Three-dimensional printing applications in veterinary surgery

Review Article

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ABSTRACT

Thanks to three-dimensional (3D) image structuring methods, 3D printing products have been used for many purposes in veterinary medicine in recent years. It can be used in many stages like vocational training in veterinary surgery, informing the patient before the operation, surgery planning, surgical method rehearsal, patient-specific intraoperative drilling and cutting guide, patient-specific implant, prosthesis, or orthosis production. The fact that the patient-specific model can be produced with 3D printing and its similarity to reality, the economic and minimal microbial risk makes 3D models attractive. It is inevitable that its effective use will become widespread in Turkey with its advantages such as the advantages it provides in treatment, being economical and allowing patient-specific procedures. In this article, the potential of the use of 3D printing products in veterinary medicine and especially in veterinary surgery, the stages of 3D printing production, current applications, areas of use, current situation, and future are examined in detail. Thanks to the 3D model, the physiopathology and treatment process can be shown more clearly on the organ model to patient owners, providing great convenience to veterinarians. Veterinarians can produce any material that they can use in clinical practice with 3D printing. Apart from these basic applications, advanced surgical planning and rehearsal procedures, production and intraoperative use of patient-specific drilling and cutting guides, production of patient-specific implants and various biomaterials, and other applications that have been studied have effective advantages in increasing the success of treatment. In case the surgical method requires a complex series of procedures and the area to be operated includes complex and intricate structures, the success of the surgery is increased by performing advanced surgical planning with 3D printing products. Thanks to this rehearsal, shortening the operation and anesthesia time, reducing the possibility of mistake and iatrogenic damage in the surgical procedure, pre-planning the materials and implants to be used according to this model, and bending the implants if necessary, giving the ideal shape before the operation provide important advantages. It is inevitable that 3D printing will be used more widely and effectively in veterinary surgery in the near future. Studies on the use of 3D printing technology in veterinary clinical sciences, especially in veterinary surgery, will provide significant benefits and original contributions to veterinary surgery practice.

Keywords: Additive manufacturing, dog, cat, animal, three-dimensional printing, 3D

INTRODUCTION

The use of new technologies in human and veterinary medicine carries the diagnosis and treatment practices one step further. Many innovations are emerging and developing in veterinary surgery such as imaging methods, diagnostic devices, surgical rehearsal models, drilling and cutting guides, new implants and biomaterials. Along with these, the treatment expectations of animal owners are also increasing. The use of current technologies by veterinarians in treatment processes is undoubtedly one of the most important factors in increasing success.

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3D printing technology enables solid products to be obtained by adding two-dimensional micron-level layers and without applying other processes such as cutting and drilling. This technology, which Physics engineer Dr. Charles Hull invented in 1984, started to become widespread in 2006 (Emre et al., 2015). While it was a very expensive technology in the beginning, its prices decreased day by day and its spread continued. With 3D printing technology, products can be produced in many areas and with various materials. Materials such as polylactic acid (PLA), polyamide (PA, nylon), polycarbonates (PC), acrylonitrile butadiene styrene (ABS) can be used as raw materials in 3D printing products that will not be implanted into the organism (Hespel, 2015). Some biopolymers, bioglass and bioceramics, metals and alloys can be used as 3D printing raw materials in medical treatment applications (Arslan et al., 2018; Emre et al., 2015). It is possible to use more than one material and color. In addition, a wide variety of cellular materials can be used in the production of artificial tissues and organs as materials in bioprinters (Jamieson et al., 2021).

In recent years, 3D printing products have been used for different purposes, thanks to methods that allow 3D image configuration such as computed tomography (CT) and magnetic resonance (MR) imaging, which are increasingly used in veterinary medicine. It can be used for undergraduate and graduate education in basic sciences such as anatomy and physiology, and at many stages in clinical sciences, both in professional education and treatment processes. It can be used in many stages like vocational training in veterinary surgery, informing the patient owner before the operation, surgery planning, surgical method trial, patient-specific intraoperative drilling and cutting guide, patient-specific implant, prosthesis, or orthosis production. Although these areas of use are not yet routinized in the world, they attract a lot of attention and are spreading rapidly. It is inevitable that its use will become widespread also in Turkey with its advantages such as the features it provides in treatment, being economical, and allowing patient-specific procedures. In this article, the potential of the use of 3D printing products in veterinary medicine and especially in veterinary surgery, the stages of 3D printing production, current applications, areas of use, current studies, and the future in the world and in Turkey are examined in detail.

