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Compressive Properties of Commercially Available PVC Foams Intended for Use as Mechanical Models for Human Cancellous Bone

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Abstract: Compressive properties of three commercially available rigid polyvinyl chloride (PVC) foams intended for use as possible model material for human cancellous bone were investigated. Quasi-static compression tests were performed on PVC foam blocks of different densities (0.10, 0.13 and 0.20 g/cm^3) with a crosshead speed of 0.15 mm/sec to determine the compressive Young's modulus, the yield strength and the energy absorbed until yield. The results were compared with data obtained on human cancellous bone and polyurethane (PUR) foams. Results showed that according to their Young's modulus and yield strength the investigated 0.1 and 0.13 g/cm^3 PVC foams are suitable as mechanical model material for Osteoporotic cancellous bone, while 0.20 g/cm^3 PVC foam is suitable as model material for normal bone. According to the energy absorbed until yield the 0.10 g/cm^3 PVC foams are suitable as mechanical model material for Osteoporotic(OP) cancellous bone. For the modeling of normal bone both the 0.13 and 0.20 g/cm^3 PVC foams are suitable. Based on these results, it can be concluded that the examined PVC foams may prove suitable as a model material for OP and normal cancellous bone.

Keywords: PVC foam; compressive properties; synthetic bone; human cancellous bone; Osteoporotic bone; cross-linking

1 Introduction

Cadaveric bone tissue is widely used for biomechanical tests and in medical implant-related research. Biological samples have a high variance in mechanical properties, caused by age, weight, sex and physical characteristics. This complicates the comparative testing of medical implants, and requires a higher number of test specimens. To reduce the high variance of properties between test specimens, the samples must be carefully selected. For these reasons the comparability and reproducibility of the results achieved often demands a larger number of test specimens. Comparative testing of orthopedic implants in human cadavers is very limited not only because of biological but of ethical, and economical reasons, too [1-4].

Animal models provide a possible solution for biomedical research, since the healing of fractures and bone defect repair can be investigated. The use of living animal models have been disputed over the last 150 years. Animal models are simplified representations of the actual system of interest; they possess the same or similar functions and structures as the system under study. Biomedical studies using animal models may offer advantages over human cadavers, since the models are often simpler to control and manipulate, and ethical concerns may be less troublesome to address. The number of test specimens must still be large for reasons of comparability and reproducibility. When selecting an animal model bone phenotype, cross-species biomechanical properties should also be considered. Since there are no established standards, and there is a wide variety of bone shapes and sizes, a large number of variables must be considered when establishing mechanical testing procedures. The need for control groups, the care of animals etc. make animal models expensive, and should only be used when studying biological processes in the body. Because of these considerations, it is desirable to refine and reduce the use of animals and to find alternative models [5-8].

Synthetic materials offer a wide range of possibilities as bone model materials. The major advantage of synthetic materials is that they can be engineered to meet certain requirements, and will have constant material properties. The cellular structure of foams resembles that of cancellous bone and their mechanical properties like strength and stiffness are also similar to those of cancellous bone. They provide an uncontaminated, clean test environment, which makes them the ideal choice when biological processes in the body are not part of the research. For this reason they can be used effectively in the development of bone fixating implants, since the measurement results are not affected by the biological diversity of even one species. Biomechanical measurements performed with the help of synthetic materials are easy to control, repeat and compare [6, 9].

Synthetic whole bones are widely used for the testing of fracture reconstruction systems in cases when anatomic correspondence is of concern. Such systems are used for example in the reconstruction of human long bones, spine and vertebra. Heier et al. compared replicate femurs and tibias made of short-glass-fiber-reinforced (SGFR) epoxy, and fiberglass-fabric-reinforced (FFR) epoxy to model human femurs under bending, axial, and torsional loads [10]. Sommers et al. studied an osteoporotic long-bone model and validated surrogate models for normal bone. They found that validated surrogate models for osteoporotic bone were also needed because of the differences between the two models [11]. Johnson et al. prepared synthetic thoracic vertebrae from open-cell rigid foam to study their morphological and mechanical (static, dynamic) properties. Their research showed that synthetic open-cell foam vertebrae with a fiberglass resin cortex offers an alternative to human vertebral bone in static and dynamic biomechanical experiments [12]. Wähnert et al. prepared a distal femur model from 0.15 g/cm^3 density PUR foam to model osteoporotic bone. Their results showed that their method for customizing artificial bones could provide suitable results, although it disregarded cortical bone [13].

