Evolution and Trends in Reconstructive Facial Surgery: An Update

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Abstract Surgical correction of congenital and acquired facial deformities has transcended the primitive era of using non biologic materials to current attempts at own face growing through biotechnology. A summative account of this trend is still lacking in the literature. The objective of this article is to present an update on current knowledge in the strides to achieve functionally and aesthetically perfect facial reconstruction. It highlights the impact of advancements in 3D imaging, stereolithographic biomodelling, microvascular surgical tissue transplantation and tissue biotechnology in the surgical efforts to solve the problems of facial disfigurement whether congenital or acquired.

Keywords Facial reconstruction · Virtual surgery · Facial transplantation · Biosurgery

Introduction

When the face is disfigured as a result of trauma, tumor resection, infectious diseases, or congenital anomalies, the physical and psychosocial effects are extremely detrimental [1]. It ranges from distortion of self-image and low self-esteem to withdrawal from social interaction which may lead to chronic stress and depression with suicidal tendencies [1, 2]. Therefore, the task of correcting facial disfigurement is a challenging one to the reconstructive

surgeons [3]. The patients have strong desire for a fully functional and aesthetic restoration without any alteration to their pre-morbid personality [1, 3]. Consequently, medical science has evolved over the years, latching on developments in related fields of science such as computer technology and tissue biotechnology, in a stride to achieve optimal outcomes in facial reconstruction [1, 4, 5].

This article reviews aspects of facial reconstruction and provides an update on the evolution, current trends and direction in this surgical art by underscoring the various landmark developments in the aspects of maxillofacial prosthetics, medical radiology, stereolithographic biomodelling, software creativity, composite tissue allotransplantation (CTA) and biosurgery.

Maxillofacial Prosthesis

Maxillofacial prosthesis assumed initial popularity in the prehistoric era because of limited expertise in reconstructive surgery [6]. After the second world war, the discovery of acrylic resins significantly advanced the field of facial prosthesis; greater transformation followed the emergence of silicone elastomers in the 1960s. By the 1980s osseointegrated implant devices came on board and were already in widespread use by 1990s essentially to support and retain dental and maxillofacial prostheses for jaw, nose, ear and eye replacement [7].

With the evolution of modern techniques in reconstructive surgery, prosthetic treatment lost its place of preference in facial reconstruction. Antagonists emphasized the drawbacks of prosthesis as limitation in simulating life form aesthetics, function and durability and lack of sufficient deformability inherent in natural human soft tissue [8]. However, some authorities still believe that prosthesis is the

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last resort where the conditions for surgical reconstruction are not met. In fact, it is now thought that by employing three dimensional imaging and advanced technology in design and construction, prosthesis could remain a viable first treatment option in facial reconstruction [7, 9].

Development in Medical Radiology: 3D-Craniofacial Imaging

Three-dimensional (3D) imaging is an innovative approach that is applicable in various aspects of medical and surgical practices. The earlier techniques such as; 3D-cephalometric radiography, 3D-occlusogram, 3D-laser surface scanning and 3D-infrared photogrammetry all derived from manipulation of images generated from traditional 2-dimensional radiography [10]. Hence, the images produced are usually of poor quality and were unable to render accurate patho-anatomic morphology of the area under examination [10]. Recent advancements in computer technology and software development has revolutionized 3D-imaging, bringing about more sophisticated techniques like 3D-ultrasonography which is useful for visualizing the salivary glands, eyes, nose and tongue [11, 12], 3D-magnetic resonance imaging (MRI) applicable to craniofacial soft tissue analysis [6, 13], and 3D-computerized tomography which has a large scope of usefulness in the investigation of the craniofacial complex [10, 14].