3D PRINTING in VETERINARY MEDICINE

Models produced with 3D printing in veterinary medicine are more attractive than cadavers and other ready-made organ models. For this reason, it has primarily been used in undergraduate and graduate training, workshops, and courses. Being able to produce patient-specific and closest to reality models with 3D printing, being very economical, and having minimal microbial risk are important advantages. Through the 3D model, explaining the pathophysiology and treatment process of the disease on the organ model to patient owners in a more understandable way also provides great convenience to veterinarians. In addition, veterinarians can design any material or part that they can use in clinical practice (such as laryngoscope, IV suspension apparatus, patient positioning materials in X-ray) in 3D and produce them with 3D printing. Apart from these basic applications, advanced surgical planning and trial procedures, production and intraoperative use of patient-specific drilling and cutting guides, production of patient-specific implants and various biomaterials, and other applications that have been studied have effective advantages in increasing the success of treatment (Bose et al., 2019; Hespel et al., 2014). Standard implants may be inadequate in areas such as the skull (with its anatomically special shape) that restrict the surgeon, in cases with large defects, or in cases such as anomalies. At this point, patient-specific implants and biomaterials have a vital function (Altuğ et al., 2015; Hespel, 2015). Printers that can produce tissue or organs (with living cells) are also called 3D bioprinters. Promising results are obtained regarding 3D printing products that are biocompatible and that can be used in tissue or organ replacement, and studies are continuing intensively (Jamieson et al., 2021). There are also studies on the production of pharmaceutical products to be used in veterinary medicine with 3D printing (Martin et al., 2020; Sjöholm et al., 2020). The first study on the clinical use of 3D printing products with 3D image reconstruction in veterinary medicine was published by Harrysson et al. (2003). In the following years, the work continued increasingly. The use of 3D printing continues to develop for different purposes at many stages from diagnosis to treatment.

The Benefits and Advantages of 3D Printing Products in Veterinary Surgery

- Providing a more detailed and realistic understanding in diagnostic procedures
- Making the most realistic training applications on the 3D model economically
- More effective and accurate explanation of diagnosis and treatment to patient owners
- Surgical planning and consultation on the 3D model in more detail, advanced, and close to reality
- Trial of the patient-specific surgical procedure on the 3D model
- Reducing the duration of surgery and anesthesia, in this way reducing other risks that may arise if prolonged
- Minimizing risks such as iatrogenic damage and blood loss in surgeries
- Implementation of the planned method with the least margin of error thanks to the 3D printed patient-specific surgical drilling and cutting guides
- Depending on all these, increasing the success and effectiveness of surgical treatments and reducing complications

How to 3D Print for Veterinary Surgical Purpose?

Simple 3D product designs can be prepared by scanning the material to be produced with 3D scanners, making the desired changes on the 3D scan image or designing it directly on the computer software. For the patient-specific 3D models, radiological images suitable for 3D reconstruction such as CT or MR imaging should be taken. CT or MR scans of each patient are taken under general anesthesia by placing the appropriate position. In these scans, the section thickness is (~0.625-2 mm) planned in accordance with the detail precision, animal type, and size of the model to be produced. The 3D image reconstruction or rendering process, which means converting two-dimensional CT or MR images into 3D images, is created in the virtual environment in DICOM (Digital Imaging and Communication in Medicine) file format with computer software. On this created virtual 3D model, the desired shape can be given to the 3D printing by performing the desired manual retouching, adding (designing a drilling/cutting guide on it, designing an implant, etc.) and isolation of certain parts (endotracheal tube, a tissue layer, etc.). This 3D model is then converted to STL (Surface Tesellation Language) format, which is a CAD (Computer Aided Design) compatible file format (Hespel et al., 2014; Li et al., 2018; Oxley, 2017; Winer et al., 2017). The reconstructed 3D image in the ready STL file format is transferred to the 3D printer and the necessary slicing is done on the software for 3D printing. The product is prepared for printing by determining the raw material suitable for the purpose. Following all the details are completed, the 3D printing process starts. The product obtained at the end of the process is kept in water or a solution suitable for the material in order to dissolve the filling material that fills the gaps in the 3D printed product. Thus, the organ model takes its final form, which is ready for use with the opening of the cavities.

