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Current applications of porous polyethylene in tissue regeneration and future use in alveolar bone defect

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Abstract

The success of dental implant depends on the quantity and quality of the alveolar bone support. Autogenous bone is still the gold standard for using as a bone graft to reconstruct or augment the alveolar ridge to properly support the dental implant placement. However, it has been associated with the increase in operation time, cost and donor site morbidity. Various allografts, xenografts and synthetic materials have been used as substitutes for autogenous bone, but they have been reported to not heal as predictably as autogenous bone and new type of bone grafts are still needed to be sought. Porous polyethylene has been successfully used in several applications such as cranial reconstruction, nasal reconstruction, ear reconstruction, orbital reconstruction and correction of maxillofacial contour deformities due to its highly stable, adaptable and has been shown to stimulate tissue regeneration by acting as a scaffold for rapid hard and soft tissue ingrowth. In this paper, the properties and current applications of porous polyethylene in tissue regeneration are reviewed and the outlook for its use in alveolar bone defect is discussed.

Keywords: Craniomaxillofacial reconstruction, Alveolar bone augmentation, Bone porous polymer interface strength, Porous polyethylene

1. Introduction

Alveolar bone defect in the edentulous area which was resulted from various causes for example periodontal status, traumatic or infection of tooth is the vital problem in implant dentistry. The survival rate of dental implant depends on alveolar bone quality and quantity. The repairing process of bone needed osteogenenic cells, an osteoconductive matrix, osteoinductive signaling, mechanical stability, vascularization and time [1]. Guided bone regeneration (GBR) with the use of bone grafts has been used to treat minor localized vertical/horizontal ridge defects for implant site preparation. For the defect site that needs alveolar ridge contour augmentation by the autogenous graft, it was harvested from donor site intraoral cavity [2]. Currently, the autologous bone graft is still the gold standard for alveolar bone regeneration. However, the harvesting of autologous bone from another location could result in donor site morbidity, neurosensory disturbances, pain, increasing operating time, impermanent function loss, incomplete wound healing, pain and iatrogenic injury [3]. Alternatively, allografts which are the transplanted bone tissue from same species, but another individual or xenograft which originates from different species could be employed. However, both types of graft carry a risk of immunogenic reaction and transmission of infectious diseases. Several synthetic bone grafts were developed and to overcome these problems. Hydroxyapatite and biphasic hydroxyapatite/tricalcium phosphate bioceramics are widely used synthetic bone grafts due to its good bioactivity and osteoconductive, but their main drawback was the brittleness nature. Modern biomaterials such as porous polyethylene has been successfully used in several applications such as cranial reconstruction, nasal reconstruction, ear reconstruction, orbital reconstruction and correction of maxillofacial contour deformities and has been shown not to simply fill the defect, but was able to stimulate tissue regeneration by acting as a scaffold for rapid hard and soft tissue ingrowth. In general, it is available as standard shape which needs to be cut and contoured during intra-operation to manually fit the defect of each patient [4]. The purpose of this review was to present the various forms and techniques of porous polyethylene produce in dentistry and was to comparison between the porous polyethylene and other standard bone replacement materials for alveolar ridge reconstruction and to explore the interface mechanical strength among surrounding tissue, alveolar host bone and PPE whether it is enough to supporting the distribution force from oral function such as the denture and the dental implant.