Currently, images generated by 3D-rendition of the craniofacial complex are employed in a wide array of applications, including; (i) diagnosis and evaluation of extent of lesion [12, 15], (ii) analysis of facial asymmetry [15, 16], (iii) rapid prototyping for stereolithographic modeling [17], (iv) fabrication of customized implantable devices [18, 19], (v) preoperative virtual surgery [5, 9], (vi) generation and transfer of data for intraoperative navigation [20–22], (vii) presurgical assessment of potential recipient vessels for microvascular anastomosis near a resection site using 3D-CT angiogram [3], (viii) interactive discussion with patients for better understanding of the extent of disease and proposed surgery [10], and (ix) training of surgical residents in an educational environment [10]. By these applications, the surgeon is able to visualize the pathology in its entirety, assess its influence on the surrounding anatomy, determine the feasibility of resection, and concurrently plan the reconstruction of a defect.

In more recent development, combination of two modalities of 3D-imaging techniques has been employed. For instance in planning an orthognathic surgery, a 3D-CT virtual simulation of the skeletal procedure could be obtained and a 3D-laser scanning could generate data of surface imaging (soft tissue). By combining the data using special computer software, the 3D surface image can be

superimposed on the 3D skeletal image to create a projection of treatment outcome which can be appreciated and assessed by both patient and surgeon [23]. Although, the projected outcome should be cautiously interpreted to patient as this may not be exactly replicated after surgery, the application still enhances the prediction and actualization of better outcome.

Stereolithographic Biomodeling

Stereolithographic biomodelling is a form of computer-aided 3D imaging manufacturing technique which provides a “hard copy” of all 3D information received. This technique was initially developed in the engineering sciences to manufacture prototype models [10]. It is currently being applied in the fabrication of human skull models for treatment planning in cranio-maxillofacial surgery [24]. Three dimensional data generated from conventional CT or MRI is guided into a manufacturing device to produce the physical model of the image using special manufacturing software packages. The manufactured stereolithographic biomodels improve the quality and precision of essential diagnostic measurements and is useful for surgical pre-planning [25], reconstruction of cranial bone, ear or orbital wall defects [26–28], primary reconstruction in cranio-maxillofacial trauma surgery [29], and for accurate, pre-operative adaptation of reconstruction plates or osteosynthesis devices [30]. Although the use of stereolithography in routine cases is quite rare, it is already used in various places with very satisfactory results especially in severe cases of maxillofacial deformities [12, 31].

Virtual Simulation of Facial Reconstructive Surgery

Virtual surgery involves manipulation of 3D image in a way to simulate live surgery using specially designed softwares. The virtual outcome may be converted into models through rapid prototyping [10]. By so doing, the surgical outcome could be previewed by both surgeon and patients. Although the original software employed in this application made virtual simulation of hard tissue manipulations possible, proper aesthetic assessment of surgical outcome would be incomplete without projecting the overlying soft tissue. Hence, software to simulate soft tissue procedures has now been developed [25, 32].

Intraoperative Navigation and Robotic Surgery

Intraoperative navigation surgery is a computerized surgical modality in which the surgical instruments are

accurately tracked and targeted to a preplanned location within the surgical field [22, 33]. By this technology, 3D image information are uploaded onto various software programs and a precise planning of resection margin, osteotomy sites or bone re-positioning can be transferred from the presurgical model or virtual surgery to the patient in the operating room with a degree of precision hitherto unachievable. To achieve this, threefold synchronization must be established between the intraoperative position of the surgical tool, the real-time position of the patient, and the patient's CT reconstructed image uploaded into a computer workstation [33]. This requires specific technicalities in setting up the imaging procedure which must be reproduced in setting up the operating theatre to ensure the same reference point for intraoperative navigation. Several reports have highlighted the value of this technology in improving the precision and outcome of surgery [25, 34].

Unlike navigational systems which simply provide guidance for the surgeon during specified steps in a surgical operation, surgical robotics further enhance precision in surgical task performance and is now applicable in facial reconstructive procedures. Surgical robots have been defined as a powered computer-controlled manipulator with artificial sensing that can be reprogrammed to move and position tools to carry out a range of surgical tasks [35]. They are commonly used as surgical assistants in the operating theatre in close cooperation with the surgeon.