Usage Areas of 3D Printing in Veterinary Surgery

In case the surgical method requires a complex series of procedures and the area to be operated includes anatomically or pathologically complex and intricate structures, the success of the surgery is increased by performing advanced surgical planning with 3D printing products. In addition, by rehearsing the surgical procedure, shortening the operation and anesthesia time, reducing the possibility of error in the surgical procedure, pre-planning the materials and implants to be used according to this 3D model, and if necessary, bending the ideal shape before the surgery provides very important advantages (Bose et al., 2019; Hamilton-Bennett et al., 2018; Hespel, 2018; Worth et al., 2019).

The use of patient-specific produced surgical drilling or cutting guides in rehearsal and real surgeries increases the success and effectiveness of surgeries and reduces the risk of complications. This is an important advantage especially in brain and neurosurgery (Figure 7 and 8), sensitive surgeries in areas containing nerve tissues in and around the skull and spine, and corrective or reconstructive surgery where the organ takes a highly abnormal form (such as angular deformities) due to disease. In orthopedics and traumatology, 3D printing products are most needed for fractures in irregular bones (such as skull), craniomaxillofacial surgeries, comminuted fractures, damage with tissue loss, anomalies, and developmental disorders. Since minor errors can cause irreversible damage in neurosurgery, especially during internal fixation procedures to be applied to the vertebrae, surgical rehearsal on a 3D model which is exactly the same as the patient's related vertebrae, and the intraoperative use of 3D printed patient-specific drilling guides have opened a new era in neurosurgery (Hamilton-Bennett et al., 2018; Hespel, 2018; Toni et al., 2020). Non-metallic 3D printing products can be produced quite economically, but it is costly to manufacture patient-specific implants from metal materials such as titanium. For this reason, patient-specific 3D printing implant production has not yet become as widespread in veterinary surgery as in humans. However, in the future, this may become widespread as it becomes more economical.

Benefiting from the advantages of 3D printing products increases the success in soft tissue surgery, in operations in regions with complex anatomical structures such as the cardiovascular system (Figure 1), in transplantation surgeries, or in the removal of tumoral masses shaped adjacent organs with important vital functions.

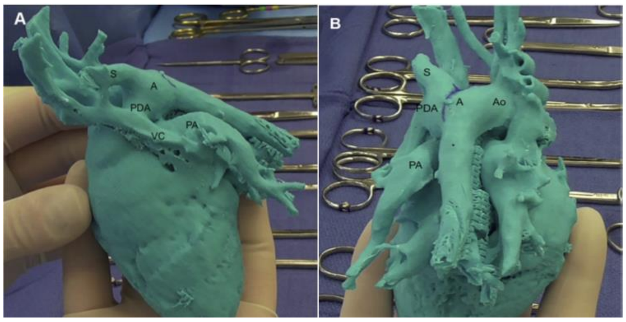

Figure 1. Left lateral (A) and dorsal (B) view of a 3D-printed full-scale model using CT angiography in a dog with multiple cardiovascular anomalies. A: aneurysmal enlargement; PDA: patent ductus arteriosus; S: abnormal left subclavian artery; PA: left pulmonary artery; Ao: right aortic arch; VC: vena cava (Dundie et al. 2017).

The development of 3D bioprinter products, which are planned to be implanted in the body in humans and animals, is also an issue that scientists work on. It is aimed to achieve great advances in the treatment of many surgical diseases by examining 3D bioprinter products with in vivo studies in experimental animals after in vitro research and developing them in accordance with the desired properties (Bose et al., 2019; Jamieson et al., 2021; Popov et al., 2019).

