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Characterization of interconnects used in PDMS microfluidic systems

Andrew M Christensen, David A Chang-Yen and Bruce K Gale

Department of Mechanical Engineering, University of Utah, 50 South Central Campus Drive
Rm. 2110, Salt Lake City, UT 84112, USA

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Abstract
This paper reports the characterization of a microfluidic packaging technique involving the use of press-fit interconnects to microfluidic channels molded in PDMS. This packaging technique is implemented by, first, coring a small hole in the PDMS to access molded or buried microchannels using a modified 20 gauge needle; and second, inserting an unmodified needle into the hole to create a direct connection to the microchannel that requires no bonding or molding. The needles can then easily be removed and reinserted multiple times since the seal is created purely by the compression of the PDMS around the needle. The luer fitting on the needles can easily be connected to standard fluid fittings. The quality of the interconnects is correlated with observations of the PDMS after coring. Methods of coring examined include pushing straight through and twisting the coring tool by hand or by machine. These comparisons demonstrated that all methods can produce viable interconnects; however, machine coring was the most consistent. The interconnects were characterized mechanically primarily by measuring their leak resistance under pressure. Leak tests were performed on interconnects (1) fabricated using different methods, (2) experiencing rotation or bending and (3) fabricated at various linear densities. Static pressure testing revealed that interconnect pressure limits varied from 100 kPa to over 700 kPa depending on the fabrication method. Suggestions are presented on how the technique could be modified to reach much higher pressures. Interconnect flexibility testing demonstrated a minimum of 30° of bending and a maximum of 60° before failure depending on the direction rotated. Density testing showed that PDMS was strong enough to allow at least six interconnects on a 1 cm linear channel.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Microfluidic devices have been developing at a rapid pace with applications in the medical, pharmaceutical and chemical industries. Packaging of these microfluidic devices has historically been a major challenge due to interface size, cost and the need for custom solutions. Microfluidic devices typically require multiple interconnects and in many cases the packaging components are much larger than the microsystems they interface [1–4]. Packaging has been identified as one of the greatest limiters on acceptability of microsystems into the broad world market [5]. Studies on packaging have shown that packaging can comprise at least 75% of the total cost of a microsystem [6]. Clearly, there is a need for a low cost, flexible packaging method for microfluidic devices to be successful long-term. An additional challenge with packaging methods is that packaging is usually ignored until commercial devices are ready to be developed, which causes most packaging methods to never be published and to become proprietary through either patents or trade secrets. Packaging is also considered an applied science with little opportunity for fundamental discoveries, which discourages academic researchers from exploring this area. Thus, literature and information in this arena can be scarce. This situation currently exists regarding microfluidic packaging. In addition, since currently there are no standards for packaging of microfluidic devices, a wide

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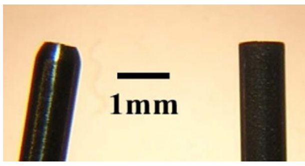

Figure 1. An unmodified 20 gauge needle (right) and a modified needle used as coring tool (left).

range of methods for packaging microfluidic systems have been implemented [5]. Accordingly, one goal of this paper is to present a robust, flexible and cost-effective packaging method for use with PDMS and other soft and flexible polymers along with the capabilities and challenges associated with the method.

A variety of techniques have been used to connect microchannels fabricated in a range of materials to external devices and to provide interfacing. The most common packaging techniques require tubing to be glued or molded to the substrate making the interconnects impractical to remove, difficult to modify and challenging to repair [7, 8]. In recent years, PDMS has become popular as an inexpensive and easily molded material for microfluidic devices [9–11]. Along with glued interfaces, press-fit holes bored with the use of a modified needle have been used as a method of interconnection. Although this method has been used by others in this field [12–14], little has been published about the method of interconnect fabrication and the characteristics of these press-fit interconnects. Press-fit holes allow for easy removal and are simple to manufacture; however, little is known about their optimal manufacturing technique and what the performance limitations are. The intent of this paper is to explain the properties of such interconnects, explore optimal coring techniques, and find performance limits related to internal pressure, interconnect flexibility, material durability and interconnect density.