2. Porous implants

Porous implant is a new class of biomaterials that was developed to address the issues that occurred with the dense form of implants which typically have minimal interaction with its surrounding tissue and no direct bond to the tissue would occur when being placed in the body. The porous structure of an implant provides channels for tissue ingrowth and neovascularization which could result in greater degree of tissue integration and in shorter period, when compared to dense materials. This can have the influence on the long-term stability of the implant in the body. All types of materials could be selected and processed into porous implants depending on the intended applications [5]. The success of tissue regeneration of porous implant was found to depend on several parameters including surface chemistry, roughness, pore size, pore interconnectivity, porosity, chemical composition of material and biocompatibility. It was stated that the ideal porous implant should has sufficient mechanical property for supporting and stabilizing new tissue regeneration and has optimally interconnected pore and pore size to provide space for the newly regenerated tissue [6]. The porosity is important since they serve as room for blood vessels and as route of nutrients and metabolic wastes. Porous implant with optimum porosity not only facilitated promote the tissue integration, but also maintaining mechanical properties [7,8]. High porosity allows a better interaction between the host and the implant, which in turn allows capillary vessel formation to occur earlier. Pore size is also the importance characteristics of porous implant for tissue regeneration. Larger pores generally allow faster fibrovascularization, but too large pore size could result in less fibrovascular ingrowth due to insufficient structural support. In general, interconnected pores and porosity greater than 60% are needed for cell migration and sustainable vascularization [9]. The pores size in the range of 100-150 µm was reported for the ingrowth of bone tissue while the pores size below 75 µm would only allow fibrous tissue formation [10, 11]. The pore sizes between 50 and 125 µm exhibited no threshold value for new bone ingrowth under non-load bearing conditions [12]. The importance of interconnecting pores was that it would assist the nutrient and oxygen transportation, vascularization and bone ingrowth deep into the inner area of the porous implant. The increase in tissue penetration into the pores could assist a higher volume of tissue-material interaction and a greater load transfer along the interface to surrounding tissues [13, 14]. It was recommended that interconnected pores size and a porosity in the range 75-100 µm and 40-80 % respectively would be suitable for transporting the nutrient to and removing metabolic waste out from living cell [15]. The mechanical property of porous implant has to be in the similar range to the intended tissue area in order to minimize the risk of implant being loosened by stress shielding [16-18]. Hence, the porous implants with defined biomechanical properties suitable for transferring the load and excellent antifatigue properties to reduce the incidence of implant failure induced by stress fractures are of great importance [19, 20]. It was emphasized that the stress shielding effect resulting from different modulus of material could cause bone resorption in some peri-implant area that are subject to high stress and the use of implants having Young's moduli similar to the surrounding host tissue was recommended [21,22].

3. Porous polyethylene

Polyethylene is a synthetic polymer that has been widely used in various medical applications for example packaging, catheters, tubing drains and artificial joint prostheses [23-25]. It is insoluble in tissue fluids and does not resorb or degenerate when being used as bone and cartilage replacement. Either dense or porous forms could be employed depending upon the final product requirement. Dense polyethylene is preferable where the mechanical performance of the product is needed while the porous form was produced to increase its bioactivity by allowing the ingrowth and integration of the patient's tissue into its pores since it is also known to be nearly bioinert. Their pore sizes directly influenced the rate and amount of bony and fibrovascular ingrowth into the implant [26]. This would lead to the increase in mechanical integrity and stabilization over times. Porous polyethylene implants have shown to be associated with low morbidity rates [27]. Their complication rates were reported to range from 10.3 to 31.8 % depending on the implanted sites [28-30]. Commercial porous polyethylenes are available to be purchased under various trade names in several preformed shape for various applications. The most widely used and studied was Medpor®, but other brands including SynPor® or Biopore were also commercially available.

3.1 Fabrication process

There are several fabrication techniques for porous polyethylene including freeze drying, gas foaming, fiber bonding, particulate leaching and phase separation [31]. The use of particulate leaching technique is mostly used due to its low cost and easy handling of materials [32-34]. Sodium chloride is the most commonly used porogen to produce the pores in the porous implants. The pore size of the construct depended on the size of the porogen and polyethylene used while the porosity depended on the amount of porogen utilized [34]. Typically, polyethylene and sodium chloride particles were thoroughly mixed and heated in the mold at the temperature which was higher than its melting point to molten connect the polyethylene particles in the presence of porogen [35]. The porogen was then extracted from the final samples by leaching in water leaving only the porous polyethylene structure [36]. Recently, modern fabrication technology like three dimensional printing has increasingly been investigated and used to produce implants since the geometries of the implants can be shaped and adapted to fit the defect accurately [37]. The use of 3-dimensional printing has increased the opportunity to customize the implant design to fit each individual patient for both external shape or internal structure and it also could be used as a manufacturing tool. 3DP technique has been successfully employed to fabricate porous polyethylene with thermal treatment and binder leaching by using a low cost & safe water-based binder [34,38, 39].