Advanced Preoperative Planning and Surgery Trial

Harrysson et al. (2003) were able to physically examine the deformities on the pre-surgical 3D printed model of a German Shepherd with multifocal deformities in the hind limbs and rehearsed advanced surgical planning and osteotomy. In this way, they stated that the use of 3D printing products is definitely more beneficial than two-dimensional evaluations or 3D images that are not printed, with their advantages such as performing the most accurate surgical technique, shortening the operation time and obtaining the advantages related to this, and therefore better clinical results (Harrysson et al., 2003). Dismukes et al. (2008) performed advanced surgical planning and rehearsal with 3D printing for angular deformity surgery in a dog and reported that it was very useful and beneficial. Crosse and Worth (2010) performed advanced surgical planning and osteotomy rehearsal with a 3D-printed prototype before the corrective surgery of an angular deformity in a dog and suggested that successful treatment with a single-stage corrective osteotomy is possible thanks to the 3D-printed prototype. In the surgical treatment of angular limb deformities, which is common in dogs, 3D printing products can be used for pre-surgical advanced planning, trial, ensuring full compatibility of the implant (with applications such as plate bending and shaping), patient-specific production of cutting or drilling guides to be used in surgery, and even the production of patient-specific plates or other implants. When used for these purposes, 3D printing products increase success, reduce complications, reduce the time of surgery and anesthesia, and save costs by eliminating the related negative causes (Harrysson et al., 2015; Marcellin-Little et al., 2008). In addition, in veterinary surgery, due to the fact that there are many anatomical differences due to species or race in veterinary surgical practices and there are no standard ready-made implants produced specifically for the bones like in human medicine, it is emphasized that the need for patient-specific implant production is more than the humans (Harrysson et al., 2015). In Hespel's (2015) study, a biopsy or surgical resection method performed with a 3D-printed skull model was described in dogs with cranial masses. In a horse where multi-part fractures in the orbit, periorbital wall and temporomandibular joint occurred together, the most accurate surgical technique is realized by pre-surgical planning and rehearsal, thanks to the 3D printing product model (Hespel, 2015). Winer et al. (2017) published a large study (including 32 cases) in which they used 3D printing products for advanced preoperative planning in oral and maxillofacial surgeries in small animals. In this study, reconstruction after mandibulectomy in 12 dogs, reconstructive treatment of fracture nonunion complication in 6 dogs and 2 cats, ostectomy of temporomandibular joint ankylosis in 4 dogs, cleft palate repair in 2 dogs and 1 cat, neoplasms in anatomically difficult areas in 2 dogs and 1 cat were investigated. In this study, 3D printing products were used for reconstruction after mandibulectomy in 12 dogs, reconstructive surgical treatment of nonunion complications in 6 dogs and 2 cats, ostectomy of temporomandibular joint ankylosis in 4 dogs, cleft palate repair in 2 dogs and 1 cat, removal of neoplasms in anatomically difficult areas in 2 dogs and 1 cat, reconstructive surgery of traumatic anatomical disorders in 2 dogs. They state that advanced preoperative planning and surgical rehearsals with 3D printing are very useful in these applications, and 3D printing is an excellent tool in this regard (Winer et al., 2017). Van Duijl et al. (2018) performed the surgical planning procedures in a cat with osteoma in the mandible with the 3D printed model and reported its advantages. Lam and Kim (2018) used 3D computer-aided planning and 3D printing modeling for the surgery of a complex articular femur fracture in a dog. In this study, they stated that it is very useful in terms of planning, implant selection and implant bending or preparation processes and surgical rehearsal, and it is also very useful in undergraduate and specialist (postgraduate) education. Bordelo et al. (2018) benefited from the advantages of advanced planning and osteotomy rehearsal with a preoperative 3D printed product model in a dog with an angular deformity (radius curvus), and they recommend it by stating that they found it useful. Mejia et al. (2019) compared the accuracy of the biomodels produced by 3D printing for the radius bone in dogs with real bones by making measurements and analyzes and showed that there is no significant difference, therefore they could be used in preoperative planning and orthopedic surgery. Blake et al. (2019) demonstrated the beneficial applications of 3D printing products in small animals and wild animal species in many areas from preoperative planning to surgical procedures in veterinary surgery and reported that their popularity is increasing day by day.

