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Optimization of Microcapillary Flow Devices 3D Printed with Stereolithography Technology

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ABSTRACT

The importance of microfluidics research is growing, especially in the fields of chemistry, biology or medicine. This is coupled with a growing demand for specialized capillary equipment that allows advanced research at the microscale. Conventional methods of manufacturing such devices are expensive, time-consuming and do not guarantee good results. An alternative to these methods is the use of 3D printing technology. Despite the existence of numerous works presenting the possibilities of 3D printing in the context of creating microfluidic devices, there is a lack of comprehensive works presenting qualitative analysis of printed objects. This paper presents a method of producing microcapillary structures for microfluidics research with the help of 3D printing using stereolithography technology. The quality requirements that the printed objects should meet are defined and all stages of production are characterized. A qualitative analysis of the obtained objects was carried out, taking into account both the influence of individual printing parameters and print processing methods. The results of microfluidic tests using printed objects are also presented. This work is aimed at providing specific knowledge that allows the manufacture of precision devices for microfluidics purposes at low cost.

Keywords: 3D printing; stereolithography technology; microfluidics; microcapillary flow devices; printing parameters impact; print quality optimization.

INTRODUCTION

Over the past three decades, microfluidics research in chemistry, biology and medicine has grown rapidly. Research based on lab-on-a-chip (LOC) or micro total analysis systems (mTAS) [1], reactionware [2], genetic analysis [3], cell analysis [4], drug discovery [5], point-of-care (POC) diagnostics [6] and organs-on-chips [7] has developed. Despite this further development of microfluidics faces many challenges, such as high cost to create microfluidics research equipment, long time their production, as well as the limitations of two-dimensional [1]. Traditional methods of creating microfluidic research devices are based mainly on micro-electromechanical systems (MEMS), such as lithography [8], micro hot embossing [9], microinjection [10], which are more for mass production than prototyping in research. In addition, traditional manufacturing methods are time-consuming [1] and require specialized and expensive equipment.

Numerous research institutions choose to acquire the necessary microfluidic chips by purchase from specialized companies. There are many commercial companies on the market offering microfluidic testing equipment (not just the microchip but all the necessary instrumentation). The price of standard microfluidic test plates (e.g., droplet generators, microreactors) is several tens of euro. Considering that only standard structures can be purchased at such prices and that these plates are often disposable, this represents a serious expense for many microfluidics research laboratories. In addition, wishing to order a plate with non-standard structures, the price is determined individually and far exceeds catalog prices.

The development of 3D printing technology in recent years offers prospects for its use in the creation of microcapillary devices [11]. This can be a great alternative to any other methods of obtaining such equipment. 3D printing offers the possibility of manufacturing any circuit in any quantity and theoretically with any possible preset capillary structure [12]. In addition, the prices of commercially available 3D printers are dropping every year, making them accessible without the need for a lot of money. However, to be able to use 3D printing technology to create microfluidic devices, it is necessary to know how, assuming certain quality standards and taking into account existing limitations, to produce preset structures that fulfill their role during testing.

There are many review works [1, 11–15] and research works [16–18] in the literature indicating the use of 3D printing for the creation of microfluidic devices, for example, the presentation of 3D printed microneedle systems for drug delivery [19]. However, these works often demonstrate the mere effect of the structures produced, and do not indicate the methods and difficulties encountered in creating them. There is a lack of specific guidance relating to the requirements and limitations of 3D printing in the context of creating microfluidic devices. There is also a lack of analysis regarding the influence of specific printing parameters on the final result, and indications regarding methods of processing the printed objects are omitted. There is also a lack of tests relating to verifying the cooperation of manufactured objects with measuring apparatus. This leads to the fact that anyone who wants to produce microfluidic devices by means of 3D printing has to come to the knowledge on their own by trial and error, without any literature support. In order to counteract this, we present a comprehensive paper relating to the characterization and optimization of the manufacturing process of microfluidic devices using 3D printing. In this work we detailed what requirements microfluidic devices should meet. We focused on the fabrication of wafers with different types of capillary structure. We presented all the stages of manufacturing such circuits and highlighted what problems and challenges should be faced in each of these stages. We demonstrated in detail the method of manufacturing microcapillary devices based on our work. In addition, we analyzed and tested the quality of the microcapillary chips we produced, taking into account the impact of various printing parameters and processing methods. We also demonstrated the results of microfluidic tests using the printed structures. The purpose of this work is to give specific guidance to all researchers who are conducting microcapillary research and want to inexpensively fabricate microcapillaries using 3D printing.

MANUFACTURING MICROFLUIDICS DEVICE BY 3D PRINTING

Requirements and limitations of 3D printing for manufacturing microfluidic devices

Manufacturing microfluidic research devices using 3D printing is challenging, as a number of requirements must be met. These requirements are schematically shown in Figure 1.

Production costs

Today's 3D printing technology offers tremendous opportunities to print all sorts of 3D objects that have very specific, advanced parameters. However, the higher the standards these objects are to meet, the higher the cost of their production is usually. First of all, this is related to the cost of purchasing a suitable 3D printer, with the help of which it is possible to obtain the assumed structure. The costs associated with printing also include the cost of the appropriate resin. It is worth noting that many companies selling 3D printers stipulate the need to source resins supplied only by their company. Sometimes the additional cost to be paid is also the price of the software necessary to operate the printer. However, in order for the use of 3D printing methods to produce microcapillary circuits to make economic sense, the costs associated with this production method should be competitive with alternative methods. Given that many research laboratories have limited financial resources, the chosen method for printing microfluidic devices should generate the lowest possible cost while maintaining the highest possible quality of the resulting prints. Therefore, production costs are the first constraint to consider and relate to one's capabilities.

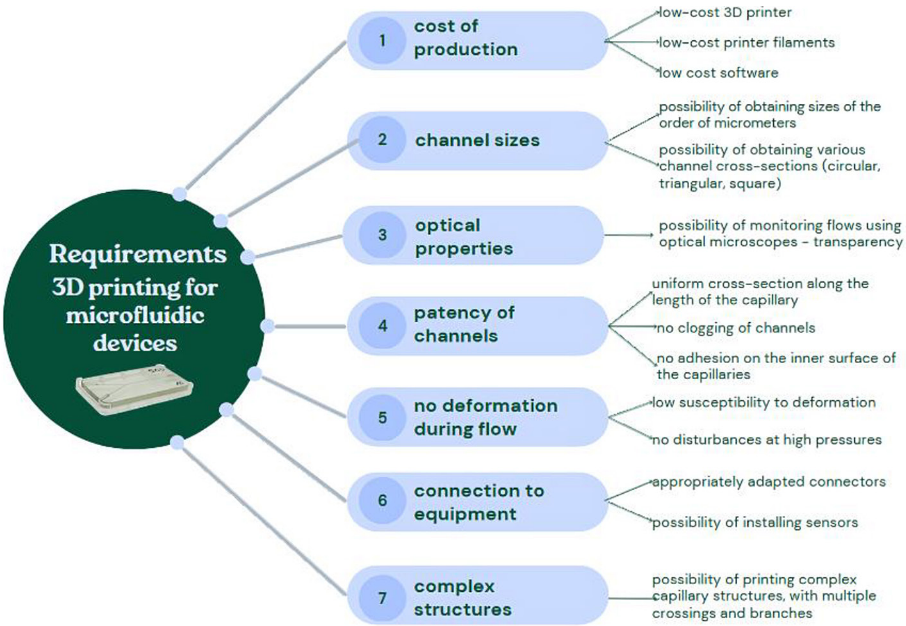

Figure 1. 3D printing requirements for microfluidic applications

Dimensions of channels

The second factor to consider is what diameters dimensions of the printed capillaries should be. Theoretically, printing a capillary with very small diameters requires a printer that cures a very thin layer of filament or resin one at a time. Otherwise, the inner diameter of the capillary will not be uniform and faults will form. However, the thickness of a single curable layer is smaller, the higher the price of the printer. It is necessary to find a compromise between the price of the printer and the capillary diameter achievable with it. In addition, if printed capillary structures have diameters other than circular, there should be consideration how this aspect will affect the quality of the print. In the case of channels with a square cross-section, the thickness of a single layer may not be as important as in the case of a circular or triangular cross-section

Optical properties

Wanting to follow microfluidic studies with an optical microscope, it is necessary that the resulting prints (plates) have sufficient transparency. This requirement determines the choice of printing method and the use of a suitable light-hardened material. The easiest way to obtain transparent prints is to use light-hardened resins using sterolithography.