3.2 Characteristics and properties

Generally, polyethylene is biocompatible polymer and has a high ductility, high toughness and a light weight. Porous polyethylene also has high fracture toughness and ductility which enabling it to be easily fixed with screws or sutures and shaped with a scalpel or power equipment and deformed to fit the contour of the defects without breakage. Its pores are interconnected and the pore size is engineered to range in size from 100 to 200 µm with more than 50% being larger than 150 µm which allows tissue ingrowth or fibro vascular ingrowth [40]. The porosity was reported to be approximately 48 % and its tensile modulus, strength and elongation at break were 122.65 MPa, 3.04 MPa and 26.97 % respectively [41]. Its modulus and strength are sufficient to maintain the porous framework under the handling conditions encountered at the implanted site. The light weight of porous ethylene which came from its low density and high porosity would also reduce the pressure due to the weight of the implant on the supporting tissue and provides better comfort to the patient.

3.3 Current applications of porous polyethylene

Porous polyethylene implant has been successfully used in several applications such as cranial reconstruction, nasal reconstruction, ear reconstruction, orbital reconstruction and correction of maxillofacial contour deformities. The use of porous polyethylene in reconstruction is not only simply replacing the missing part but also stimulate tissue regeneration by acting as a scaffold for tissue regrowth. The light weight property of biomaterial and ability to place the implant deep in the defect contribute to the overall popularity of this implant [42].The use of porous polyethylene in load bearing area was not recommended since it could inevitably lead to implant failure and micromotion at the implant-bone interface. In addition, the use in the area that are exposed to the sinuses could be contaminated with bacteria and become infection.

3.3.1 Otolaryngology

In a prospective study, porous polyethylene was used as dorsal and spreader graft in reconstruction of severe nose deformity with lowest complication rate and without infectious complication and extrusion [43]. Liebelt *et. al.* [44] retrospectively studied 200 medical charts of patients who underwent endonasal transsphenoidal surgery using commercial porous polyethylene and concluded that porous polyethylene implant was safe and the postoperative complication rate was similar to or less than other reconstruction techniques. Moreover, the porous polyethylene implant showed a minimal risk of infection after implantation. Porous polyethylene could also be used in conjunction with other materials. A composite of polyethylene and purified acellular human dermal graft were employed to reconstruct the collapsed dorsum and tip. The aesthetic improvement is coupled with a recovery of function was possible by the strong support offered by porous polyethylene while the cover with acellular dermal graft was done to avoid an abrupt demarcation in the soft tissues of the dorsum along the lateral aspect of the porous polyethylene [45]. Porous polyethylene was reported as the suitable framework material with a temporoparietal flap and full-thickness skin cover for ear reconstruction [46]. It provided better definition and projection while decreased the hospitalization time and surgical interventions in comparison with traditional microtia operations that used rib cartilage.

