Original paper

Comparison of the tensile modulus of three 3D-printable materials used in dentistry

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Abstract

Background. Three-dimensional (3D) printing technology has brought much innovation to medicine and has been successfully adopted in many areas of dentistry. Although 3D printing techniques are being increasingly used, their advantages and disadvantages still need to be investigated, particularly with regard to the materials used in dentistry. Dental materials should be biocompatible and non-cytotoxic, and have sufficient mechanical integrity in the oral environment in which they are intended for use.

Objectives. The present work aimed to identify and compare the mechanical properties of three 3D-printable resins. The materials included IBT Resin, BioMed Amber Resin and Dental LT Clear Resin. The Formlabs Form 2 printer was used.

Material and methods. A tensile strength test was performed on 10 specimens of each resin. Tensile modulus was measured on 2-millimeter-thick dumbbell-shaped specimens, 75 mm in length and 10 mm in width. The 10 specimens of each resin were mounted between the grips of a universal testing machine (Z10-X700).

Results. The results showed that BioMed Amber specimens cracked easily, yet no deformation was observed. The amount of force used to test the tensility of the specimens was the lowest for IBT Resin, while it was the highest for Dental LT Clear Resin.

Conclusions. IBT Resin was the weakest material, whereas Dental Clear LT Resin was the strongest.

Keywords: dentistry, 3D printing, resins, tensile modulus

Introduction

Three-dimensional (3D) printing is becoming more and more popular in today's world, including the fields of medicine and dentistry. In dentistry, it has been applied for preparing prosthetic devices and conservative restorations. It also finds a use in other branches of dentistry, e.g., for manufacturing surgical guides, anatomical models and custom-made parts. The high print precision allows the development of perfectly fitting elements that are needed to restore the tissues. Although printable materials and traditional ones have similar properties, the former help to reduce chair time. The greatest disadvantage of this technology is its high total cost, as additional scanners and printers are needed.[1]

Although the 3D printing technology is developing quickly, some limitations are present, and the need for improvement is high. The search for an ideal restoration material is based on comparing various materials, especially in terms of their biocompatibility and resistance to general conditions. Esthetics is also taken into account.[2–4]

More advanced techniques, such as surgical planning, involve cone-beam computed tomography (CBCT) scanning. The most common procedure aided by 3D printing and CBCT is the preparation of surgical guides for the insertion of implants and orthodontic mini-implants. These guides help to find a precise implantation route, thus reducing the risk of tooth root damage, especially when there is little space between the roots.[1,5,6] The scan precision depends on the skills of the operator. With respect to the place of the tooth in the arch, more precise guides can be obtained at the buccal segments of the arch, as for premolars and molars, scanning is highly accurate. In the case of incisors, the scanner may fail to recognize their surfaces, as they are less characteristic as compared to other teeth.[7,8] Nonetheless, the advantages of using surgical guides outbalance the risk of potential complications and failure.

Apart from their use as an aid in surgical procedures, dental scans are performed to prepare casts for prosthodontic and conservative restorations.[9,10] The copings and frameworks for tooth restorations which are prepared with the use of highly precise special software perfectly fit the anatomical space.[11] Such techniques are termed computer-aided design/computer-aided manufacturing (CAD/CAM).[12] Although 3D printing is very common in surgery, prosthodontics and conservative dentistry, its applications are far more extensive. In orthodontics, 3D printing is most commonly used for preparing aligners and orthodontic trays for indirect bracket bonding. The techniques can also be used for manufacturing other customized items, such as occlusal splints and Michigan splints.[13] Other types of appliances can also be printed, including very precise items, like distalizers, or individual appliances used in more severe cases, such as palatal plates or obturators for cleft lip and/or palate patients.[14,15]