During microscopic studies, in addition to the transparency of the plates, an important factor is the depth of field of view of the microscope. This parameter should be taken into account already during the design of prints and adjust the depth at which the flow channels are to be located to the viewing capabilities of the microscope we are using.

Channel patency

An important requirement to be met is to ensure the patency of all capillaries in the printed structure. The idea here is to ensure a uniform cross-sectional area of the channels with no flooding, blocking or distortion. Depending on the printing method chosen, the internal channels may deform. The right processing method for printed structures plays a big role here. With the wrong processing method, the light-hardened material deposited inside the capillaries will polymerize when exposed to sunlight, causing the capillary to become blocked.

It should also be taken into account that some light-hardened materials, such as resins, leave a sticky layer on the surface after polymerization. If this layer is not properly removed, there may be adhesion on the inner surface of the capillary of the substances flowing through it during research. This will not only disrupt the flow in the capillary, but will also affect microscopic observation capabilities by disrupting the transparency.

Absence of deformation

It is also an important factor that the printed structures do not deform during flows. This factor is particularly important when the flow takes place at high pressures and higher temperatures. Deformation of the structure under such conditions can lead to various problems, so it is necessary to use the right materials and 3D printing techniques. Some of the most important methods that can prevent structure deformation during flows are:

- Choosing the right printing parameters, such as printing temperature, printing speed and layer thickness, to ensure the stability of the structure.
- Using support for structural components that may be prone to deformation during printing.
- The use of special materials, such as reinforced fibers, which have greater resistance to deformation.
- Monitoring the printing process in real time to quickly respond to potential problems and avoid deformation of the structure.
- Testing and optimizing the 3D printing process to minimize the risk of structure deformation during flows at high pressures and temperatures.

Cooperation with apparatus

The development of microcapillary research is combined with the creation of increasingly complex, advanced structures that require the use of various types of sensors, connectors and other structural elements. Printed plates should provide the possibility of mounting appropriate additional elements, in such a way as not to upset the ongoing process. It is necessary to assure full tightness, as this is essential to ensure the proper functioning of the microcapillary device. Thus, it becomes a major challenge to design structures that, despite their high complexity, will also be practical and functional in use.

Complexity of the structure

An important advantage of 3D printing is the theoretical possibility of obtaining any designed micropillar structures. In practice, these possibilities are also limited. Depending on the quality (and therefore price) of the printer possessed, more complex layouts may not be possible. This is combined with ensuring adequate patency in all capillaries, even those that have complexity. These capabilities are largely influenced by the proper configuration of printing parameters. When fabricating microcapillary devices using 3D printing, it is necessary to optimize printing parameters to obtain the most complex objects. The method of processing the obtained structures is also not without significance.

Stages of 3D printing

The use of 3D printing for the purpose of manufacturing microfluidic equipment requires a thorough understanding of all the limitations and challenges we face when using this method. Knowing the requirements for printed structures, as well as financial and technological constraints, it is possible to try on our own to manufacture equipment for our needs using 3D printing. However, this requires going through a number of steps related to this. Figure 2 shows the listed stages of 3D printing of microfluidic devices.

Choice of 3D printer

The first dilemma of using 3D printing to produce microfluidic devices is selecting the right printing method to suit our needs. More than a dozen 3D printing methods are known to produce

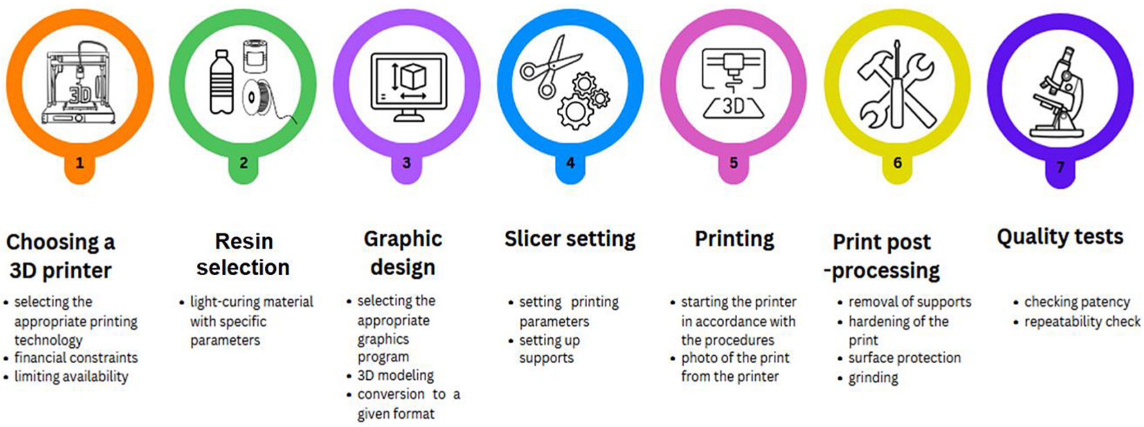

Figure 2. Stages of 3D printing of microfluidic devices

a product with the desired properties. The most popular 3D printing technologies are shown in Figure 3. These methods can be divided into those based on thermoplastic materials, powder technologies and photo-hardened resins. In order to choose a specific printing method, it is necessary to know the advantages and disadvantages associated with their use.

Among the 3D printing methods shown in Figure 3, stereolithography (SLA) deserves special attention in the context of manufacturing microfluidic devices. The principle of the SLA-type printer is based on the photopolymerization of liquid monomers, which under the influence of light become cross-linked and form a hardened polymer. The device consists of three main components: a tray filled with photo-hardened resin, a working table on which the printed object is formed and a UV laser. During printing, the laser exposes the resin layer, selectively curing it. When the layer is ready, the work area is moved up by the height of one layer and the process is repeated [20]. With SLA printing, it is necessary to use supports. Otherwise, the print would be distorted, and in extreme cases it is possible to detach from the work table and damage the printer. The undoubted advantage of stereolithography, which has determined its application in the medical field, is the high accuracy of the print. According to the study, the average absolute deviation between the dimensions of the original skull and its SLA prints is 0.62 ± 0.5 mm [21]. On an SLA-printed object, the layers are not visible to the naked eye. Objects produced by the SLA method are strong and relatively lightweight, and their surface is smooth. Depending on the resin used, the prints can be characterized by high transparency. However, the high resolution of the prints results in a long printing time, which can reach dozens of hours. In addition, the surfaces on which the supports were inserted require additional processing, and thus are of lower quality. Removing the supports themselves can also be problematic, depending on their location. The disadvantages of SLA can also include the specific properties of the resins used. They must be stored out of sunlight. In addition, SLA printing involves a number of additional costs. It is necessary to purchase post-processing materials, i.e. chemicals, UV lamp, tools for removing supports, as well as personal protective equipment (gloves, safety glasses). Moreover, resin residue and containers of resin and chemicals should be disposed of. Unhardened resin must not be poured down the drain, and it is recommended to cure the residue before discarding it.

In summary, the main advantages of stereolithography are the high accuracy, smoothness and transparency of the prints and the high quality of the details; while the disadvantages are the long printing time, the need for supports, problematic resin storage and high operating costs. Considering the presented advantages associated with this method and the requirements for microcapillary devices presented in subsection 2.1, the choice of this method seems reasonable for microfluidic plate fabrication with microcapillary arrays.