3.3.2 Neurosurgery

Cranial bone defects could be resulted from several causes including traumatic comminuted or depressed skull fractures, decompressive craniectomy, cranial infection, skull tumors or congenital abnormalities of the skull. A cranioplasty is; thus, needed to be performed for both reconstructive and therapeutic reasons. Cranioplasty was performed in 9 children, average age of 6.8 years old, by using customized porous polyethylene implants to reconstruct large defected area (average 152 cm^2) [47]. The postoperative follow up showed stable wound healing and acceptable cranial contour in all patients were achieved. A cohort study in 100 patients treated for skull base tumors or craniofacial trauma who underwent reconstruction with 156 titanium mesh and/or porous polyethylene implants reported the both materials achieved excellent result in esthetic and functional reconstruction and also early good stability of wound healing [48]. In a larger sample size study, 611 porous polyethylene implants were employed in cranial reconstruction and excellent cosmetic outcomes and no postoperative complication (infection or wound dehiscence) were observed after 4 years follow up [49]. Recently, three dimensionally printed porous polyethylene were utilized for reconstructing cranial defect resulting from trauma, infection, tumors or congenital abnormalities causes [38]. None of the patients showed any complications and these customized implants fitted well with the defects and showed excellent contour restoration. New bone formation from the rim of the defect into the implant was also observed.

3.3.3 Maxillofacial surgery

Porous ethylene implant was reported to be an excellent biomaterial for correcting various maxillofacial deformities due to its versatility and relatively ideal pore size that allows for excellent soft tissue ingrowth and coverage. It was also strong, flexible and easy to shape to fit the contour of the defect. A retrospective review of 21 patients who underwent a temporalis myofascial flap (TMF) transposition by the prefabricated porous polyethylene implants reported both good long-term functional and aesthetic outcomes [50]. Patients with orbital floor fracture were reconstructed with porous polyethylene sheets and good results with few complications were noted [51]. Thirty porous polyethylene implants were implanted in 16 patients who underwent the correction of congenital deformities, posttraumatic defects and aesthetic improvement in nasal, paranasal, malar, chin, mandibular angle, body and orbital areas [52]. The outcomes showed good aesthetic and functional results without signs of discomfort, rejection or exposure. Sixteen patients with facial deformities requiring skeletal defect reconstruction or augmentation was treated with 24 porous polyethylene implants [53]. The excellent soft tissue ingrowth and coverage of porous polyethylene was noted, but the disadvantages were its rigidity and possible palpable extraorally. Generally, the use of porous polyethylene implants in the maxillofacial region was successful with minimal risk and complications. The most frequent complications associated with this material were patient dissatisfaction with the aesthetic results and infection.

3.3.4 Oculoplastic surgery

Ocular or orbital implant is used to replace the eyeball and help maintaining the volume of the eye socket after evisceration or enucleation. It could be made of many materials for example glass, plastic or ceramic and could be a dense and smooth ball or a porous one. Recently, a porous orbital implant is more favorable than a smooth one since it can allow the ingrowth of tissue and lower the complication and adverse event resulting from implant migration and extrusion [54]. Common materials that have been used for porous ocular implants are hydroxyapatite, alumina, and high density polyethylene. Porous polyethylene has several benefits in this application as no wrapping material is needed and the extraocular muscles can be sutured directly to the implant. Many studies have demonstrated that fibrovascular tissue ingrowth occurs from adjacent tissue into the porous polyethylene from the periphery area toward the center of the implant [55-57]. Porous polyethylene orbital implant fabricated by three dimensional printing technique having a spherical shape was used in approximately 70 patients [39]. All patients showed natural appearance and nearly normal function of eyeball with low complication rates. After 6 months follow up, the average tissue ingrowth percentage was approximately 57 %.

3.3.5 Dental surgery

With the advancements in the field of dentoalveolar reconstruction, the repairing and maintaining the normal anatomy of alveolar bone could be performed to reduce the bone defect space, restore aesthetic and prepare the site for dental implant placement [58]. In a retrospective study, individualized porous polyethylene implants was employed in patients to reconstruct the mandibular contour with the aid of computer-aided design/computer-aided manufacturing (CAD/CAM) in 12 patients with mandibular contour deformities [59]. Satisfactory facial contour was achieved post-operatively in all patients, but delayed infection was seen in one case.

