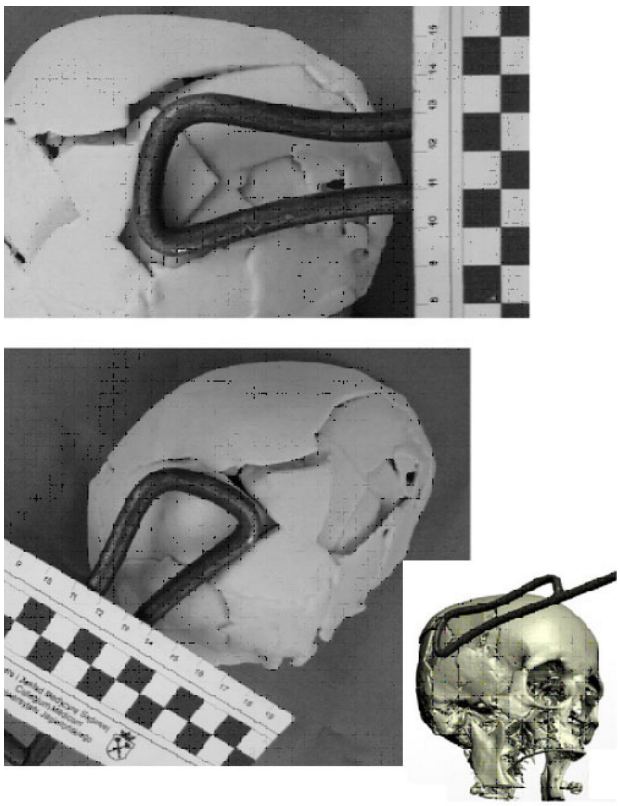


Source: Lorkiewicz-Muszynska et al.[32]

Figure 2. Reconstruction by 3D computed tomography of the head (a, b) and skull (c, d, e, f) performed in the In Space software program

The tomography data acquired in cases when the forensic exam underwent delay were due to the priority of clinical needs in attempting to rescue the victim, creating a digital database. Afterward, it can be loaded on appropriate manufacturing equipment, and the evidence can be printed when necessary during the investigation process[33].

A weapon (or a weapon model) can be identified based on, or corresponding to, a 3D model of an osseous lesion. It is possible to identify an object's shape morphologically, interpreting the rendering of the volume or using stereolithography[34], as shown in Figure 3.



Source: Adapted Woźniak et al.[18]

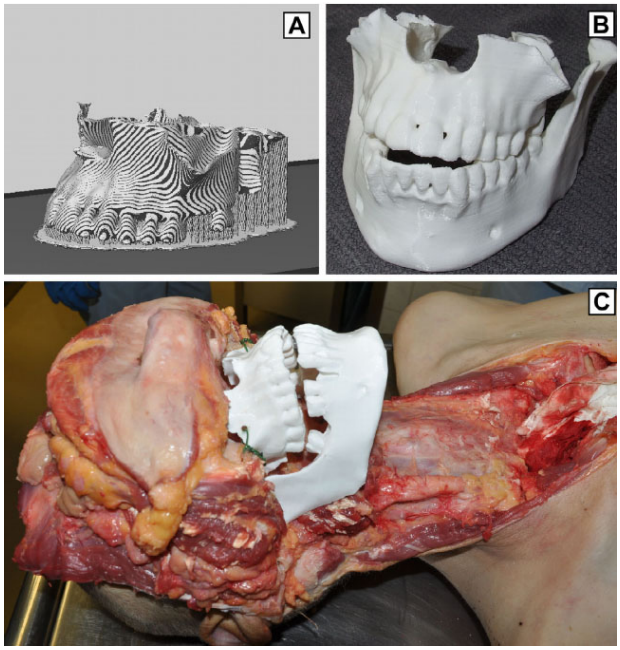
Figure 3. Images of a 3D skull produced based on clinical data from computed tomography and compared to the fracture with the corresponding weapon

Forensic anthropologists and artists can reconstruct the temporary appearance of a victim, thereby aiding in identification, especially those who have yet to be identified[35,36]. 3D printing is currently based on skeletal elements. It is useful in varied applications, ranging from bone replications, facial replications, identification of the fracture pattern, identification and reconstruction of the weapon used in the crime[18, 37].

Advantages and disadvantages of 3D printing in criminal forensics

The utilization of computed tomography entirely

respects the dignity of the deceased person. It is consistent with medical ethics and, besides that, it provides an excellent 3D printing of the anatomic structures and lesions[35]. The 3D objects are useful in demonstrating tridimensional relationships among structures, characteristics, or evidence. They protect the integrity of forensic evidence. They are produced dimensionally in the actual size or increased or reduced scale for emphasizing the specifications of the evidence[4,24], as shown in Figure 4.



Source: Urbanová et al.[17]

Figure 4. Addressing 3D structure reconstructions. A) 3D maxilla model adjusted to the victim. B) 3D printed models for implementations. C) Hard and soft tissue treatment in the autopsy room

Although we depend on 2D and 3D images, 3D printed models provide various advantages over 3D images and photographs[17]. As printed models are minimally graphic, they effectively demonstrate three-dimensional relationships between lesions and osseous characteristics. The printed matter can be used as permanent documentation of the trauma and as an aid to teaching[20].

The process is non-invasive and nondestructive by and of itself; however, it is worthwhile to add that 3D printing is far from being instantaneous. Depending on the models' size and complexity, it can take from half an hour to up to twenty-five hours to manufacture replicas[17,38].

Due to the enormous technological advances in the past few years, 3D printing nowadays is broadly utilized. There is a variety of simple, obtainable, and low-cost printing devices available on the market.