For our purposes, taking into account financial constraints, we focused on choosing a 3D printer

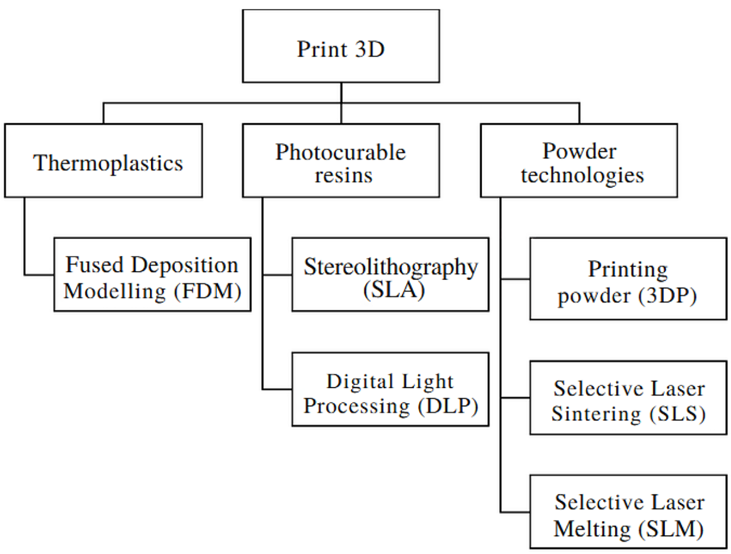

Figure 3. Types of 3D printing

in the budget of 15.000 euro. This is a low cost, so the technological limitations of the chosen printer are also high. For the production of microcapillary circuit boards, we used the XFAB 2500PD 3D printer from DWS, whose photo and technical specifications are shown in Figure 4 and Table 1.

The above model was chosen because of:
- the use of stereolithography technology, which guarantees the accuracy and tightness of the print, as well as its high transparency,
- the thickness of the built layer in the range of 10-100 µm, which made it possible to produce objects with high resolution. This is especially important for sub-millimeter prints,
- a dedicated, free Fictor program was used to operate the printer from a computer. It allows automatic setting of printing parameters (such as the thickness of the layer being built) depending on the chosen resin, but it is also possible to enter parameters manually. Its additional features include printing time estimation.

Material selection

Another issue to consider is the choice of the right material for the production of specific microfluidic devices. Depending on the chosen 3D printing method, these will be thermoplastic, powder or resin materials. When manufacturing microfluidic research plates, transparency and surface smoothness are of great importance. For this reason, light-hardened resins seem to be the most suitable for these applications. There is a wide selection of such products on the market, however, in many cases the choice is limited to the indications of the 3D printer manufacturer, who is also its distributor.

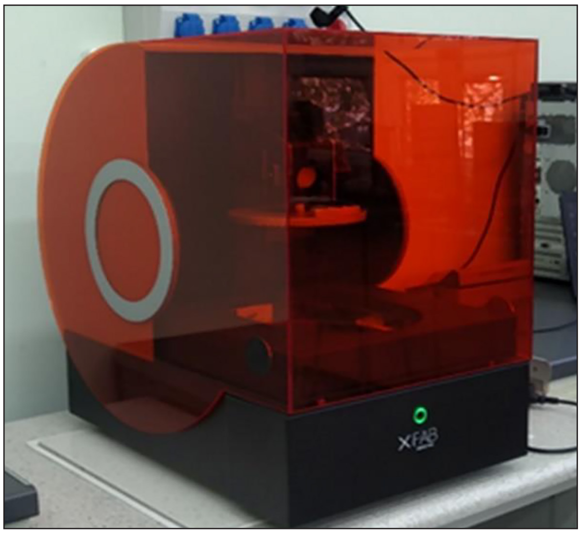

Figure 4. Photo of the XFAB 2500PD 3D printer

Table 1. Technical specifications of the XFAB 2500PD 3D printer

Printer specification	
Parameter	Value
Working area	ϕ 180 × 180 mm
Laser	Solid state BluEdge® BE-1300X
Thickness of the layer being formed	10–100 µm
Printer dimensions	400 × 606 × 642 mm

Resin, of which structures were manufactured, was Vitra 430 (company DWS). It was a blend of multifunctional acrylic monomers (acrylic acid esters). Selected properties of the resin are summarized in Table 2.

The choice of Vitra 430 resin was dictated primarily by its low price, high availability, sufficient technical parameters, but most importantly by the transparency of the printed objects. The disadvantage of this material is the great difficulty of getting rid of unhardened material from inside the structure after the printing process.

Graphical modeling

After choosing the printing method, purchasing the printer and the appropriate printing material, it is necessary to prepare the print design. To do this, one should use a chosen graphics program to draw 3D object. There are many 3D CAD programs available on the market, both free and paid. Among the popular paid programs used for this purpose are Autodesk Inventor, Autodesk Fusion360, Solidworks, PTC Creo. There are also free programs (at least in the basic version). Among them, the most common are: FreeCAD,

Table 2. Vitra 430 resin parameters

Liquid resin parameters	Value
Viscosity (25 °C)	900–1400 mPa·s
Density (25 °C)	1 g/cm
Hardened resin parameters	
Extension at break	12–20%
Tensile strength	30–40 MPa
Tensile modulus of elasticity	1250–1450 MPa
Bending strength	55–70 MPa
Modulus of elasticity at bending	1200–1400 MPa
HDT at 0.46 MPa	51–55 °C

TinkerCAD, SketchUp Free. The choice of the program is basically arbitrary, the only important thing is that the program allows you to save the file with the appropriate extension (.STL).

After selecting the appropriate program, it is necessary to draw the desired structure. This is a very important stage, since the dimensions established here will define the resulting print. Wanting to produce microfluidic research plates, it is necessary to determine not only how the internal structure of individual microcapillaries should look like, but also to plan the type and dimensions of connectors (sleeves). If the installation of sensors or other components is planned, this should already be provided for at the drawing stage. The overall dimension of the plate is also important, as well as the depth at which the capillary structures will be located, which must be related to the parameters of the optical microscope.

Figure 5 shows examples of the graphic designs that were used to print microcapillary plates. In order to test the printing capabilities, various capillary structures with different diameters and cross-sectional shapes were designed. The overall dimensions of the plates, which were based on a rectangle with rounded edges, were 40 × 20 × 2.25 mm.

Various possibilities for connecting supply channels have been tested. Internal sleeves proved to be the most effective. Their shape and dimensions had to be adjusted to the dimension of the supply pipes. External connections did not work well due to difficulties during processing and were damaged during operation in the system.

Slicer setting

The stage preceding the printing process itself is the conversion of the 3D model into instructions for the printer. For this purpose, special software is used, i.e. slicer, which "cuts" the model into layers, the height of which depends on the parameters of the printer. The individual layers are then described as linear movements of the actuator (laser, extruder, etc.), which are written in G-Code language and sent to the printer. Many printer manufacturers offer dedicated software, for example, PreForm from Formlabs, Nauta by DWS or Z-SUITE by Zortrax. A popular free slicer program is Ultimaker Cura.

For most printing methods (powder technologies are an exception - Section 2.2.1), it is necessary to use supports on which the model rests. Simple shapes can be printed directly on the work table, but for more complex geometries this is not recommended. Many slicers allow automatic generation of supports, which can then be edited manually. Incorrectly adding supports can result in the model detaching from the workspace and warping thin walls and features.

The inclination of the printed object with respect to the working table is also an important parameter. This aspect is relevant for optimizing print quality. This is especially important when printing capillary systems, as printing structures at the right angle can ensure the patency of channels.