3D-printable materials appear to be appropriate for use. However, since they are exposed to oral cavity conditions for a long period of time, many factors, including food, beverages, as well as compressive and tensile forces, influence their properties, which should be considered before treatment planning. Indeed, external factors may lead to unfavorable changes in the properties of the materials, such as color fading or darkening, decreased hardness, and hence decreased resistance to breaking.[4,16–18] This issue is of utmost importance when considering dental restorations, but also when the long-term wear of splints is taken into account. As the reaction of the material to external conditions may change its properties, it may also affect its usage.[17–19] Moreover, it turns out that one change may evoke another, e.g., the color change correlates with changes in the microhardness, roughness and texture of the material.[18,20]

Among the producers of 3D-printable materials, Formlabs has found its place as a manufacturer of biocompatible resins. Their materials include IBT Resin, BioMed Amber Resin and Dental LT Clear Resin, which are novel and commonly used. According to the manufacturer, the transparent resins BioMed Amber and Dental LT Clear are strong, rigid and biocompatible. BioMed Amber has a yellowish glow, while Dental LT Clear is highly esthetic. BioMed Amber consists of several chemical compounds, including 7,7,9(or 7,9,9)-trimethyl-4,13-dioxo-3,14-dioxa-5,12-diazahexadecane-1,16-diyl bismethacrylate, 2-hydroxyethyl methacrylate and phenyl bis(2,4,6-trimethylbenzoyl)-phosphine oxide. The chemical composition of Dental LT Clear is more complex, and comprises 7,7,9(or 7,9,9)-trimethyl-4,13-dioxo-3,14-dioxa-5,12-diazahexadecane-1,16-diyl bismethacrylate, 2-hydroxyethyl methacrylate (Note D), reaction mass of bis(1,2,2,6,6-pentamethyl-4-piperidyl) sebacate, methyl 1,2,2,6,6-pentamethyl-4-piperidyl sebacate, diphenyl(2,4,6- trimethylbenzoyl)phosphine oxide, acrylic acid, monoester with propane-1,2-diol, ethylene dimethacrylate, 2-hydroxyethyl acrylate, mequinol, 4-methoxyphenol, and hydroquinone monomethyl ether. The properties of the third resin (IBT) differ – it is elastic and flexible, although transparency and translucency remain. The IBT has optimized tear strength.[17,21]

The present study aimed to compare the behavior of 3 materials designed for medical use by subjecting them to pressure and tension tests to increase knowledge of 3D-printable materials. Such comparison of biomechanical properties is not a commonly discussed issue. The current study is part of a series of papers prepared previously by the authors.[17,21]

Material and methods

The study compared 3 selected materials 3D-printed with the use of the Formlabs Form 2 printer (Formlabs, Sommerville, USA), which is dedicated for medical purposes. The examined materials were IBT Resin (Formlabs), BioMed Amber Resin (Formlabs) and Dental Clear LT Resin (Vertex-Dental, Soesterberg, the Netherlands). All of them are designed for medical uses, mainly in dentistry, though the literature on them is poor as compared to other dental materials. Therefore, the authors of this study decided to plan and present novel research, comparing the 3 resins recently introduced for use in dentistry.

Table 1 summarizes the manufacturers' recommendations regarding the applications of the selected dental resins.

The Formlabs Form 2 printer is self-adjustable, and all printing parameters were built into a chip in the resin container. All prints were performed using a Class 1 405-nm violet laser (250 mW) at a temperature of 35°C. The printing layer thickness was 100 µ for all resins. Printing was conducted according to the manufacturers' specifications and printer settings.

A tensile strength test was conducted for the printed specimens, with tensile modulus measured on 2-millimeter-thick dumbbell-shaped samples of 75 mm in length and 10 mm in width (type 1BA), following the ISO 527-2:2012 standard[22] (Fig. 1). The samples were air-incubated at 23°C and 50% relative humidity (RH) for 24 h after printing. Then, their height, width and length were measured at 5 points with the use of a Magnusson Vernier digital caliper (Limit, Wroclaw, Poland). The mean values were calculated. Subsequently, the specimens were mounted between the grips of a universal testing machine (Z10-X700; AML Instruments, Lincoln, UK). The test was performed at a speed of 5 mm/min, and the force was measured until each specimen broke. Only the section between the widened parts of the sample was tested, and specimens that broke outside of this area were discarded.