3D Printing in Veterinary Orthopaedics and Traumatology

Many orthopedic and traumatological pathologies such as congenital anomalies, developmental skeletal deformities, dysplasias, traumatic fractures in anatomically intricate regions in animals are the most common and difficult to treat cases in veterinary surgery (Altuğ et al., 2015). There are significant gains in overcoming these difficulties with the work done with 3D printer products. Marcellin-Little et al. (2008) stated that in the tibial plateau corrective osteotomy (TPLO) technique, thanks to the cutting guide and TPLO plates that they produced specifically for the patient with 3D printing, the technique provides better stability as well as faster and more accurate application. Crosse and Worth (2010) found that 3D printed products such as corrective surgical limb models or cutting guides are beneficial in providing more accurate treatment in dogs. Kuipers von Lande et al. (2012) achieved successful results in a dog in which they applied rapid prototyping with 3D printing technology and permanent hard palate defect repair with a patient-specific produced titanium plate. Petazzoni and Nicetto (2014) produced a patient-specific plate with the 3D printed prototype they produced for pancarpal arthrodesis surgery in a dog and stated that the results were quite successful. Another study has shown a 3D printed patient-specific titanium alloy prosthetic implant was successfully used in a dog with a large defect in the radius bone (Harrysson et al., 2015). In a study, the stem of a total hip replacement implant placed in the femur in dogs was produced by 3D printing and tested in vitro (Marcellin-Little et al., 2010). 3D printing was used to prepare a patient-specific full knee replacement in a dog with irreparable loss of bone tissue due to a gunshot injury, and for producing a humeral head implant in another dog (Liska et al., 2007; Sparrow et al., 2014). Castilho et al. (2017) produced tricalcium phosphate (TCP) cages with 3D printing to be used as an implant in tibial tuberosity advancement (TTA) surgery of cranial cruciate ligament ruptures in dogs and achieved successful results. Lee et al. (2017) applied the bone grafts they produced using PCL/TCP composite material with 3D printing together with stem cell therapy in the treatment of maxillary bone defects in dogs and achieved successful results. Oxley (2017) stated that the 3D printed patient-specific cutting (osteotomy) and drilling guides for bilateral shoulder arthrodesis surgery in a dog are very useful, effective in the reduction and optimal implant placement, and also reduce the surgical time. In another study by Oxley (2018), a 3D printed patient-specific guide was successfully used for the treatment with the minimally invasive plate osteosynthesis (MIPO) technique of a comminuted humeral fracture (Figure 5) in a cat. Park et al. (2018) produced PCL/TCP composite bone grafts with 3D printing and used them successfully in experimental canine maxillary defects (Figure 2). Kim et al. (2018) were used a 3D printed patient-specific graft in the repair of a large maxillary bone defect caused by tumor resection in a dog, and they found the results to be successful.

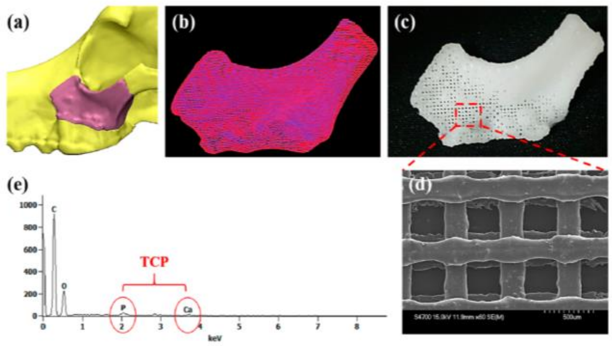

Figure 2. The 3D printing process of PCL/TCP composite bone grafts used in experimental canine maxilla defects: (a) 3D configuration of the defect; (b) print design; (c) 3D printed graft, (d) its SEM image, and (e) energy emissive spectrometry results (Park et al. 2018).

Due to the irregularly shaped bones, 3D printing provides significant advantages in craniomaxillofacial applications where patient-specific implants are required in the mandible, maxilla and skull bones. In cases such as defects in this region, mandibulectomy and large oronasal fistula cases, it is possible to use exactly compatible 3D printed patient-specific implants (Harrysson et al., 2015; Schöllhorn et al., 2013). Carrel et al. (2016) used 3D printed TCP/HA bone grafts to the canine mandible as a pilot study and reported that the results were promising and that further studies should be done. Southerden and Barnes (2018) also reported that they achieved very good results with the advantages of 3D printing technology in the treatment of mandibular fracture in a cat, and excellent jaw occlusion was provided. Popov et al. (2019) reported that 3D printed patient-specific prosthetic implants for bone defects after osteosarcoma resection in dogs gave successful results. Zanfabro et al. (2021) have employed a 3D printed pre-operative surgical planning model for monolateral temporomandibular joint ankylosis treated with piezoelectric surgery in a cat.