In the case presented in the paper, Nauta software provided by the printer manufacturer was used to prepare the model for printing, It allowed to define the position of the model on the working table and create supports on which the printed

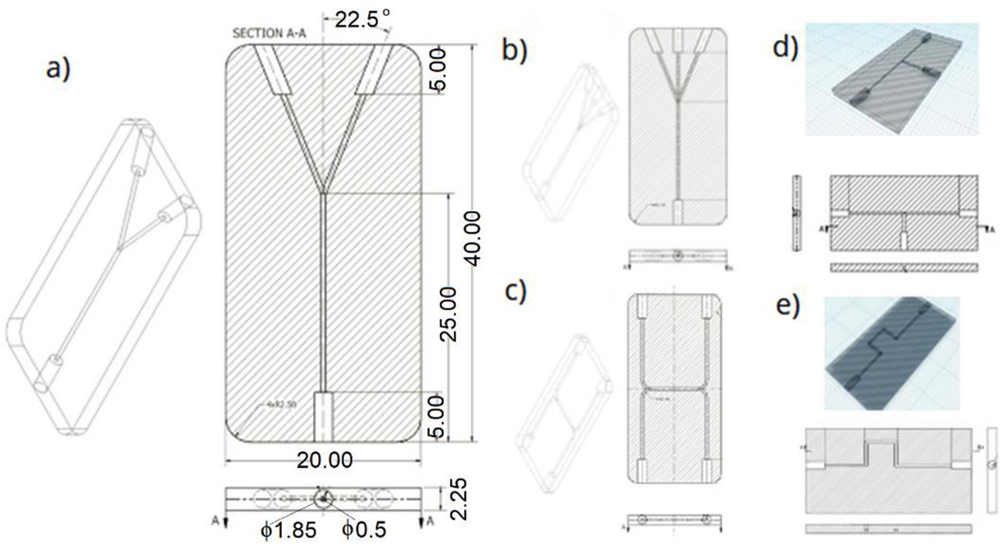

Figure 5. Examples of graphic models of printed structures

model rests both manually and automatically. The program also calculates the weight of the finished print and estimated resin consumption. The design of a sample print, including supports, is shown in Figure 6. If the workspace allows it, it is possible to print several objects simultaneously. It is necessary to arrange them properly on the work table and adjust the appropriate supports. Then such a design is converted to a file supported by a slicer, in our case it was the Fictor program provided by the manufacturer. This program made it possible to specify printing parameters, the most important of which was layer thickness. The Fictor program also made it possible to control printer settings.

Printing

The next stage is already related to the printing process itself. However, in order for it to happen, it is necessary to prepare the printer. First of all, it is necessary to fill the tray with resin. This should be done in accordance with the procedures recommended by the manufacturer. After filling the tray with resin, the level calibration of the working table followed. Then it was necessary to manually immobilize the working field. Only after these steps were completed it was possible to start printing. It should be noted that the thinner the set thickness of a single layer, the longer the printing time of the object will be. In the case of the layouts we presented on the indicated printer, this time reached several hours. It should be noted that during this time there should be no interruption in the supply of electricity and (if the printer is connected to an external network) Internet access. Otherwise, the printing process may be interrupted. The process can be resumed, however, the last layer may not be properly hardened, resulting in a non-uniform structure of the printed object. Once the printing process is complete, it is necessary, following the manufacturer's procedures, to open the printer and remove the print from the work area. This is not a simple task, as prints are often firmly attached to the work area, and detaching them firmly can cause them to crush.

Print processing

It should be kept in mind that prints taken off the printer's workbench have attached supports, are dull, sticky, and there is unhardened resin lodged inside the capillary structure. Leaving such prints exposed to sunlight will matte and harden the resin deposited. Therefore, such prints should immediately undergo processing. This is a very important stage and often the quality of the resulting prints depends on it. As part of the processing of microcapillary structures activities can be distinguished aimed at:

- removing supports and making the outer surface smooth
- removal of the resin remaining inside the capillaries
- final hardening of prints using UV light
- giving the surface of the prints optimal optical parameters

The exact procedures may vary depending on the printing method and material parameters. Developing a suitable processing procedure often involves multiple trials.

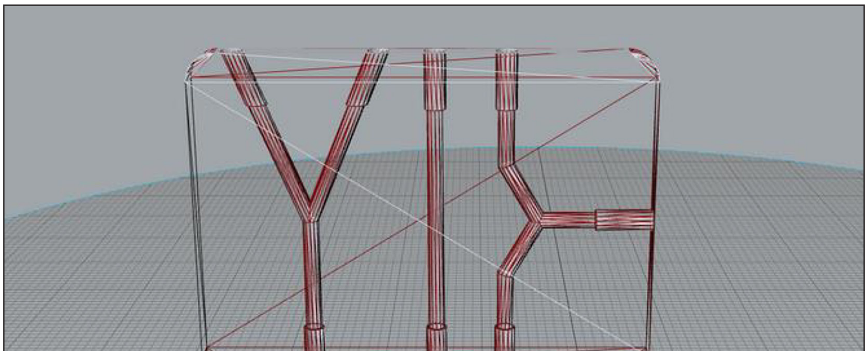

Figure 6. Model of the example project with supports

Quality tests of the completed prints

The final step in the preparation of printed microcapillary systems, is to conduct appropriate quality tests to verify their suitability for specific applications. It is necessary here to determine the required quality standards that should characterize the printed objects. These standards, in the case of microfluidic systems, should mainly concern the structure and patency of the internal capillary structure. In order to carry out such verification, it is necessary to adopt a certain standard evaluation method. It must ensure comparability of results and unambiguity of assessment. One of the methods of assessing patency that works well for microcapillary systems may be the tracer method. It involves applying markers to microscopic images of structures in the form of a line perpendicular to the edge of the canal, and then comparing the total width of the canal to its patchable part. The method of measurement is illustrated in Figure 7 using a Y-type divergent capillary as an example. The number of markers for each channel was 10. The arithmetic average of the obtained values was used for calculations. In order to determine the degree of patency, the printed structures can also be subjected to pressure drop tests by connecting them to a suitable measuring apparatus and using the chosen liquid medium. The measured values can be compared with the theoretical values calculated on the basis of the known Hagen-Poiseuille relations and on this basis appropriate conclusions can be drawn. However, the results obtained will give information about the overall patency of the capillaries. The final verification should be tests in a specific microcapillary system and check how the given structures cooperate with the equipment.

PRINT QUALITY OPTIMIZATION

According to the procedure outlined in the previous section, microcapillary structures were printed for microfluidic studies. A variety of capillary systems with different structures and channel shapes were made, such as converging Y-shaped, H-shaped and Ψ-shaped channels. Photos of examples of the fabricated structures are shown in Figure 8.

A Y-shaped channel arrangement was used as the basic structure for comparison purposes. In order to optimize the quality of the obtained objects, a number of attempts were made to print this

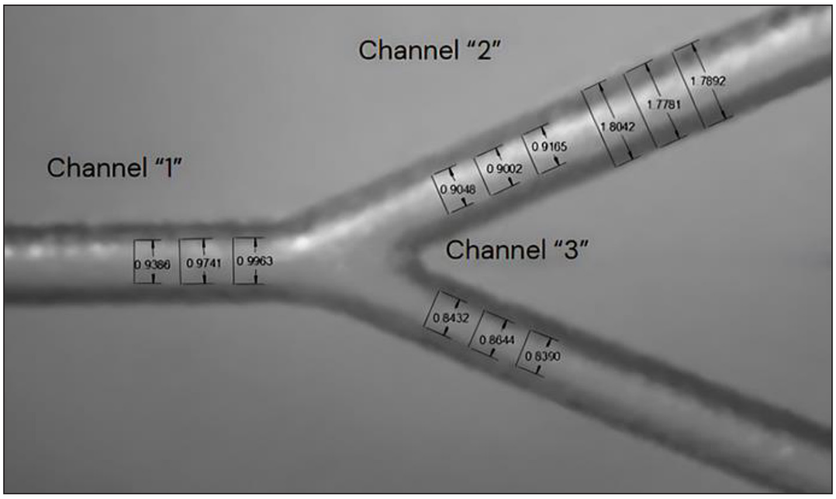

Figure 7. Assessment of microcapillary patency using the tracer method

Figure 8. Photos of microcapillary structures for microfluidic studies: (a) Y-channels, (b) H-channels, (c) Ψ-channels

structure at different set printing parameters and using a variety of processing methods. This section will present a study of the influence of certain factors on the quality of the obtained structure. It should be noted that given the selected factor, all other printing parameters (or processing methods) were the same for the comparison objects, moreover, they were printed simultaneously. Such factors as the slope of the structure, the size of the channels and their shape, and the processing method were analyzed.