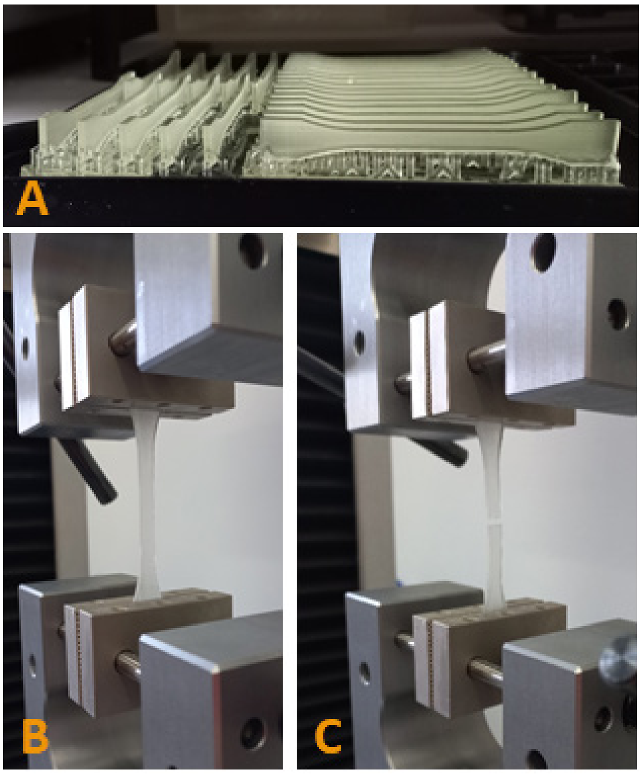

Fig. 1. Tensile strength test

A – set of specimens after printing; B – finished specimen mounted between the grips before the application of a tensile force; C – specimen broken by a tensile force.

Table 1. Brief description of the applications of the selected 3D-printable resins, recommended by the manufacturers

Resin	Applications
Dental LT Clear Resin	long-term biocompatible resin ideal for hard splints, occlusal guards, and other direct-printed long-term orthodontic appliances
BioMed Amber Resin	biocompatible applications requiring short-term skin or mucosal membrane contact; suitable for strong, rigid parts, such as functioning threads, end-use medical devices, cut + drill guides, implant-sizing models, and specimen collection kits
IBT Resin	ideal for manufacturing indirect bonding trays for a cost-effective, rapid dental bracket placement process for high-quality orthodontics

Tensile stress and nominal strain were calculated according to the following formulas (Equations 1,2):

$$\sigma = \frac{F}{A} \tag{1}$$

where:
σ – tensile stress [MPa];
F – force [N]; and
A – initial cross-sectional area [mm^2].

$$\varepsilon = \frac{\Delta L}{L} \tag{2}$$

where:
ε – nominal strain;
L – initial distance between the grips [mm]; and
ΔL – increase in the distance between the grips after the test [mm].

Finally, the tensile modulus of each specimen was calculated based on the following formula (Equation 3):

$$E_t = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \tag{3}$$

where:
E_t – tensile modulus [MPa]; and
σ – stress [MPa] measured at the strain value ε_1 = 0.0005 and ε_2 = 0.0025.

The research was planned using the applicable ISO standards.[22,23] The minimal number of samples required, according to the norm for this type of research, is 5. In our study, the size of each group was n = 10.

Statistical analysis

The statistical analysis employed the Polish version of Statistica, v. 13 (StatSoft, Cracow, Poland). Since the results varied in the normality test, a non-parametric analysis of variance (ANOVA) test according to Kruskall–Wallis was used to compare the values ($p < 0.05$).

Results

Table 2 compares the basic statistics of the tensile modulus of the 3 presented resins. From the data shown, IBT differed the most from the other 2 resins (Dental LT Clear and BioMed Amber).