The whole bone model is not always in *in vitro* biomechanical tests, in most cases it is enough to use a part of the bone (eg. only the femoral head instead of the whole femur). In practice, several materials have been used as model material for bones. Filled epoxy resins, glass or carbon fiber composites, or solid polyurethane (PUR) are all used to substitute cortical bone [9]. For the modeling of cancellous bone mostly rigid or semi-rigid porous polymeric foams are used. Szivek et al. studied several PUR mixtures for the substitution of cellular bone. They measured the elastic modulus, yield and compressive strength of different, closed cell PUR foams, and concluded that with appropriate ratios of isocyanate to polyol a porous bone-like foam structure can be achieved. The mechanical properties of such foams are reproducible and could resemble those of human bone [14-15]. Thompson et al. studied under torsion and axial loading the shear and compressive properties of four types of rigid polyurethane foams, which are sold for biomechanical tests. They concluded that these foams may be used to simulate the elastic but not the failure properties of cancellous bone [16]. Shepherd et al. compared the compressive properties of three kinds of PUR foam to that of normal and osteoporotic human bone. In their study they measured the Young's modulus (E), yield strength (σ_y) and energy absorbed utill yield (ΔE_y) of the studied foams. They concluded that the 0.16 g/cm^3 foam could substitute osteoporotic human bones during *in vitro* testing of biomedical implants in cases when fracture stress is of concern. The 0.32 g/cm^3 foam could substitute normal human bones in the same situation. Furthermore, neither of the studied PUR foams should be used when energy dissipation or fatigue is of concern [17]. Although PUR foams are widely used as bone model material, Shikimani et al. used polycarbonate (PC) plates and compared their results with measurements made on the mandibular bone of dogs [18-19]. Palissery et al. studied cross-linked, closed-cell PVC foam as the potential model material for cancellous bone for *in vitro* biomechanical tests of orthopedic devices. In their work, they studied the cyclic tension and compression behavior of the PVC foam applying 1/3 of the ultimate strength in each cycle. In their work they concluded that the performance of PVC foam during tension and compression testing is qualitatively similar to that of cancellous bone. Furthermore, bone model material should be selected based not only on similar static behavior, but also on similar compression/tension strength ratio and similar fatigue properties as well, particularly with respect to material property degradation [20].

The aim of this paper was to determine whether PVC foams could also be suitable for the mechanical modeling of normal and OP bone. Suitability was determined by the method developed by Li and Aspden [21] for the comparison of cancellous bone of patients with osteoporosis or osteoarthritis. Li and Aspden compared the Young's modulus, yield strength, and energy absorbed until yield as a function of the density of the studied bone samples. Shepherd et al. [17] used the same method in their study on commercially available PUR foams used as a mechanical model for OP human bones. We used this method since both Shepherd and Apsden used the same method during their research, which enables us to compare our result not only to human bone, but also to PUR. Determining such mechanical properties may help us to select the relevant PVC foams as appropriate models in studies about the mechanical evaluation of implant performance.

2 Methods and Materials

2.1 Materials

Closed-cell, cross-linked PVC foams with a density of 0.10, 0.13 and 0.20 g/cm^3 were examined in this study. The results were compared with those of PUR foams of a density of 0.09, 0.16 and 0.20 g/cm^3 studied by Shepherd et al [17] and human bones studied by Li and Aspden [21]. The mechanical properties of the PVC foams used for this study and those of the PUR foams used by Shepherd are listed in Table 1, as provided by the manufacturer. Shepherd used the 0.16 and 0.20 g/cm^3 PUR foams to model low and medium density cancellous bone, and the open-cell rigid 0.09 g/cm^3 PUR foam to model very low density cancellous bone. To facilitate comparison, the PVC foams were selected to have similar density, compressive and tensile strength to the PUR foams studied by Shepherd. All PVC foams were delivered by Alcan Airex AG free of charge for research purposes in block form, with dimensions of 400×800×30 mm.