So far, the role of robots in oral and maxillofacial surgery include [35–37]: (1) the drilling of holes with an automatic stop after penetrating the bone in order to protect the tissue lying deep to the bone, (2) the milling of the bone surfaces according to a three dimensional operation plan, (3) performing osteotomies and allowing for precise three-dimensional transposition of the subsequent bone segments, (4) positioning of dental or surgical implants, and (5) preoperative selection of osteosynthesis plates and their intraoperative positioning in defined positions.

Two groups of surgical robotic systems can be distinguished which differ substantially from each other [35]. The first group, the telemanipulators, is not preprogrammed. The basic principle is that on a so called slave console the movements of the surgeon, who is sitting at the master console and moving steering paddles, are exactly copied by the robot within the operation field. The master console displays the images directly on a monitor for a feedback with the surgeon. The other group of systems, the preprogrammed surgical robots, executes a preoperatively defined trajectory within the operation field. Nevertheless, they are controlled by the surgeon during the whole operation and can be stopped at any time.

The additional benefits derived from surgical robots are more accuracy and reliability in transferring preoperative

plan to the operative situation, less vibration; unlike human hands, flexibility and miniaturization to access locations where surgeons hand may not easily reach. The overall value of intraoperative navigation and surgical robots in facial reconstruction is in enhancing the achievement of a preoperatively determined outcome in the real patient. This is a giant stride in facial reconstruction.

Tissue Substitutes for Facial Reconstruction

The face is a complex meshwork of skin, muscles and underlying bone organized into delicate aesthetic and functional units. Occasionally, facial deformities involve loss of one or more of the original facial tissues with attendant disruption of the aesthetic and functional anatomical relationships. The greatest challenges to reconstructing these deformities are the need to replace lost native tissues with matching substitutes and precision in restoring the disrupted relationships. While developments in 3D craniofacial imaging, intraoperative navigation and robotics enhance precision, substituting native tissue is another major hurdle in facial reconstruction.

Currently, facial defect are mainly restored by the patient's own tissues (autologous), allogeneic tissues, xenogenic tissue, synthetic materials, or prosthesis [1]. All of these may require multiple staged surgeries and even then in the best of cases may not achieve satisfactory appearance and function [2]. Autologous grafts are often considered the clinical gold standard, because allografts, xenografts, and synthetic materials are associated with complications such as pathogen transmission, immune rejection, and suboptimal integration [38–43].

The advent of microsurgery significantly revolutionized and increased the versatility of autologous tissue transfer in facial reconstruction [9]. Initial challenges such as limited options, multiple staging, and vascular insufficiency can now be readily overcome by moving distant tissues with their native blood supply (and/or nerves) from a donor site and anastomosing to corresponding structures within the recipient bed. In cases where the desired donor tissue lack adequate vascularity for transfer to the recipient site or where there is vascular insufficiency at the recipient bed; such as after therapeutic irradiation of the face, prefabricated flaps have been adopted. The concept of flap prefabrication was first described by Shen Tzu Yao in 1982 [44]. The technique involves vascular induction of a transplantable tissue by implanting a definite vascular pedicle to the donor tissue and allowing sufficient time for the donor tissue to assume supply from the transplanted vessels [44, 45]. The donor tissue can then be harvested and transferred pedicled on the implanted vessel as a vascular carrier or transferred as a free flap which can be

anastomosed to a recipient vessel in the facial region [44, 46–48].

Closely related to the technique of flap prefabrication is the concept of prelamination flap. Prelamination is a viable option for the reconstruction of composite aesthetic units of the face such as the ear, nose and eye lids [47, 49]. Using this technique, tissues such as bone, cartilage, muscles and skin can be preassembled to form a precise composite structure [45]. The composite is vascularized by burying in a vascular territory and later harvested as a free flap and anastomosed to the recipient bed to replace the missing part [44, 47]. These developments have enhanced facial reconstruction and can be used in combination with intra-operative navigation to accomplish pre-planned surgical objectives.