Influence of the print slope on the quality of the obtained structure

In order to test how the print slope affects the quality of the resulting structures, tests were conducted to simultaneously print four Y-shaped capillary structures with the same print parameters. The only variable factor was the print slope relative to the working table. The set diameter of the capillary channels was 700 µm, the thickness of the print layer was 30 µm. Prints set at 0° (S1), 30° (S2), 45° (S3) and 90° (S4) were made as shown in Figure 9a.

Microscopic analysis of the printed structures showed a strong influence of the print slope on the quality of the obtained structures. In Figure 9b, it can be observed how the print slope affected the deformations of the capillary structure. The largest deformations could be observed in the case of a structure printed at an angle of 90° (S4). The bifurcation of the channels was significantly deformed, while the channels were flooded and, consequently, their diameter was much smaller than designed. Significant irregularities can also be observed in S2 and S3 structures. To quantify the degree of patency of individual canals, a tracer analysis was carried out in accordance with the procedure outlined in Section Print processing. The results of these analyses are shown in Figure 9c as percentages of canal patency calculated as the ratio of the average diameter value obtained from the tracer analysis to the set diameter value. Based on this analysis, it can be seen that in every case the value of channel patency was below 100%, which means that the patency was lower than the planned one. The best patency was obtained for a structure printed at 0° (S1), where the main feed channel was perpendicular to the working field. When it was set parallel (structure S4), the patency was the lowest (less than 50%). The orientation of the prints at 30° (S2) and 45° (S3) resulted in intermediate patency values. Based on these analyses, it can be concluded that the best quality results can be achieved when the main capillary structures are located parallel to the printing direction. This results in the most stable structure, the smallest deformations and the highest degree of capillary patency. In addition, with such an orientation, for the presented object, an additional benefit was the lower amount of material consumed for supports.

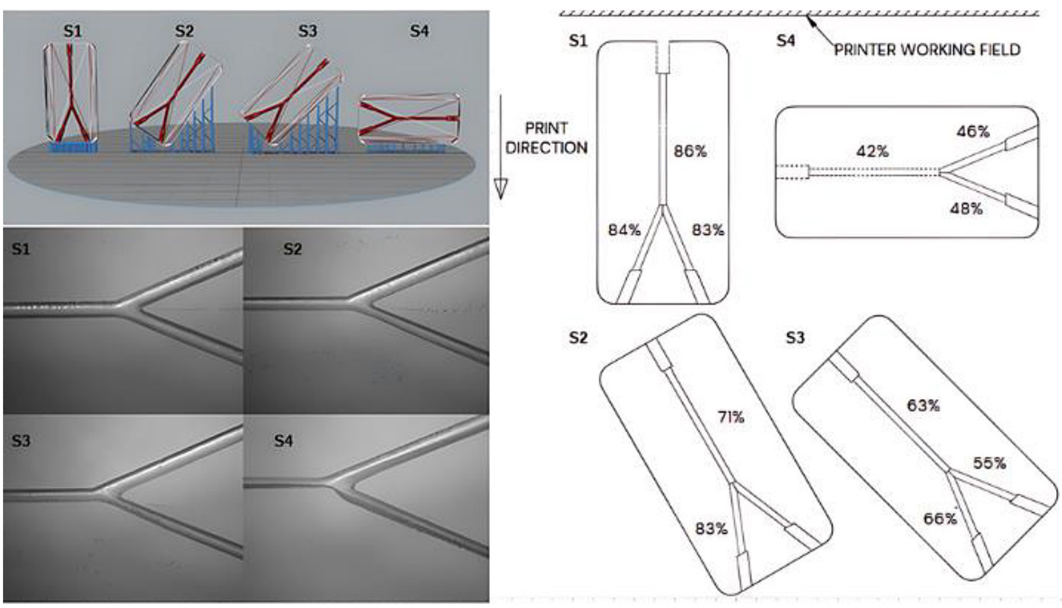

Figure 9. Analysis of prints at different angles of slope: a) alignment of print with respect to working table, b) microscopic images of printed structures, c) results of capillary patency analysis

Effect of the processing method on the quality of the obtained prints

As written in the previous sections, the most important thing for printing objects for microcapillary research is the patency of the channels and appropriate optical properties that guarantee the possibility of microscopic tracking of the phenomena occurring inside the structures. In order to obtain the best possible quality of printed capillary structures, various processing methods were used. A variety of tools were used and different agents were applied. In order to get rid of the resin deposited inside the capillary structure, alternate pumping of a suitable washing liquid (isopropanol solution) and compressed air through the structure was used. These were extremely important steps and omitting them resulted in the lack of patency of the channels as shown in Figure 10 (S6 – no washing, S7 – no pumping of air). Multistage polishing (see Figure 10 – S8) and smoothing with a viscous liquid (paraffin) (see Figure 10 – S9) were used to make the surface transparent. Polishing the print was a time-consuming process and did not guarantee the desired transparency. Better results were obtained by smoothing the surface. The most effective method, giving the most satisfactory results, was the method consisting of exactly the following steps:

1) preliminary washing of the print in a solution of isopropanol (Lalill Cleaner) - this step allowed to get rid of the sticky layer from the print surface,
2) removal of supports with pincers and straightening of the surface,
3) removal of resin deposited in the internal structure by washing the channels with isopropanol - for this purpose, a syringe system was used with appropriate connections to reach the channels. This step was repeated several times, for each canal outlet,
4) removal of residual resin and solution by flowing compressed air at a pressure of 3.5 bar for one minute; the procedure was repeated for each canal outlet,
5) hardening the print in a 100 W UV lamp for 15 minutes,
6) smoothing the support residue with 1500 – grit sandpaper,
7) applying a thin layer of paraffin (L.G. Olsztyn) to the surface of the printout.

Quality of obtained structures in relation to capillary diameter

When printing capillary systems, their size is of great importance. The smaller the structures we want to obtain, theoretically, the quality of