Table 1
Material properties as provided by the manufacturers

Foam	Material	Density [g/cm^3]	Compressive strength [MPa]	Young's modulus [MPa]	Tensile strength [MPa]
Sawbones®	PUR	0.09	0.6	16	1.0
Sawbones®	PUR	0.16	2.2	58	2.1
Sawbones®	PUR	0.32	8.4	210	5.6
AIREX® C70.90	PVC	0.10	1.9	125	2.7
AIREX® C70.130	PVC	0.13	2.8	170	3.8
AIREX® C70.200	PVC	0.20	5.2	280	6.0

Using a fine saw blade on a jigsaw machine, cube-shaped specimens were machined with nominal dimensions of 10×10×10 mm. The size of each specimen was measured and recorded with a Mitutuyo Digimatic digital caliper and the actual dimensions of the specimens were used for calculation. Six blocks were prepared from each PVC foam.

2.1 Method

The quasi-static unconstrained compression tests were conducted on a Zwick Z005 materials testing machine fitted with a load cell of 1000 N, and a self-aligning compression plate (Fig. 1). The use of a self-aligning compression plate was necessary so that the compression would be uniaxial and no buckling of the specimens would occur because of shape inaccuracies.

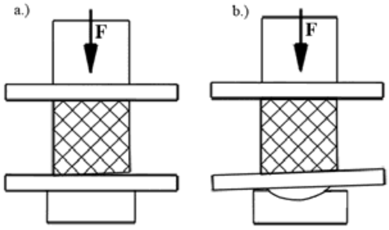

Figure 1
Measurement setup: a) Parallel plate, b) Self-aligning compression plate

Engineering stress was calculated with formula 1.

$$\sigma(x) = \frac{F(x)}{A_0}, \tag{1}$$

where *σ(x)* is the engineering stress [MPa] as a function of the crosshead displacement *(x)* of the machine, *F(x)* is the force [N] recorded by the load cell as a function of the crosshead displacement of the machine and A_0 is the original cross-sectional area [mm^2] of the PVC foam block. In order to simplify the evaluation process, a fifth grade polynomial was fitted to the results of the stress-strain curve. This polynomial was used for the calculation of the absorbed energy and the first derivative needed for the calculation of the Young modulus. formula 2 is the typical form of a fifth grade polynomial.

$$\sigma(x) = C_5 x^5 \pm C_4 x^4 \pm C_3 x^3 \pm C_2 x^2 \pm C_1 x \pm C_0, \tag{2}$$

where *x* is the crosshead displacement in [mm]. C_i-s are the constants specific to each measured foam block, where *i={0, 1 , 2 , 3 , 4 , 5}*.

The engineering strain was calculated by dividing the displacement of the machine crosshead (at each data point) by the initial height of the PVC foam block (formula 3.)

$$\varepsilon = \frac{\Delta h}{h_0} \tag{3}$$

where *ε* is the engineering strain [%], *Δh* is the displacement [mm] of the machine crosshead and h_0 is the initial height [mm] of the PVC foam block.

The yield strength was calculated according to the method described by Li and Apsden [21] and used by Shephard et al. [17] for the study of commercially available PUR foams as mechanical model material for OP human bones. Li and Apsden defined the yield strength as the stress at which Young's modulus is reduced to 97% of its original value. In this work, the yield strength was calculated according to formula 4.

$$\sigma_y = \sigma(x = \varepsilon_y) \tag{4}$$

where σ_y is the yield strength [MPa], ε_y is the strain at yield.

Young's modulus was calculated with formula 5.

$$E(x) = \sigma'(x) \tag{5}$$

where $E(x)$ is Young's modulus [MPa] as a function of the crosshead displacement, $\sigma'(x)$ is the first derivative of the stress-strain curve as a function of the crosshead displacement of the machine.

The energy absorbed until yield was calculated by integrating the polynomial equation of the engineering stress-strain curve between the limit of zero and the strain point at which the yield strength was determined (Eq. 6).

$$\Delta E_y = \int_0^{\varepsilon_y} \sigma(x)dx \tag{6}$$

where ΔE_y is the energy absorbed until yield [kJ/m^3], ε_y is the strain at yield, and $\sigma(x)$ is the fifth grade polynomial fitted to the stress-strain curve.

3 Results and Discussion

Six cube-shaped specimens were machined with nominal dimensions of 10×10×10 mm from each studied PVC foam. The size of each specimen was measured and recorded and in the evaluation of the measurements the actual size of the specimens were used for calculation. Statistical comparisons were made using a two-sample t-test with a significance level set at 0.05.