The homogeneity of variance test, presented in Table 3, revealed that some values (F, ΔL, σ, and ε) differed significantly when the 3 resins were compared. Welch's correction revealed even more differences, and the results are presented in Table 4.

Post-hoc tests were carried out to assess more detailed values, with Tukey's honestly significant difference (HSD) tests performed to compare pairs of materials. The results are shown in Tables 5–8. Almost all of the parameters were significantly different between the groups of materials. The lowest force required for damage occurred in

Table 2. Basic statistics of the tensile modulus of 3 dental materials

Young's modulus [MPa]	Material			p-value
	Dental LT Clear n = 10	BioMed Amber n = 10	IBT n = 10	
M ±SD	1.97 ±0.13	1.24 ±0.07	0.019 ±0.001	< 0.01*
Me (IQR)	1.96 (1.86–2.05)	1.24 (1.19–1.30)	0.019 (0.019–0.019)	
min–max	1.80–2.15	1.14–1.34	0.019–0.020	

M – mean; SD – standard deviation; Me – median; IQR – interquartile range; min – minimum; max – maximum; * statistically significant.

Table 3. Homogeneity of variance test according to Brown–Forsythe

Variable	SS effect	df effect	MS effect	SS error	df error	MS error	F	p-value
Mean height [mm]	0.000	2	0.000	0.006	28	0.0002	0.03740	0.963343
Mean width [mm]	0.000	2	0.000	0.021	28	0.0007	0.11910	0.888167
A [mm²]	0.011	2	0.005	0.224	28	0.0080	0.67597	0.516767
F [N]	2,834.040*	2	1,417.020*	7,406.310*	28	264.5111*	5.35713*	0.010716*
ΔL [mm]	6.141*	2	3.070*	5.085*	28	0.1816	16.90864*	0.000015
L [mm]	0.000	2	0.000	0.000	28	0.0000	–	–
σ [MPa]	22.566*	2	11.283*	64.393*	28	2.2998	4.90626*	0.014904
ε	19.189*	2	9.595	15.888*	28	0.5674	16.90864*	0.000015

A – initial cross-sectional area; F – force; ΔL – increase in the distance between the grips after the test; L – initial distance between the grips; σ – tensile stress; ε – nominal strain; SS – sum of squares; df – degrees of freedom; MS – mean sum of sqares; * statistically significant.

Table 4. Variance analysis with Welch's correction

Variable	SS effect	df effect	MS effect	SS error	df error	MS error	F	p-value	df Welch effect	df Welch error	F (Welch)	p-value (Welch)
Mean height [mm]	0*	2	0*	0.01*	28	0.0004*	58.423*	0.00000*	2	17.78163*	55.904*	0.000000*
Mean width [mm]	0*	2	0*	0.04*	28	0.0015*	33.666*	0.00000*	2	18.18302*	27.073*	0.000004*
A [mm²]	1*	2	0*	0.43*	28	0.0152*	29.630*	0.00000*	2	17.77987*	38.270*	0.000000*
F [N]	3,466,267*	2	1,733,134*	17,697.53*	28	632.0545*	2,742.063*	0.00000*	2	12.44415*	6,023.038*	0.000000*
ΔL [mm]	79*	2	40*	17.25*	28	0.6161*	64.175*	0.00000*	2	17.20851*	597.287*	0.000000*
L [mm]	–	2	0	0	28	0.0000	–	–	2	–	–	–
σ [MPa]	31,176*	2	15,588*	141.88*	28	5.0670*	3,076.380*	0.00000*	2	12.59515*	8,246.560*	0.000000*
ε	247*	2	124*	53.90*	28	1.9251*	64.175*	0.00000*	2	17.20851*	597.287*	0.000000*

* statistically significant.

the IBT tensile test, whereas Dental LT Clear showed the highest resistance to damage.