However, a key drawback of autologous tissue grafting is donor site morbidity [41]. The patient will invariably experience additional trauma, pain, scarring, disfigurement or other donor site complications [50–52]. In addition, it has been noted that though autologous grafts and flaps do a good job of replacing skeletal and soft tissue defects, they may not adequately restore the delicate complex facial anatomy [2]. Also, in respect of the skin, there is often a mismatch between the transferred and adjacent original tissues giving a patchwork appearance thereby falling short of the ultimate goal of facial reconstruction [2]. In the light of this consideration, facial allotransplantation has been adopted.

Facial Allotransplantation

The ultimate goal when reconstructing facial deformities is to achieve normal function and appearance without asymmetry or mismatch of facial tissues. Up to date, conventional reconstructive methods have not been satisfactory, hence the advent of CTA

CTA involves the transplantation of various complex tissues, including skin, muscle, nerves, bone, tendon, and vascular tissues [53]. CTA as well as solid organ transplantation were first attempted after world war II [54]. CTA was however abandoned because of greater antigenicity of the skin. However, following significant strides in immunosuppression therapy by mid 1990s, the first successful CTA in modern history was accomplished with a hand transplant performed by a team of surgeons in Lyon, France under Jean-Michel Dubernard in September 1998 [55–57]. However, facial CTAs presented much more complex problems because of more pertinent ethical and psychological considerations. This was gradually overcome and the first facial CTA was done by Devauchelle, Dubernard, and co-workers in November 2005, in Amiens, France [58]. Since then, a considerable number of facial

allotransplantations have so far been accomplished with impressive outcomes.

Although, facial allotransplantation is built on the fundamental techniques of microvascular and microneural surgery, like any form of allograft, it is confronted by a lot of immunologic, ethical, psychological and socio-cultural considerations [2]. Hence, a clear guidelines of indications and contraindications must be followed and a case-by-case consideration of patients undertaken before embarking on facial allotransplantation [59, 60]. At the moment, current indications for face transplantation remain limited by unknown long-term outcomes and the requirements for lifelong immunosuppression [59]. In addition, there must be a realistic back up reconstruction strategy in the event of failure of the transplant [60–62]. Consequently, facial allotransplantation, as at today, is reserved for patients with severely disfigured face of more than 25 % facial area or involving complex aesthetic/functional subunits such as the nose/central face, the eyes, the ears etc., especially where conventional reconstructive options have failed [59, 63]. The absolute contraindications are history of poor medical compliance, lack of finance to support the long term course of immunosuppression therapy, unfeasible long term follow-up, and more importantly, psychological issues compromising the patient's ability to understand and cope with the procedure and to comply with the consequent medical management [47, 59]. Other contraindications such as post oncological disfigurement, presence of other handicapping condition (e.g. blindness, limb amputations), immunodeficiency state (e.g. HIV) and self induced facial disfigurement are debatable [59, 61, 64, 65].

Patient selection is a major predictor of success in facial CTA. It involves a rigorous screening by a multidisciplinary team consisting of reconstructive surgeons, transplant physicians, psychologists and social workers [2]. The selection criteria for both recipient and donor must include physical characteristics (skin color, gender), immunological characteristics (immune status, blood type, HLA, previous sensitization), psychological characteristics (willingness to undergo the procedure, and to accept life-long immunosuppression, coping skills, expectations), social characteristics (family support, religious beliefs, etc.) and economic status (ability to sustain prolong medical care) [2, 50, 51].

Where it is successful, facial allotransplantation portends a real solution to severe facial deformity with near perfect restoration. Although an argument of identity change has been put forward, the counter argument is that facial identity depends more on the underlying skeletal framework. Once this is maintained, and there is appropriate matching of the soft tissue characteristics of donor and recipient, identity may not alter significantly. However, it must be stated that the aesthetic results of transplantation

are far from flawless [66]. The colouration of the grafted facial tissue may not match that of the recipient's original face, and the degree of expressivity regained is highly dependent on the extensive regeneration of nerves between the patient's undamaged tissue and the allograft [66].