Results

Figure 2 shows two characteristic stress-strain and modulus-strain curves from the compression testing of two PVC foam blocks. Figure 2a shows the characteristic stress-strain curves of a 0.20 g/cm^3 and 0.10 g/cm^3 density foam blocks. The expression for Young's modulus of the material is given by the gradient of the curve. Figure 2b shows Young's modulus as a function of the strain. Young's modulus was determined as the maximum value of the curve in Figure 2b. The yield point was defined as the stress at the end of the peak region, when Young's modulus is reduced by 3%.

Figure 2a and 2b have the same strain axes to allow easy comparison. The curves on the figure are typical of those obtained in this study. The energy absorbed until yield is the area under the stress-strain curve up to the yield point (hatched area on Figure 2a for the 0.20 g/cm^3 density PVC foam).

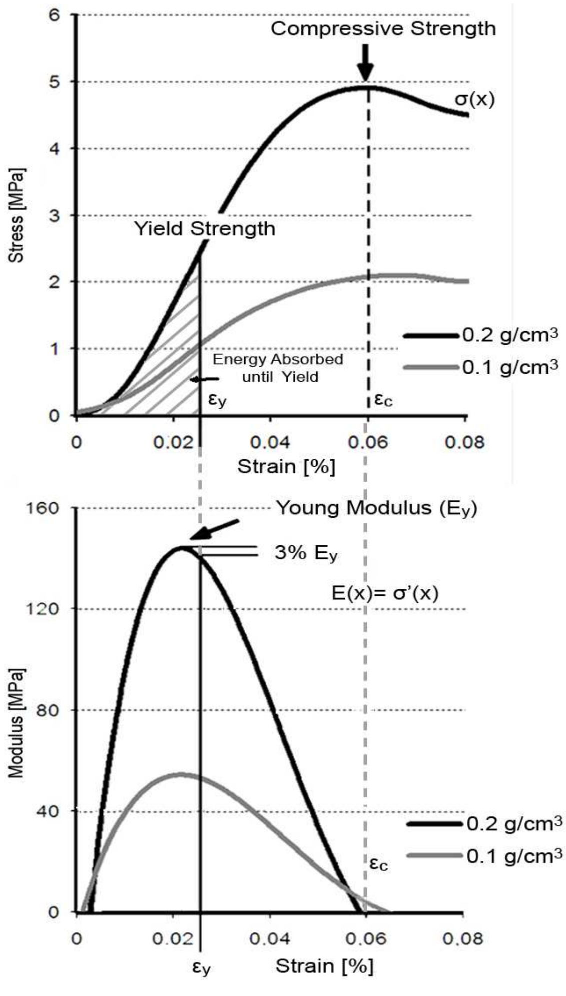

Figure 2

Characteristic Stress-strain and Young's modulus curves of high and low density PVC foams. (a) Stress-strain curves of low and high density PVC foams, (b) Young's modulus determined as the gradient of the curve. The yield point is defined as the point at which Young's modulus decreases to 97% of its maximum value. The area under the stress-strain curve up to the yield point is defined as the energy absorbed until yield.

Table 2 summarizes the results for the three studied PVC foams and compares their values with those obtained by Shepherd et al. and Li and Apsden. The values compared are Young's modulus, yield strength and energy absorbed until yield.

Table 2
Compression testing results of human bone, PUR and PVC foams.
Results of foams are given as mean± standard deviation. The results for bones are given as mean and min-max of measurement range.

	Material	Young's modulus [MPa]	Yield strength [MPa]	Energy absorbed until yield [kJ/m^3]
Shepherd et al. [16]	0.09 g/cm^3 PUR	0.7±0.2	0.03±0.01	1.0±0.5
	0.16 g/cm^3 PUR	42.0±3.0	1.1±0.1	10.0±3.0
	0.32 g/cm^3 PUR	146±6	3.7±0.9	30.0±6.0
Aspden and Li [21]	OP bone	247 (50-410)	2.5 (0.6-5.8)	16.3 (2-52)
	Normal bone	310 (40-460)	3.3 (0.4-9.0)	21.8 (2-90)
Our results	0.10 g/cm^3 PVC	53.7±5.0	1.3±0.1	17.8±1.5
	0.13 g/cm^3 PVC	66.4±5.1	2.2±0.1	42.4±6.0
	0.20 g/cm^3 PVC	123.2±14.9	3.0±0.1	41.2±11.4

Discussion

The purpose of the study was to determine whether closed-cell, cross-linked PVC foams could be suitable for the mechanical modeling of normal and OP bone. The method used was first published by Li and Aspden for the comparison of cancellous bone of patients with osteoporosis or osteoarthritis [21]. Shepherd et al. used the same method in their study on commercially available PUR foams as mechanical model materials for OP human bones [17]. Using exactly the same method as Li and Aspden, and Shepherd et al. provides a unique opportunity to compare the studied mechanical properties of human bone, PUR and PVC foams. Such comparative studies for different bone model materials are extremely rare, since different research groups use different methods for the validation of their material.