2. Concept

Microfluidic channels made of PDMS are quite common and fabrication techniques for these channels using SU-8 molds can be found in several publications [12, 15–17]. In this work, interconnect channels are created using a coring tool created from a 20 gauge, flat-tipped needle (Kontes, number 868280-2001). A Dremel Multipro 395 was used to shape the outer edge of the needle to a sharp, beveled edge, as shown in figure 1. Using a twisting motion, the coring tool is used to cut a hole from the outside of the PDMS to the buried channel. The cored hole has a diameter identical to the inner diameter of the 20 gauge needle (610 μm). When a second unaltered 20 gauge needle is inserted into the hole, a compression seal is formed around the needle since the outer diameter of the needle is 953 μm, which is over 50% larger than the hole (figure 2). Standard tubing or capillaries can then be connected using the luer connector on the needle. These interconnects are highly robust, yet easily created. The interconnects can be disassembled and reassembled a number of times without significantly affecting the seal between the needle and the PDMS. These interfaces can withstand significant displacements and bending stresses, which are typically not the case with interconnects affixed using adhesives. These techniques could be easily automated and can be done in parallel to create multiple connections. The technique is not limited to 20 gauge needles, but can be performed with any size of flat-tipped needle, or even capillary tubing assuming an appropriate coring tool is available. An example of the complete interconnect system is shown in figure 3.

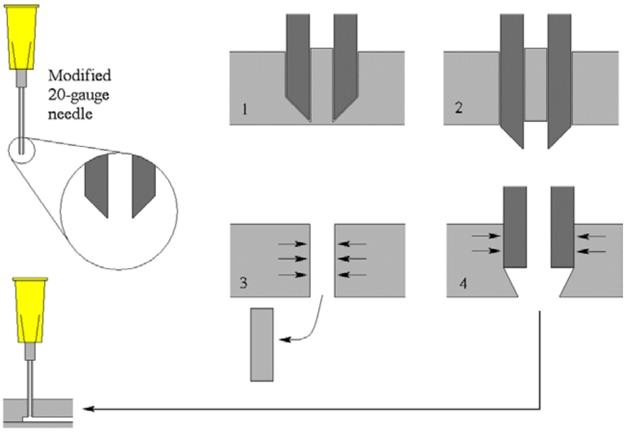

Figure 2. Diagram of the coring process and the interconnect fabrication method.

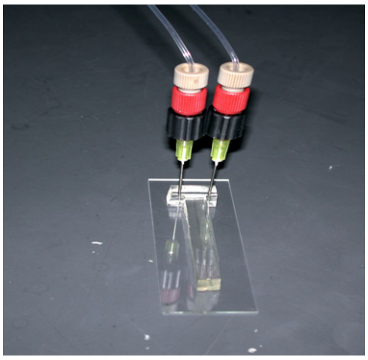

Figure 3. An example of the completed interconnection implemented at the inlets of a PDMS T-channel on a 6.45 cm × 7.62 cm slide.

3. Methodology

To explore the capabilities and limitations of this packaging system for use with PDMS, a number of experiments were carried out including static pressure limits, bending limits, maximum interconnect density and variable coring method tests. These tests are described in the following sections.

3.1. Microfluidic channel fabrication

Microfluidic PDMS channels were required for all experiments and were fabricated by using a standard PDMS molding technique [18, 19]. SU-8 (MicroChem SU-8) was spun onto a 4 inch silicon wafer resulting in a uniform layer of SU-8. For most of the testing, 100 μm-thick layers of SU-8 were used, but some tests were run with layers as thick as 200 μm with similar results (theoretically the size and type of the channel should have little or no effect on the performance of the interconnect).

The SU-8 was then exposed using a photo-resist mask after which the wafer was baked at 90 °C for 60 min and the unexposed SU-8 was developed away. To prevent the PDMS casting from sticking to the SU-8 mold, a silanizing agent, (tridecafluoro-1,1,2,2-tetrahydrooctyl)triethoxysilane (Gelest Inc.), was vacuum-deposited for 2 h onto the mold. Once the mold was completed, liquid PDMS (Dow Corning Sylgard 184® Silicon Elastomer Base) was mixed thoroughly with the cross-linking agent (Dow Corning Sylgard 184 Silicone Elastomer Curing Agent®) at a volumetric ratio of 10:1 and pored over the mold in a plastic dish to a thickness of 6 mm. The dish was then placed in a vacuum chamber to remove air bubbles from the prepolymer mixture.

Once the PDMS was completely degassed, the PDMS was cured for 2 h at 65 °C. The PDMS was then peeled carefully from the mold. Typically, the holes into which the interconnects are inserted were created after the PDMS was removed from the SU-8 mold but prior to bonding to another substrate, thus minimizing damage to the opposite side of the microfluidic channel. The interconnects were created by first, coring a small hole in the PDMS to access molded or buried microchannels using a modified 20 gauge needle, and second, inserting an unmodified needle into the hole to create a direct connection to the microchannel. No bonding or molding was required for the interconnects themselves.