Non-parametric values were compared with the Kruskal–Wallis test. This referred to the initial cross-sectional area (*A*) of the probe. The obtained values (H) were not significantly different when Dental LT Clear and IBT were compared. However, the values were significantly different when either of the two materials was compared to BioMed Amber. The *Z*-value presents the standardization of the results, while the *p*-value refers to the significance of the obtained data. The data is presented in Table 9 and Table 10.

Table 5. HSD (honestly significant difference) – mean height [mm]

Pair comparison	Dental LT Clear (*M*: 1.9198)	BioMed Amber (*M*: 2.0182)	IBT (*M*: 1.9693)
Dental LT Clear	–	0.000125*	0.000144*
BioMed Amber	0.000125*	–	0.000148*
IBT	0.000144*	0.000148*	–

M – mean value of the assessed parameter; * statistically significant.

Table 6. HSD (honestly significant difference) – mean width [mm]

Pair comparison	Dental LT Clear (*M*: 5.3074)	BioMed Amber (*M*: 5.2264)	IBT (*M*: 5.1682)
Dental LT Clear	–	0.000317*	0.000125*
BioMed Amber	0.000317*	–	0.006543*
IBT	0.000125*	0.006543*	–

M – mean value of the assessed parameter; * statistically significant.

Table 7. HSD (honestly significant difference) – mean initial cross-sectional area (*A*) [mm^2]

Pair comparison	Dental LT Clear (*M*: 10.189)	BioMed Amber (*M*: 10.548)	IBT (*M*: 10.177)
Dental LT Clear	–	0.000125*	0.975750
BioMed Amber	0.000125*	–	0.000125*
IBT	0.975750	0.000125*	–

M – mean value of the assessed parameter; * statistically significant.

Table 8. HSD (honestly significant difference) – breaking force used (*F*) [N]

Pair comparison	Dental LT Clear (*M*: 437.25)	BioMed Amber (*M*: 830.35)	IBT (*M*: 17.718)
Dental LT Clear	–	0.000125*	0.000125*
BioMed Amber	0.000125*	–	0.000125*
IBT	0.000125*	0.000125*	–

M – mean value of the assessed parameter; * statistically significant.

Table 9. Kruskal–Wallis test for the initial cross-sectional area (*A*) [mm^2]

Pair comparison	Dental LT Clear (*R*: 11.100)	BioMed Amber (*R*: 25.800)	IBT (*R*: 11.545)
Dental LT Clear	–	0.000900*	1.000000
BioMed Amber	0.000900*	–	0.000999*
IBT	1.000000	0.000999*	–

H – obtained value (2; $N = 30$) = 17.16603; $p = 0.002$; * statistically significant.

Table 10. Kruskal–Wallis test for the initial cross-sectional area (*A*) [mm^2]

Pair comparison	Dental LT Clear (*R*: 11.100)	BioMed Amber (*R*: 25.800)	IBT (*R*: 11.545)
Dental LT Clear	–	3.615240*	0.112131
BioMed Amber	3.615240*	–	3.588185*
IBT	0.112131	3.588185*	–

H – obtained value (2; $N = 30$) = 17.16603; $p = 0.002$; * statistically significant.

Discussion

The present study of 10 samples of 3 selected materials (IBT, BioMed Amber and Dental LT Clear) met the ISO standards for this type of research,[22,23] and is in agreement with similar previously performed studies.[17,21] All 3 materials are dedicated for dental use, but have distinct characteristics. It means they are used for different purposes, which is supported by data on the mechanical features of these materials. Technically, all 3 materials could be used for surgical guides.[17,24] Dental LT Clear is willingly used for occlusal splints, e.g., in bruxism treatment.[25] Due to its perfect translucency and high esthetics, this transparent biomaterial could also be used in orthodontic treatment with clear aligners.[26] Although the manufacturers claim that IBT can be used for the production of surgical guides, it is primarily applied in the preparation of transfer trays, most often used for indirect bracket bonding in fixed-appliance techniques.[27] The presented tensile properties showed that IBT differed much from BioMed Amber, which is typically (according to the producer) used to prepare surgical guides. Since 3D printing is a developing branch of dentistry, there are not too many papers describing and comparing resins. Therefore, this paper is novel, and should provide more understanding of the nature and properties of resins.