Titanium reinforced porous polyethylene was employed as a space maintainer device or barrier for bone morphogenetic protein (rhBMP-2) grafted alveolar defects in 8 patients [60]. Early exposure of the barrier was found in 2 defects and the barrier had to be removed which resulting in the no bone regeneration. One barrier became exposed 3 months postoperatively and moderate bone formation was observed. In seven nonexposed cases, bone formation was excellent and dental implants were successfully placed. Bi-layered porous polyethylene membrane was developed and used in conjunction with allograft in guided bone regeneration (GBR) to reconstruct posterior mandibular ridge defects prior to implant installation in 15 patients [61]. The vertical bone high mean increased 0.9 mm up to 8.3 mm and gained maximum bone width up to 4.8 mm after augmentation. The complications were seen in early wound healing such as minor local infection, membrane exposure/extrusion, mini-screw loosening and extrusion and mild paresthesia, however; soft and hard tissue healing after implant installation was achieved in all the patients.

4. The possible use of porous polyethylene in alveolar bone augmentation

Alveolar bone defect or inadequate bone volume could be resulted from any causes such as periodontal diseases, tooth extraction and traumatic or infection of tooth. Since the placement of dental implant needed sufficient bone bed both in terms of bone quality and quantity, augmentation of alveolar bone defect would be performed to regain or restore the volume and the contour of the bone prior to dental implant placement. Bone grafting by using various types of materials is the most frequently technique that was employed. Currently, autologous bone graft is still the first of choice for alveolar bone regeneration since it contained both osteoinductive and osteoconductive properties required for efficient new bone formation. Allogeneic graft which originates from living donors or cadaveric bone and xenograft could be used and do not require an additional surgery for harvesting. However, donor site morbidity associated with autologous graft harvest and a risk of immunogenic reaction and infectious diseases transmission of allograft and xenograft led to the increasingly use of alloplastic bone graft materials. Hydroxyapatite and biphasic hydroxyapatite/tricalcium phosphate bioceramics are widely used alloplastic grafts due to their good bioactivity and osteoconductive. However, their main drawbacks are brittleness, poorly defined ridge and the displacement to undesirable location and exposure from submucosal to oral cavity [62,63].

In general, bone grafts used could be in either block form or granular form depending on the defect size, shape and location [64]. Large volume vertical augmentations of the alveolar ridge typically required the use of bone blocks to provide sufficient gain in height which could not be achieved well by using granular graft. For smaller volume augmentation, granular bone graft of various origin could be used and expected to perform reliably well similarly to the use of block graft [65]. The block graft should provide strong structural support within the first 6 weeks after implantation and should be stabilized to achieve an intimate contact to the recipient bed with rigid fixation to avoid bone grafts displacement [66]. Although the natural origin block graft either autograft, allograft or xenograft could be well utilized and rigidly fixed during a healing process, they were prone to fracture and resorb [67, 68]. The use of hydroxyapatite and biphasic HA/tricalcium phosphate block graft, especially in the porous form, was possibly used, but their brittleness nature could result in the breakage during rigid fixation or during healing phase. Moreover, they were hard to shaped into desired shape for properly fitting to the alveolar defect [69].