Although studies on the use of 3D printing products in veterinary orthopedics and traumatology are limited, it is increasing day by day. In Turkey, there is no published research article on this subject yet. However, there are two different case report congress presentations, a poster and an oral presentation. These are the reports presented as the use of a 3D printed titanium alloy jaw prosthesis in a sea turtle (Caretta caretta) with irreparable defects (Figure 3) in the mandible and maxilla (Altuğ et al., 2015) and a prosthesis made of PLA material with 3D printing in an amputated dog (Sen, 2020). Therefore, the use of 3D printing in veterinary orthopedics and traumatology has begun and will develop in Turkey.

Figure 3. Postoperative image of 3D printed patient-specific titanium alloy prosthetic implants for large defects of mandible and maxilla damage in a Caretta caretta sea turtle (Altuğ et al. 2015)

3D Printing in Veterinary Neurosurgery

With the help of 3D printing, Hespel (2015) has provided detailing of the pre-surgical diagnosis, advanced surgical planning, rehearsal of the surgery, preparing the plates and screws to be applied according to the 3D model of atlantoaxial luxation in two dogs. These are important especially in terms of preventing possible iatrogenic damage (to not entering the medullary canal and preventing damage to the spinal cord). In a dog with comminuted axis vertebra fracture, the fracture was evaluated in detail and medical treatment was decided, and recovery was achieved successfully. In the research of GM2 gangliosidosis, which is a genetic disease, prototypes of the skull and cervical vertebrae of two cats were produced by

3D printing and evaluated. Bronchial structures were produced by 3D printing and used for the purpose of training in endoscopy application in healthy cats and dogs. In addition, it was stated that many problems in communication were overcome thanks to the explanation of many pathologies through physical examples to patient owners with 3D printed models (Hespel, 2015). In spinal surgery, 3D printing products provide unique advantages when intervertebral disc prosthesis, spine stabilization, and fixation are required (Harrysson et al., 2015; Schöllhorn et al., 2013). Hamilton-Bennett et al. (2018) produced patient-specific drill guides with 3D printing for cervical transpedicular screw applications in 3 dogs and applied a total of 32 screws in 3 cases. They reported that screw applications can be successfully performed in the desired direction and placement, clinical results are improved, and surgery time and morbidities are reduced (Hamilton-Bennett et al., 2018).

Suñol et al. (2018) reported that 3D printing model production is beneficial and economical in the identification and education of vertebral fractures in dogs. The fact that studies showing that a surgeon in the field of neurosurgery can perform the same surgery in a 25-33% shorter time after 20 years of experience reveal the importance of 3D printing technology's contribution to shortening the operation times (Hespel, 2018). Years of experience have been gained by the surgeon's ability to predict more accurately the surgical manipulations and complete the procedure in a shorter time, such as examining the 3D printing product by touching, grasping the details, advanced planning before the surgery and rehearsing the surgical method. Patient-specific drill guides also provide a very important advantage by reducing the margin of error.

In one of the recent studies, Gutmann et al. (2020) demonstrated with measurements and analyzes that they are more successful than other standard brain biopsy tools used for the same purpose as the stereotactic brain biopsy guides they produced for dogs with 3D printing (Figure 6). Successful applications with these guides, being suitable for skulls of all sizes, and high millimetric accuracy in the positioning of brain biopsy needles are important results. Toni et al. (2020) produced patient-specific drilling guides with 3D printing for pedicle screw application in the lumbosacral region in dogs and showed that the placement directions of the screws are more accurate and safe for use in surgery. They state that patient-specific drill guides produced with 3D printing are safe, effective, and successful (Toni et al., 2020). De Armond et al. (2021) developed a special surgical guide system for bipolar coxofemoral osteochondral allograft transplantation in dogs with 3D printing and tested it on canine cadavers. They reported that thanks to this special guide, the surgical time is reduced and the accuracy of the surgical procedure is improved (De Armond et al., 2021).