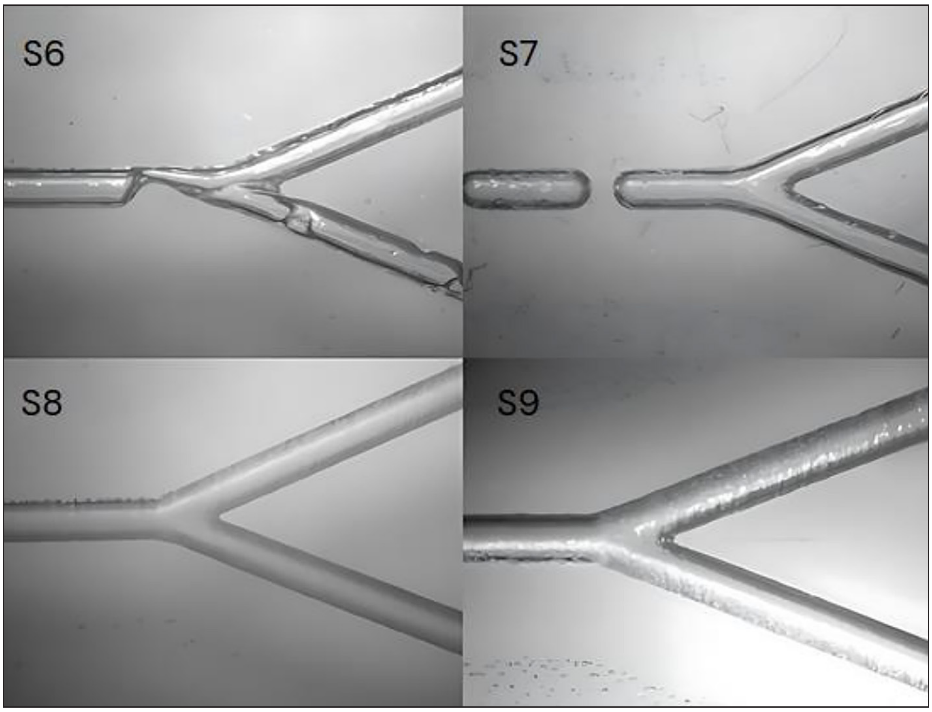

Figure 10. Microscopic images of printed structures showing the effects of different print processing methods: S6 – no washing, S7 – no air pumping, S8 – surface polishing, S9 – surface smoothing

printing will deteriorate. This is influenced not only by the capabilities of the printer, the printing material used, but also by how the finished structures are processed. In our tests, we tried to achieve capillary structures with the smallest possible internal diameters. Figure 11 shows microscopic images and Table 3 shows results of patency analysis of capillary systems with internal diameters of 600 µm (S9), 400 µm (S10), 300 µm (S11) and 200 µm (S12).

On the basis of the analysis, it can be concluded that the printed structures at the given internal diameters of the channels, had a patency of less than 100%. This means that the printed capillaries had an actual diameter smaller than the design diameter. The smaller the set diameter was, the lower the patency of the channels was as well. Printing the designed structure with a diameter of 300 µm allowed to obtain the smallest diameters of the passable channels. However, tracer analysis showed that the average patency of the channels was 39%. This means that the actual channel diameter was about 120 µm. Attempts to create capillary systems with diameters below 300 µm were unsuccessful. All channels became flooded, resulting in zero patency.

Based on the work carried out, it should be concluded that using the 3D printing technique (and processing methods) presented in the paper, when intending to print capillary structures with diameters below 1000 µm, it should be taken into account that some of the resin may not be removed from inside the capillaries. The resin remaining in the capillaries during the processing will be hardened, and this will diminish the capillary clearance. The actual diameter of the channels will therefore be much smaller than designed. There are two ways to deal with this situation: either to look for more and better ways to make the channels passable, using more advanced processing methods (although this will be extremely difficult in the case of very small diameters), or to take into account the degree of resin deposition in the capillaries already during the design stage. In such a situation, in order to obtain a capillary of the final set diameter, it is

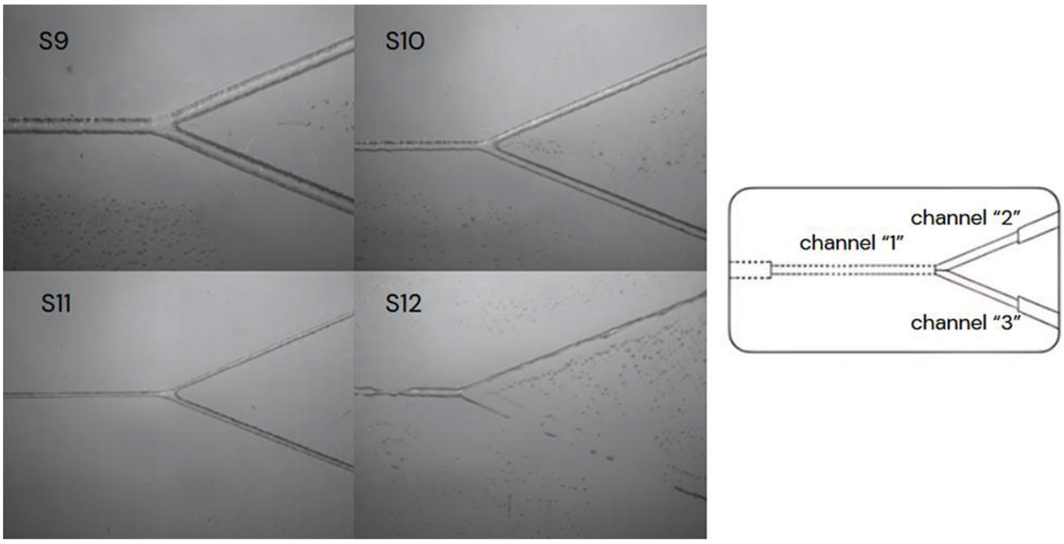

Figure 11. Microscopic images of capillary structures with internal diameters of 600 µm (S9), 400 µm (S10), 300 µm (S11) and 200 µm (S12)

Table 3. Results of patency analysis of capillary structures with internal diameters of 600 µm (S9), 400 µm (S10), 300 µm (S11) and 200 µm (S12)

Channel	Structures			
	600 µm (S9)	400 µm (S10)	300 µm (S11)	200 µm (S12)
1	77%	54%	40%	0%
2	75%	51%	39%	0%
3	74%	47%	39%	0%
Average	75%	51%	39%	0%

necessary to design a larger one and include an allowance for resin deposit. Of course, such an approach requires experimental knowledge of the relationship between the diameter of the capillary and its patency.

Quality of the obtained structures in relation to the cross-sectional shape of the channels

An analysis of the possibility of producing channels with a cross-section other than circular was carried out. For this purpose, structures with a square and triangular cross-section channel were printed (see Figure 12). The square and triangular sides were 500 μm, the layer thickness was 10 μm. Visual evaluation and tracer analysis showed that the produced structures were passable. Channels with a square cross-section showed high average channel patency – on the order of 87%. In the case of channels with a triangular cross section, the average patency of the channels was 48%.

Based on the work carried out, it can be concluded that printing straight canal walls gives good results because the individual layers are hardened uniformly. However, when the cross-sectional shape of the canal has sharp angles, there is a difficulty in cleaning the canal from the resin deposited in these areas. This should be kept in mind, as it affects the actual shape of the canal cross-section.

Quality of obtained prints for different shapes of capillary structures

An analysis of the quality of printed structures with other shapes, for example, an H-shaped or Ψ-shaped structure, was also carried out. Photos of exemplary printed structures are shown in Figure 8b and 8c. In addition, microscopic images of fragments of printed structures are presented in Figure 13. The set diameter of the capillary channels was 400 μm, the thickness of the printing layer was 10 μm.

Tracer analysis of the fabricated structures showed that in the case of structure H, there was a significant disproportion between patency in the lateral canals and the connecting canal. The average patency of the side channels was 54%, while that of the connecting channel was only 11%. In addition, the internal structure of the connecting canal was severely deformed and heterogeneous. The reason for this is that the connecting channel was positioned parallel to

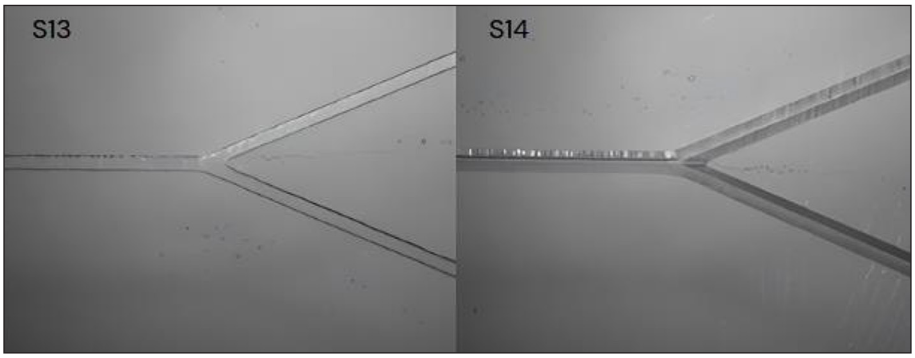

Figure 12. Microscopic images of square (S13) and triangular (S14) cross-section channels