The more boisterous argument against facial allotransplantation is in relation to the risks associated with lifelong immunosuppression which include susceptibility to infection, malignancies, and numerous drug related toxicities [1]. Although, it is hoped that as the technology for immunosuppression improves, this limitation can be overcome and facial allotransplantation can become a common place for even less severe deformity [2, 67]. Meanwhile, there is increasing advocacy for biosurgery as the final panacea to the challenges of facial tissue reconstruction.

Biosurgery in Facial Reconstruction

Biosurgery is the new paradigm for facial reconstruction and augmentation. It is based on the principles and practice of tissue engineering and stem cell biology which involve the delivery of bioactive cues, biopolymers (cytokines, chemokines and growth factors), and/or cells that are tailored to restore facial defects [1]. It is a technique that allows host tissue to remodel and achieve the desired characteristics, producing long lasting results with the most minimum surgical trauma. There are two approaches to biosurgery; 'cell homing' and 'cell transplantation' [1].

Cell homing is defined as active recruitment of endogenous cells, including stem progenitor cells, into an anatomic compartment [1, 68]. It involves the delivery of active biomolecules like growth factors, bone morphogenic proteins, cytokines and chemokines to induce cellular ingrowth by recruiting native stem cells into the definitive lineage of tissues being replaced over an appropriate scaffold [7, 69]. Cell transplantation is the active delivery of autologous stem cells or end-stage cells into an anatomic area to regenerate a target tissue [1, 68, 69].

Cell homing has been used with significant success in bone engineering, but effort in translating the approach into clinical setting of soft tissue reconstruction or augmentation has made little progress until very recently [1, 70]. At this time, it is now possible to restore small facial defects involving bone and soft tissue by cell homing but the restoration of large facial defects may still rely on cell transplantation approach [1]. However, cell homing is likely to enter the mainstream of the clinical market before cell-transplantation, because cell delivery may require in vitro manipulations, training of current clinical practitioners on cell handling, and the undesirable problems of excessive cost and potential contamination have to be resolved [1].

Biological regeneration of orofacial tissues (biosurgery) overcomes most, if not all, of the drawbacks of autologous grafting or artificial materials. Compared with autologous tissue grafts, one of the key advantages of cell-based therapies is to minimize donor site morbidity [1, 70]. Unfortunately however, a number of drawbacks have become apparent with early attempts at autologous cell therapies [1]. First, there could be insufficient numbers of healthy donor cells in the target area and therefore cells may have to be obtained by inducing some degree of donor site trauma. Second, delivered cells without carriers sometimes migrate away from the intended location or transform into undesirable cells. For the regeneration of structural tissues such as bone or cartilage, cell delivery without carriers fails because of a lack of the obligatory structural and mechanical scaffold. Third, delivered end-stage cells, because of programmed cell death or necrosis, are often incapable of regenerating or maintaining the volume or the function of target tissue. Stem cells may overcome these deficiencies of autologous end-stage cells transplantation. Because they are capable of multiple population doublings, therefore potentially serving as a replenishable source for facial tissue reconstruction [71, 72, 73].

Conclusion

The clear objective of facial reconstruction is to restore pre-morbid aesthetics and function. This article has provided an update on the evolution of technology and techniques currently applied in reconstructive surgery. It has highlighted the trend of development in 3D craniofacial imaging and its applications in both diagnostic and pre-operative surgical planning. The development of special software for virtual simulation of both hard and soft tissue outcomes of surgery is elucidated.

The application in modern surgery of computer assisted real-time surgical maneuvers via intraoperative navigation and robotics is described. Also, the giant strides in microsurgery, culminating in increasing tissue replacement possibilities is presented, with emphasis on the adoption of facial allotransplantation as a viable treatment option.

Ultimately, there is an evolving advocacy for own face growing through biosurgery. If this would be sufficiently developed and moved into mainstream clinical practice, it shall be a veritable tool and the final solution to the problems of severe facial disfigurement.

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