BioMed Amber broke easily, though its dimensions did not change much. Although this material seems very promising, the resin is poorly described in the literature due to its novelty. Since the authors of the present study are aware of the limited amount of research on the properties of BioMed Amber, further investigations of the resin are planned. The current paper is part of a series presented by the authors.[17,21]

IBT proved to be the least resistant material. As presented in other studies, besides its original application in trays for indirect bracket bonding, IBT, due to its flexibility, could be used to produce mouth guards for protecting dentition during contact sports training, to prevent tooth trauma.[28] Other authors claim that the precision of trays for indirect bracket bonding does not depend on the material used, and is comparable when using resins from different manufacturers.[27] Other uses of this resin are disputable, and therefore research should be broadened. Although IBT Resin by Formlabs has not been thoroughly investigated, similar resins are described in the literature, as mentioned by the authors.

Dental LT Clear was the most resistant to damage; the force needed to break the sample was the highest. A comparison of Dental LT Clear and BioMed Amber in another study revealed that the tensile test situation was the opposite of the compression test outcome.[17] This material seems to raise great interest of other researchers, as several studies were conducted using it. Although Dental LT Clear was originally designed for occlusal splints and clear aligners, its other potential novel use was for a surgical tray in a Japanese study.[24] That study showed that the material could be more versatile, and the potential uses for Dental LT Clear resin could be widened.[24] Also, Dental LT Clear was tested for use in dental aligners; this specific resin shows high biocompatibility, but provides less precision as compared to a similar resin – Tera Harz.[29] Due to its biocompatibility and, after all, high precision, the material could be used for the preparation of individual appliances, such as those used in the rehabilitation of patients with clefts.[30] This aspect makes the resin worthy of further research.

Our study shows the advantages and disadvantages of three 3D-printable resins in terms of their mechanical features, and may be the key to a further investigation of potential resins uses. Dental LT Clear has also found its use in treating patients with cleft deformities, including those with the Pierre Robin sequence.[31] In the present study, the material showed the highest resistance to one type of external condition in the fracture load test. Although the above-mentioned research compared Dental LT Clear to other resins, it still required multiple printers, as the resins were produced by different companies.[31] Such a solution would be expensive for a technical laboratory or a dental office with regard to the equipment needed. Our study used 3 resins from the same manufacturer, so only one printer (Form 2 by Formlabs) was required. The examined resins displayed different properties and could be further investigated. Another study by the authors showed that samples which underwent compression testing differed in the texture and fractal dimension analyses.[32] In the compression test, the texture and fractal dimensions of Dental LT Clear did not change much,[32] which demonstrates that the material could be the most stable, as in the current study.

Although the research led to the formation of the presented conclusions, the authors are aware of some study limitations. The 1st limitation is that only 3 resins were analyzed, and they were chosen by the researchers. Another limitation might be the fact that the properties of the 3 chosen resins are different, which could cause difficulties in comparing the materials. However, the authors believe this is an advantage and could lead to further valuable research. The 3rd limitation is that the study was conducted in vitro, which is always the first step for this type of research. Nonetheless, the presented materials and methodology might be helpful in the examination of a higher number of specimens and materials in the future. The authors are also aware that the comparison of the material properties should be widened for the reasons outlined above.

Conclusions

In the tests performed on the IBT, BioMed Amber and Dental Clear LT materials, we found that:
- BioMed Amber Resin, tested for tensile strength, was the most repeatable; similar values of force were needed to break all of the resin specimens;
- the lowest tensile force was needed to cause damage to IBT Resin, which makes it the least stable and the least rigid resin tested;
- Dental LT Clear Resin was the most resistant to damage as compared to the other 2 resins, with the force needed to break the sample being the highest.

Ethics approval and consent to participate

Not applicable.

Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Consent for publication

Not applicable.

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