3D Printing in Soft Tissue Surgery

The prevalence of diseases requiring surgery in organs with delicate and anatomically intricate structures such as eyes and ears is substantial (Altuğ and Deveci, 2016; Deveci et al., 2020; İşler et al., 2015). Dundie et al. (2017) produced a full-scale 3D print of the heart and vessels before the surgical procedure of a patent ductus arteriosus (PDA) case with 5 different cardiothoracic vascular anomalies in a 10-week-old dog, with significant advantages in terms of detailing the diagnosis, full evaluation, advanced surgical planning, intraoperative communication, and coordination. In this study, it was emphasized that thanks to the 3D model, the anesthesia and surgery times were shorter, and it was especially beneficial in providing atraumatic vascular dissection in surgery (Dundie et al., 2017). Soares et al. (2018) achieved successful results in a cat with chronic oronasal fistula by applying a 3D printed patient-specific soft tissue flap (mesh). In another study, the bronchial structures of a Savanah monitor lizard and a Nile crocodile were 3D printed (Hespel, 2015). Nibblett et al. (2017) produced a canine external ear canal model with 3D printing for use in otoscopy training and stated that the same application can be made on this model with a real dog. Dorbandt et al. (2017) used 3D printing to take advantage of advanced surgical planning and other advantages in the treatment of orbital and periorbital masses in three dogs. While discussing its advantages, they stated that revolutionary developments can be achieved in veterinary ocular surgery with the use of 3D printing (Dorbandt et al., 2017).

The Future of 3D Printing in Veterinary Surgery

There is no workshop, course, or published research article on this subject in Turkey, either in veterinary surgery or other veterinary clinical sciences. There are only two papers mentioned above (Altuğ et al., 2015; Sen, 2020). Therefore, the studies carried out in this field are studies of the extremely high original value. The ability to obtain 3D bioprinted products with the development of 3D printer technology is a groundbreaking advance in human and veterinary surgery applications. 3D bioprinting differs from traditional 3D printing. In order to allow for the generation of complex functional tissues, it utilizes bioinks comprised of cells and other biomaterials. It has found success in human medicine studies both in vitro and in vivo. Recent efforts investigated its veterinary application and continue. To date, it has been produced cardiovascular, cartilage, bone, corneal and neural constructs in animal species, by 3D bioprinting. Moreover, the use of animal-derived cells or models in human research has provided additional information for veterinary translation (Jamieson et al., 2021).

Shim et al. (2014) produced a bone regeneration membrane with 3D printing to be used in experimental calvarial defects in rabbits (Figure 4) and obtained promising results.

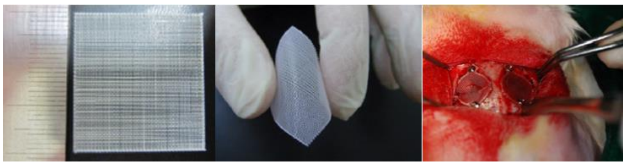

Figure 4. Preoperative and intraoperative images of 3D printed bone regeneration membrane containing PCL/PLGA/β-TCP fixed with screws for bilateral full-thickness calvarial defect repair in an in vivo experimental study in rabbits (Shim et al. 2014).

Li et al. (2014) produced polyethylene lung prostheses with 3D printing to prevent displacement of the mediastinum in order to prevent late postpneumectomy complications in their experimental research on dogs. Irradiation has been used to sterilize these 3D bioprinter products. Dogs which underwent pneumectomy with a 3D printed prosthesis were successful, results in significantly fewer complications after one-year follow-up compared to dogs without prostheses (Li et al., 2014). Many unsolved problems have been solved with studies using 3D printing in human and veterinary surgery, and significant progress is being made with ongoing studies (Akbaş et al., 2018). Promisingly, the production of tissues and organs with 3D bioprinting is a field of study that has been intensely researched and progressed in recent years. The beginning and progress of the use of 3D printing studies carried out in the world in both clinical and experimental veterinary studies in Turkey will also make significant contributions to comparative scientific studies in human medical sciences. Witowski et al. (2017) stated that the models produced with 3D printing are more beneficial than 3D image reconstruction, and they emphasize that studies on this subject in clinical and surgical fields are very necessary. Harrysson et al. (2015) report that in their research on the use of 3D printing technology in veterinary surgery, superior advantages have been obtained with diagnosis, surgical training, advanced planning and rehearsal before surgery, and patient-specific implant and biomaterial production.

Scientific studies around the world on the use of 3D printing in the field of veterinary surgery are summarized above. It is seen that this technology, which has become widespread day by day in various countries of the world, has been used in veterinary clinical sciences, positive and effective results have been obtained, recommended, and still developing by continuing to be studied intensively. It is obvious that its use will be much more common in the future (Carrel et al., 2016; Demirkan et al., 2018; Dorbandt et al., 2017; Hespel, 2018; Hespel et al., 2014; Kinns et al., 2011).