The 0.10 g/cm^3 PVC foam was used to model very low density cancellous bone the same way as the 0.09 g/cm^3 PUR foam studied by Shepherd et al. The PVC foam is much stronger than the PUR foam, and the results suggest that it could model severely osteoporotic bones. The Young's modulus of this material is close to the lower limit of the modulus of the OP bone. The yield strength is one-half of the average value for osteoporotic bone, but it is within the limits measured by Aspden and Li. The lightest foam's absorbed energy until yield is practically equal to that of the OP bone. According to these results the lowest density closed-cell, cross-linked, PVC foam studied in this paper is suitable as a mechanical model material for severely osteoporotic cancellous bone.

In terms of yield strength and Young's modulus, the 0.13 g/cm^3 PVC foam is a more suitable model material for osteoporotic cancellous bone than the 0.10 g/cm^3 PVC foam. In contrast to the 0.10 g/cm^3 density PVC foam and the 0.16 g/cm^3 PUR material studied by Shepherd et al., the yield strength of this PVC foam matches that of the osteoporotic human cancellous bone, although its Young's modulus is still at the lower end of the range of human osteoporotic bone's Young's modulus.

The results for the 0.20 g/cm^3 PVC foam quantitatively match those for the 0.32 g/cm^3 PUR material, and those for normal human bone. This makes it a suitable material for the modeling of normal human cancellous bone during *in vitro* biomechanical tests.

Previous papers used different methods to study possible substitute materials for human cancellous bone during *in vitro* biomechanical tests. Fatigue tests on rigid PUR foams showed that these materials do not model the behavior of cancellous bone precisely under dynamic and cyclic loading [9, 22]. Fresh animal and human bone (both cortical and cancelous) have viscoelastic properties that make their properties and behavior unique [23-25]. PVC foams have also displayed such properties, which could make them a better model material for trabecular bone during *in vitro* biomechanical tests [20, 26, 27].

The results of this paper indicate that cross-linked, closed-cell PVC foams could be more suitable for the modeling of human cancellous bone than currently used PUR foams. Based on Young's modulus, yield strength and energy absorbed until yield, they represent human cancellous bone better than PUR foams. Their viscoelastic, and energy absorbing properties also make them a more suitable material for the modeling of cancellous bone.

The different test specimen geometry used in our study does not affect the properties measured since these were calculated from the original cross section of the specimens. Furthermore, our test specimens and those of Aspden et al. and Shepherd et al. have comparable dimensions and cross section/height aspect ratios. Keaveny et al., and Pilkey et al. showed in their works that much higher cross section/height aspect ratio is needed for a significant difference in measurement results [28, 29].

In this paper we compared the Young's modulus, yield strength and energy absorbed until yield of three cross-linked, solid, closed-cell PVC foams, with those of rigid closed-cell and open-cell PUR foams, and osteoporotic and normal density bones. Our results indicate that further comparative research would be needed on these materials. Not only compressive but bending and tensile tests would be needed, and fatigue behavior should also be compared under different loads. Any similarities found between the mechanical properties of PVC foam and cancellous bone would strengthen the case that PVC foams are suitable as a human cancellous bone model.

Conclusions

From the results of the above-mentioned and discussed measurements, the following conclusions can be drawn:

- The investigated cross-linked, rigid cellular PVC foams are adequate model materials for osteoporotic and normal cancellous human bone.
- Based on Young's modulus and yield strength, the investigated 0.1 and 0.13 g/cm^3 PVC foams are suitable as mechanical model materials for osteoporotic cancellous bone.
- Based on Young's modulus and yield strength, the investigated 0.20 g/cm^3 PVC foam is suitable as a model material for normal bone.
- Based on energy absorbed until yield, the 0.10 g/cm^3 PVC foam is a suitable mechanical model material for osteoporotic cancellous bone. For the modeling of normal bone, both the 0.13 and 0.20 g/cm^3 PVC foams are suitable.

In summary, it can be concluded that according to the results of this research, cross-linked closed-cell rigid PVC foams are suitable as mechanical model materials for human cancellous bone.

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