Some hindrances involved in forensic analysis can be overcome by using replicas of parts of the human body. The first problem is the health hazard posed by biological tissue[39], the second is the potential damage that excessive handling can cause to the anatomical object being studied, and the third is the emotional and moral effects on the facts from handling actual human remains that may affect the investigator as well as the victim's family[24]. One of the significant difficulties pointed out is that 3D printed models make it possible to demonstrate and reproduce forensic evidence in a tactile format[23]. It represents a new means of presenting and exhibiting proof in the digital data era, from the scope of accelerating forensic examination steps and enhancing the understanding of scientific conclusions[17].

Significant statistical differences may occur in measurements observed between actual bones/lesions and 3D printed models more infrequently. That could be visual as printed models resemble actual lesions a great deal, except for very minute details (the endpoints of fracture lines and some porosity). It can be problematic when defining the point of impact using the fracture line visible on the bone. In this case, the observations must be made directly on the same[20].

Scanning is a critical step that can be even affected by noise and resolution, causing problems, especially in photometry. There are subjectivity levels involved in the alignment process, especially when it is necessary to perform this step manually (as the user must select the same points in various scans to input this data in the computer where as to align the images). If it is not performed correctly, the scanning process will be negatively impacted, which will result in a 3D model that does not replicate the original adequately.

Bright or dark surfaces can also hinder image capturing, resulting in areas where data or details are missing that can affect 3D printing. In this case, verifications are done to fill in areas where data are missing[38]. In some situations, printed elements do not display the sharpness of originals, especially in borderline regions[4].

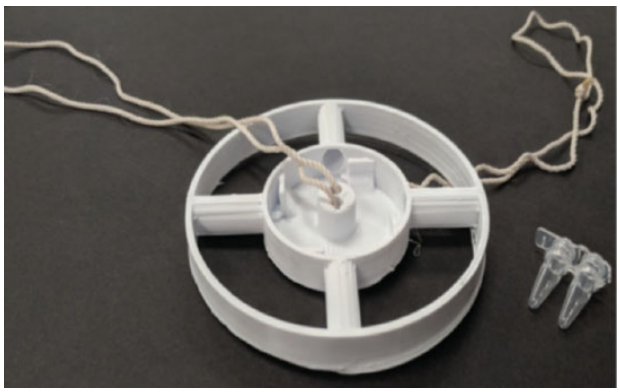
Although the process implies a certain degree of simplification and generally decreased cost, 3D printing requires post-manufacturing treatment. The extra structures sustaining the actual object are removed (manually or using the aid of a scalpel). It is easily manageable due to the constructed supports' fragility, but the extra material can leave visible or palpable residues on the final physical model[4].

Molecular techniques in 3D printing in solving crime

As 3D printing is an increasingly expanding methodology, it faces the challenge of defining which combinations to use to achieve the best results in the field of criminality. Scientists consider its capacity to quickly extract and purify nucleic acids using a low-cost manual centrifuge, performed in real-time on-line surroundings, useful in molecular applications when there is no access to conventional lab equipment, for example, on crime scenes[40,41].

3D printing can become an attractive platform for users to create their own high-performance molecular devices and the proven-low cost to provide mechanisms for developing their molecular tests. Generally, it is unfeasible in the surrounding where there are scarce resources[40].

The 3D-Fuge, displayed in Figure 5, is a 3D printing device. It can centrifugate different solutions, as rotating specimens assigned as biomarkers, and can extract nucleotides as part of molecular lab gear. It is extremely portable and does not require a continual supply of electricity, thereby facilitating the transport and utilization in varied applications[41].



Source: Byagathvalli et al.[41]

Figure 5. 3D-Fuge utilized in a case study using 0.2 ml PCR tubes next to it for comparative purposes

Portable sequencing projects arise in applied field surroundings, including real-time types or identifying specimens from the surrounding areas[42,43], pathogen[44,45], and metagenomic diagnostics[46,47]. Another methodology that can be used is in aiding in solving crimes and modifying 3D printed models, which can be adapted to low-cost, automated, and average yield molecular detection platforms. The modified 3D printer moves magnetic particles (MP) in different reactants for concluding the isolation and purification of nucleic acids (NA). Furthermore, modifications in 3D printing are small enough, as they are reversible; thus, the printer's capacity is not wasted[40], currently, regarding molecular biology and the cited innovative technologies that can be utilized in elucidating issues involved in criminal investigations, DNA analysis of the victim and the collection of fingerprints47 are high-lighted as favoring the identification of the involved parties.

CONCLUSIONS

The application of 3D printing in solving crimes still presents scarcity in its databases, mainly in studies originating from Brazilian sources. 3D printing technology has displayed significant forensic science applications, enabling the non-invasive reconstruction of detailed anatomic structures, aiding in the solution of cases, even providing the integrity of biological matter being analyzed. Another purpose that can be attributed to printing is the courtroom exposure of essential details for adequate comprehension of the investigated crime. Such procedure abides by ethical aspects involved in the conservation of the deceased's mortal remains, as well as respect for the family members and the other involved parties in the process.

The printer's performance often depends on the scanning process, where small errors can generate objects that are not similar to the actual structure. The structures reproduced through the referred process, supplies low-cost, providing the possibility of sending it for analysis to other locations without undergoing any damages, which would occur in anatomical parts from the respective crime scene.

Reports have not yet been described on 3D printing associated with molecular techniques; however, there is portable printing equipment to enlarge DNA and genetic sequencing, making it possible for handling it in criminal analyses shortly.

Author's participation: *Vargas BFS*: bibliographic survey in databases, data analysis and article writing. *Coutinho MA*: data analysis, adaptation of the article to the *Revista de Medicina* norms and final review of the article. *Coutinho FS*: Advisor, conception and elaboration of the project, assistance in discussions on data analysis and article submission.

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