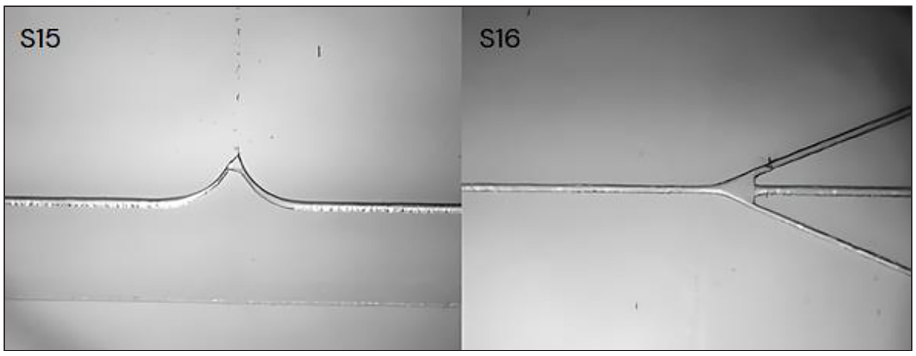

Figure 13. Microscopic images of fragments of the H – structure (S15) and the Ψ – structure (S16)

the working table during printing. As shown in Section 3.1 (structure S4), such channel alignment during printing results in significant channel flooding. In addition, in the case of structure H, there was a difficulty in clearing this channel. In the case of structure Ψ, the average patency of the channels was 52%, which was similar to the patency obtained for channel Y with the same set dimensions (structure S10).

EXAMINATION OF THE OPERATION OF THE PRINTED DEVICE DURING MICROFLUIDIC FLOW TESTS

In order to check whether the printed capillary structures could find application in microfluidic studies, microscopic tracking experiments were carried out for microfluidic flows. For this purpose, the measuring apparatus shown in Figure 14 was used. It consisted of a syringe pump (1) supplying liquid to the printed capillary system (7). The flow of liquid was tracked using a Levenhuk microscope (2) and transmitted with camera (3) to PC (4). Pressure sensors (6) and flow meters (5) were mounted in the system. An aqueous suspension of glass microspheres at a concentration of 3% was used for the study. The particle size range was 60–80 μm. A Y-shaped structure with a preset diameter of 400 μm (S10) was selected for testing. The liquid flow rate was 80 μl/h. Figure 15 shows microscopic images of a sequence of consecutive images captured during the transport of the microsuspension.

The pressure drop at the capillary inlet was also monitored during the flow. During the tests, there were no instabilities and turbulence suggesting unpredictable effects of the structure on the flow. As can be seen from the microscopic images (Figure 15), the printed structures were sufficiently homogeneous, transparent and permeable to allow tracking of microsuspension transport. It should be noted, however, that in the case of microscopic images of liquid-filled capillaries, the capillaries may take on a color close to the background, which can make visual analysis difficult.

Based on the experimental work carried out, it can be claimed that the printed structures fulfill their role and can be used as microfluidic devices.

CHALLENGES AND LIMITATIONS

The method presented in this paper has made it possible to obtain microcapillary devices in the form of various types of connected or branched channels for the purpose of tracking the transport of dispersion systems. However, wishing to print microcapillary devices tailored for other purposes will require facing various challenges that must be overcome to obtain satisfactory results. The main challenges are linked to the size and geometry of the channels. Based on our methods, we have been able to obtain satisfactory quality objects with diameters above 300 μm in the form of circular branched channels. Wanting to print channels with smaller diameters and more

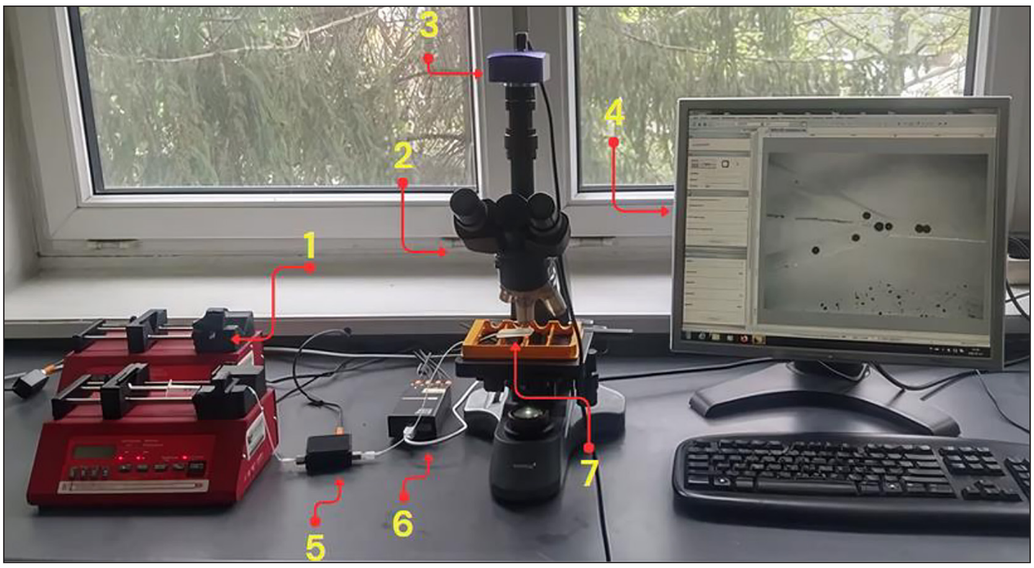

Figure 14. Photo of microfluidic research equipment: 1) syringe pump, 2) microscope, 3) camera, 4) computer, 5) flow meter, 6) pressure sensor, 7) printed capillary system

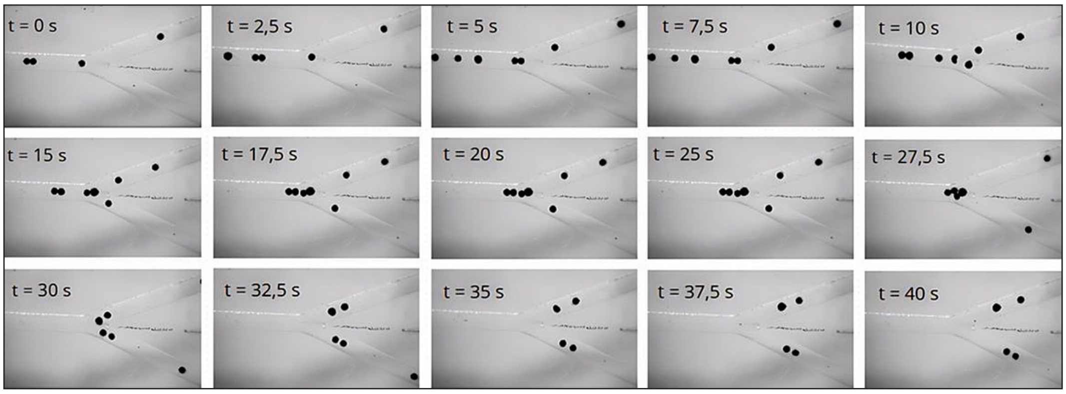

Figure 15. Sequence of time-lapse microscopic images recorded while tracking the flow of microsuspension through the printed structure (S10)

complex shape, one encounters the problem of channel flooding, variable inner diameter and often lack of throughput. This is related to both the limitations of the printer (10 μm is the thickness of a single curable layer) and the inability to remove the resin deposited inside the channel after the printing process during processing. If the single cured layer is too thick, unevenness in the internal structure of the channels (in the form of jaggedness) will appear on small objects. To overcome this limitation it is necessary to buy a printer that is more accurate and allows to cure thinner layers, however such printers are already quite expensive. When it comes to removing the resin from inside the structure to ensure throughput, it is necessary to improve processing methods. This is a huge challenge that will require a customized approach, but it is crucial to the quality achieved. Another challenge that is important in optical microcapillary testing is to achieve adequate transparency. Both the processing methods and the resin used with the right properties will matter here. Optical aspects should be taken into account already during the design of the print and care should be taken to ensure that the appropriate objects are at the right depth to be in the field of view of the microscope. Another challenge, especially important in more advanced research, is related to the ability to properly connect and mount additional instrumentation on the printed capillaries, Any connections must remain tight during operation, and must not be mechanically damaged. This must be taken into account already in the design phase of the facility. This can sometimes involve printing objects in parts and putting them together using various methods. It should be noted that the rapid development of 3D printing technology offers prospects for overcoming most of the challenges encountered when printing microcapillary devices. However, the main limitation is cost. Therefore, when using 3D printing technology to manufacture microcapillary devices, it is necessary to individually establish a compromise between economic aspects and quality aspects. It is also not insignificant to know how to shift this trade-off to one's own advantage.