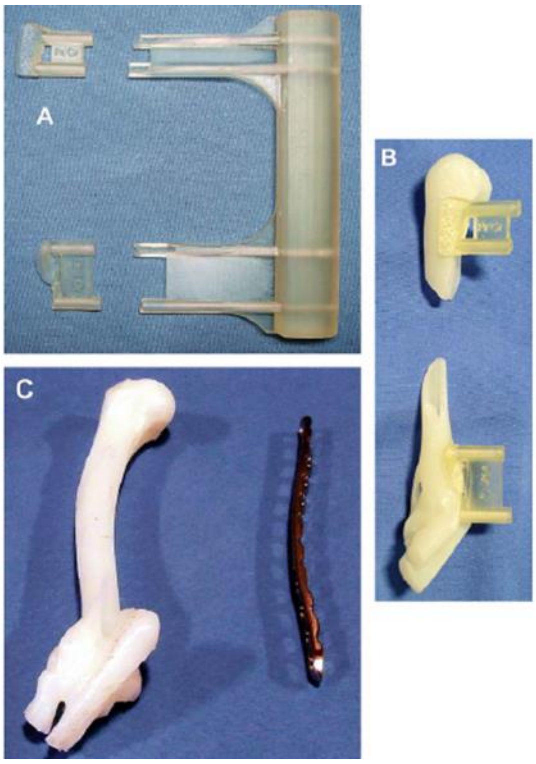

Figure 5. A: Two Ellis pin routing guides and reduction guides produced by 3D printing; B: View of Ellis pin routing guides superimposed on proximal and distal bone fragments produced by 3D printing. C: 3D printed bone mold by modeling the opposite intact humerus bone in the other limb, and the plate shaped with this mold before surgery (Oxley 2018).

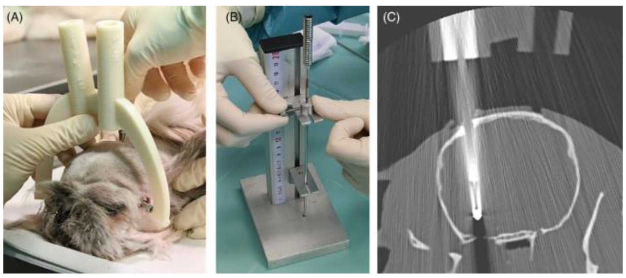

Figure 6. A: Patient-specific 3D-printed brain biopsy guide in a dog. B: Adjusting the depth of the biopsy needle. C: Transversal CT image with a biopsy needle (Gutmann et al. 2020).

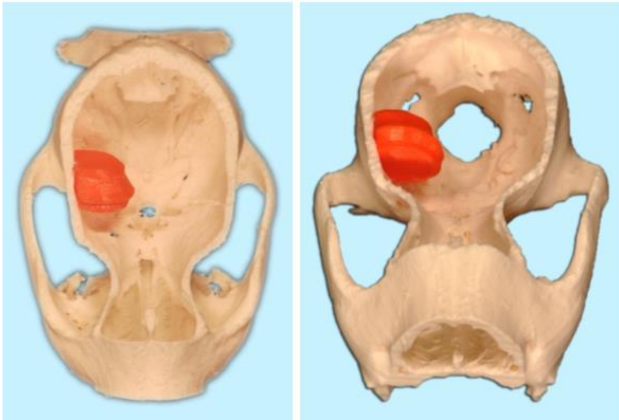

Figure 7. Dorsoventral (a) and oblique (b) view of a 3D printed model of an open cranium with a brain tumor (Hespel et al. 2014).

Figure 8. Dorsoventral view of a 3D printed model of cervical vertebrae with atlanto-axial luxation. On this 3D printing model, the appropriate shaping of the plates by bending and screw applications was rehearsed (Hespel et al. 2014).

CONCLUSION

In veterinary surgery, unique and important advantages are provided by the use of 3D printing technology at all stages from diagnosis to treatment. It is inevitable that 3D printing will be used more widely and effectively in veterinary surgery in the future. While developments in the use of 3D printing technology continue rapidly in both human and veterinary medicine applications around the world, its use in veterinary clinical sciences continues as a fairly new field for various reasons in Turkey, despite the fact that studies on this subject have started and progress has been made in human medicine. Studies on the use of 3D printing technology in veterinary clinical sciences, especially in veterinary surgery, should be encouraged and supported as they will provide significant benefits and original scientific contributions to veterinary surgery practice in Turkey.

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