Porous polyethylene implant has been successfully used in both hard and soft tissue regeneration applications due to its biocompatibility, stability and porous structure that allows tissue ingrowth of host tissues to promote strong anchorage to its implantation site. Currently, the intraoral use of porous polyethylene implant was still limited and it was recently employed as only a bone graft containment for ridge preservation, not a tissue regenerated implant. It was; thus, hypothesized whether porous polyethylene could possibly be employed as a bone graft block for alveolar defect or not. Due to its stable nature, limited resorption would occur in comparison to natural origin block grafts. Unlike bioceramic block graft, porous polyethylene has a much higher fracture toughness and ductility which enabling it to be shaped and deformed to fit the contour of the defects without breakage. It could also be screwed, sutured or fixed by any rigid fixation techniques which were necessitated requirements for block graft. In a preclinical study, porous polyethylene rods which were implanted into the femurs of mongrel dogs was capable to induce bone growth into its pores even as small as 40 μm although the optimum pore size for bone ingrowth was in the range of 100 to 135 μm [70]. Degree of fibrovascular ingrowth into the porous polyethylene orbital implants at 4 weeks after implantation in rabbits ranged between 54.9%-92.0% depending on the types of growth factor treatments of the porous polyethylene [56]. Various sophisticated strategies were also experimentally developed to increase vascularization and tissue incorporation to prevent complications, such as material infection, migration and extrusion [71]. Several clinical studies reported in Table 1 also show good outcome and proves of tissue regeneration and ingrowth capability of porous polyethylene. Recently, the concept of using porous polyethylene block for alveolar defect regeneration was demonstrated preclinically as an onlay block graft in a rabbit mode [72]. Porous polyethylene block was fixed directly on the buccal body of the mandible with a titanium screw and covered with a collagen membrane. The histologic and histomorphometric analyses showed the ingrowth of both fibrovascular tissue and new bone at both the interface and the volume deep inside the center of the porous polyethylene even the bone bed was not decorticated to provide the vascular supply and placed the graft in direct contact with mesenchymal stem cells, osteogenic cells and neovascularization cells together with osteoinducing and osteogenic factors presented in the blood. The osteoconductive and osteogenic properties of porous polyethylene were observed within and outside the contact interface. Stable interfacial integration between the porous polyethylene graft and mandibular bone was also noted. This obviously proved the efficacy of bone regeneration and stimulation of porous polyethylene in such only block regeneration and the possibility of its use for alveolar defect regeneration. However, further studies are still needed to evaluate and ascertain the performance of porous polyethylene for being used as a bone block graft in actual clinical situation.

Table 1 Tissue regeneration and ingrowth of porous polyethylene in clinical reports

Sample size	Locations	Outcomes	Tissue regeneration	References
70 patients	Ocular implants	Normal shapes of eyeballs were restored and the appearances of the natural eyes were regained.	Fibrovascular ingrowth into porous orbital implant with MRI. Soft tissue ingrowth. Average ingrowth percentage at 6 months postoperatively was 57 %.	[39]
16 patients (24 implants)	Facial deformities	Significant improvement in facial esthetic.	Good soft tissue ingrowth and coverage by observation.	[53]
12 patients	Ocular implants	N.A.	Fibrovascular ingrowth into porous orbital implant with MRI. Homogeneous enhancement (n=4), peripheral and posterior part enhancement (n=7), and anterior part enhancement (n=1) of implants.	[57]
19 patients	Cranioplasty	Excellent contour restoration	Bone ingrowth with CT. Ingrowth of bone density materials from the rim of the defect and they increased with follow up periods.	[38]
10 patients	Cranioplasty	Excellent contour restoration	Soft and hard tissue ingrowth with CT. Increase in the HF units of the implant, particularly at the marginal areas. Indirect evidence for the ingrowth of vascularity, soft tissue and bone from bony edge area.	[73]

5. Conclusion

Porous polyethylene is a frequently used implant in various soft tissue and hard tissue reconstruction and augmentation. Its rapid vascularization and tissue integration are major advantages contributing to its long-term stability and low complications. Its high ductility and high toughness were also advantageous for shape modification and fixation by several techniques. In addition, the pressure due to the weight of the implant on the underlying tissue was low due to its low density which would provide a comfort to the patient. Currently, the use of porous polyethylene in intraoral applications was still scarce. By reviewing and analyzing previous studies, it was hypothesized and discussed in this study that there was a reasonable possibility for using porous polyethylene as an implant block for alveolar defect regeneration prior to dental implant placement due to the benefits which have already been shown in other applications. However further well-designed studies and clinical trials are needed to reach a definitive conclusion.

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