CONCLUSIONS

The use of 3D printing with stereolithography technology for the purpose of creating microcapillary testing devices makes it possible to obtain a variety of objects at a modest cost. However, each method and the equipment involved has its limitations. Wanting to use 3D printing to produce objects for microfluidics research, it is necessary to determine in detail the quality requirements they should meet. Only on this basis is it possible to choose the manufacturing method, the equipment used and the materials. The creation of an appropriate graphic design, the choice of printing parameters and processing methods are also essential for the quality of the objects obtained. Carrying out quality tests of the obtained objects based on a standard evaluation method gives the opportunity to optimize the creation of the set structures. Verification of the cooperation of printed objects with the apparatus during flow tests gives a final view relating to the possibility of using the obtained objects in practice.

In this paper, the possibilities of using 3D printing with stereolithography technology to create microcapillary objects for microfluidic studies are presented. Results were demonstrated for structures with different shapes (Y, H, Ψ), different sizes and channel cross-section shapes. It was also presented how the quality of the print is affected by the slope of the object with respect to the working table and the processing method. In order to test the possibility of using the printed objects during specific microfluidic studies, the tracking of microsuspension flow through a Y-type structure was carried out.

REFERENCES

1. Wu Y.H., Fu J.Z., Gao Q., Qiu J.J. Developments of 3D printing microfluidics and applications in chemistry and biology: a review. Electroanalysis 2016; 28: 1658–1678.
2. Bubliauskas W., Kitson A., Francoia P.J., Powell-Davies J.P., Parrilla-Gutierrez H., Manuel J., Frei P., Sebastián M.J., Leroy C. Automatic generation of 3D-printed reactionware for chemical synthesis digitization using ChemSCADHou. ACS Central Science 2021. DOI: 10.1021/acscentsci.0c01354
3. Ferguson B.S., Buchsbaum S.F., Wu T.T., Hsieh K., Xiao Y., Sun R., Soh H.T. Genetic Analysis of H1N1 Influenza Virus from Throat Swab Samples in a Microfluidic System for Point-of-Care Diagnostics. Journal of the American Chemical Society 2011; 133(23): 9129–9135.
4. Lecault V., White A.K., Singhal A., Hansen C.L. Microfluidic single cell analysis: from promise to practice. Current Opinion in Chemical Biology 2012; 16(3): 381–390.
5. Neuži P., Giselbrecht S., Länge K., Huang T.J., Manz A. Revisiting lab-on-a-chip technology for drug discovery. Nat Rev Drug Discov. 2012; 11(8): 620–632.
6. Chin C.D., Linder V., Sia S.K. Commercialization of microfluidic point-of-care diagnostic devices. Lab on a Chip 2012; 12(12): 2118–2134.
7. Huh D., Torisawa Y., Hamilton G.A., Kima H.J., Ingber D.E. Microengineered physiological biomimicry: Organs-on-Chips. Lab on a Chip 2012; 12(12): 2156–2164.
8. Xiang N., Yi H., Chen K., Wang S., Ni Z. Investigation of the maskless lithography technique for the rapid and cost-effective prototyping of microfluidic devices in laboratories. J. Micromech. Microeng. 2013; 23(2): 025016.
9. He Y., Fu J.Z., Chen Z.C. Research on optimization of the hot embossing process. J. Micromech. Microeng. 2007; 17(12): 2420.
10. Attia U.M., Marson S., Alcock J.R. Micro-injection moulding of polymer microfluidic devices. Microfluidics and Nanofluidics 2009; 7(1): 1–28.
11. Amin R., Knowlton S., Hart A., Yenilmez B., Ghaderinezhad F., Katebifar S., Messina M., Khademhosseini A., Tasoglu S. 3D-printed microfluidic devices - Topical Review. Biofabrication 2016; 8: 022001.
12. Pranzo D., Larizza P., Filippini D., Percoco G. Extrusion-Based 3D Printing of Microfluidic Devices for Chemical and Biomedical Applications: A Topical Review. Micromachines 2018; 9: 374; DOI: 10.3390/mi9080374.
13. Su R., Wang F., McAlpine M.C. 3D printed microfluidics: advances in strategies, integration, and applications. Lab Chip 2023; 23: 1279.
14. Zhang J.M., Ji Q., Duan H. Three-dimensional printed devices in droplet microfluidics. Micromachines 2019; 10: 754. DOI: 10.3390/mi10110754.
15. Li F., Macdonald N.P., Guijt R.M., Breadmore M.C. Increasing the functionalities of 3D printed microchemical devices by single material, multimaterial, and print-pause-print 3D printing. Lab Chip 2019; 19(1): 35–49. DOI: 10.1039/C8LC00826D.
16. Vijayanab S., Hashimoto M. 3D printed fittings and fluidic modules for customizable droplet generators. RSC Adv. 2019; 9: 2822.
17. Razavi B.S., Rouhi O., Raoufi M.A., Ejeian F., Asadnia M., Jin D., Ebrahimi W.M., 3D Printing of Inertial Microfluidic Devices. Sci Rep. 2020; 10(1): 5929. DOI: 10.1038/s41598-020-62569-9.
18. Filho P., Antonio L., Paixão T.R.L.C., Nordin G.P., Woolley A.T., Leveraging the third dimension in microfluidic devices using 3D printing: no longer just scratching the surface. Anal. Bioanal. Chem. 2024; 416: 2031–2037. DOI:10.1007/s00216-023-04862-w.
19. Carnero B., Bao-Varela C., Gómez-Varela A.I., Álvarez E., Flores-Arias M.T., Microfluidic devices manufacturing with a stereolithographic printer for biological applications. Mater Sci Eng C 2021; 129: 112388. DOI: 10.1016/j.msec.2021.112388.
20. Li R., Zhang L., Jiang X., Li L., Wu S., Yuan X., Cheng H., Jiang X., Gou M., 3D-printed microneedle arrays for drug delivery. J. Cont. Rel. 2022; 350: 933–948. DOI: 10.1016/j.jconrel.2022.08.022.
21. Kim G.B., Lee S., Kim H., Yang D.H., Kim Y.H., Kyung Y.S., Kim C.S., Choi S.H., Kim B.J., Ha H., Kwon S.U., Kim N. Three-Dimensional printing: basic principles and applications in medicine and radiology. Korean Journal of Radiology 2016; 17(2): 182. DOI: 10.3348/kjr.2016.17.2.182.
22. Choi J.Y., Choi J.H., Kim N.K., Kim Y., Lee J.K., Kim M.K., Lee J.H., Kim M.J. Analysis of errors in medical rapid prototyping models. International Journal of Oral and Maxillofacial Surgery 2002; 31(1): 23–32. DOI: 10.1054/ijom.2000.0135.