Three different methods for producing the cored holes were used. The first method involved twisting the coring tool while pressing the tool through the PDMS to the buried microchannel. The second method did not employ any twisting motion, but simply required pressing the coring tool through the PDMS to the buried microchannel. Other researchers have employed a variation on this method, sandwiching the PDMS between polycarbonate sheets with a hole where the interconnect is to be placed, and a rubber stopper supporting the PDMS during coring [11]. The third coring method involved placing the coring tool in a drill chuck and using a drill press to core the hole for the interconnect. The feed rate was done slowly by hand with RPM ranging from 120 to 170.

Once the holes for the interconnects were created, the PDMS was bonded to another PDMS specimen (created using the same process only without using the SU-8 layer). Several bonding methods for PDMS were employed in these experiments including oxygen plasma [14], using liquid PDMS as a sealing agent [10] and clamping (using mechanical systems to force the layers together). PDMS bonding using oxygen plasma methods has been performed using a variety of parameters [14]. In this case, oxygen plasma bonding was accomplished by exposing the two PDMS substrates to be bonded to an oxygen plasma using an Oxford Plasmalab 80 Plus with pure oxygen flowing at 23.4 sccm; a pressure of 243 mtorr and an applied RF power of 73 W for 20 s before placing the two substrates in contact with each other. Once in contact, all the air bubbles between the PDMS layers were squeezed out. The specimen was then baked for 2 h at 65 °C. To yield the best results, the PDMS layers were bonded within 6 h of curing, though acceptable results were also found when bonding was performed within 24 h of curing. The use of liquid PDMS as a bonding agent involves mixing a small amount of PDMS and cross-linking agent (ratio of 10:1 as before) and applying a thin layer of the PDMS to the previously cured surfaces using a razor blade before allowing the completed system to cure at 65 °C for 2 h. The third bonding method, clamping, involved using polycarbonate plates and screws to compress the two PDMS substrates containing the microchannels together. Clamping the bonded substrates together was avoided if possible since it is very tedious due to the need to drill holes in the polycarbonate plates and align them with the interconnects. Clamping was used when it was discovered that the bonds tended to fail before the interconnects. Thus, clamping enabled testing of the interconnects rather than the bonding of the substrates. When clamping was used along with oxygen plasma or PDMS bonding, the maximum pressure sustainable before bond failure increased significantly.

3.2. Thickness limitations

Six millimetre thick PDMS specimens were used in these tests because thicknesses below 3 mm created difficulties in both coring the interconnect and supporting the needle after insertion, though the technique is still valid with these thinner PDMS layers. Coring is possible with thinner layers, but the quality is less consistent and a sharp coring tool is required. The difficulty of supporting the needle can be overcome by further modifying the needle used to form the interconnect. Modifications that reduce the support requirements include removing the luer fitting or shortening the needle. In addition, a packaging fixture can be used to maintain the geometry and position of the interconnect needles, but the additional requirement of a fixture reduces some of the simplicity of the proposed packaging method. In most commercial applications, a fixture will likely be used in most situations, so this additional manufacturing step will likely be less of a concern.

Many current PDMS microfluidic devices are much smaller than 3–6 mm, but the testing of such specimens is still considered valuable for four reasons. First, the present technique will be useful in systems containing multiple layers that result in a system total thickness of 3–6 mm. Second, the top covering layer of most microfluidic devices can be of larger dimension in most cases, so a thicker connection layer of PDMS could be considered as a part of the packaging of the system. In addition, a thicker PDMS layer often eliminates the need for bonding to a glass or other solid substrate to maintain the structure of the microfluidic system. Third, the presented technique allows for a high density of interconnects per surface area (shown by density testing) resulting in an overall decreased size of the system in many cases. Fourth, test results using a 6 mm-thick specimen provide information on general trends and upper limits on thinner systems.

3.3. Interconnect quality

The observed quality of the cored holes was determined to be a major factor in the physical limits measured for the interconnects. However, it is quite difficult to quantitatively assess the quality of a cored hole. Accordingly, a more qualitative approach to assessing interconnect quality was used. The cored holes, and the resulting interconnects, used in this work were described as either poor, moderate or good,

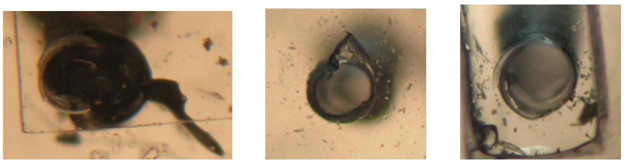
(*a*) (*b*) (*c*)

Figure 4. Examples of varying interconnect quality: (*a*) a 'poor' interconnect due to the vertical tearing on the right side, (*b*) a 'moderate' interconnect due to circular tearing on the surface, but otherwise internally intact, (*c*) a 'good' interconnect shows no damage on the surface and is internally intact.

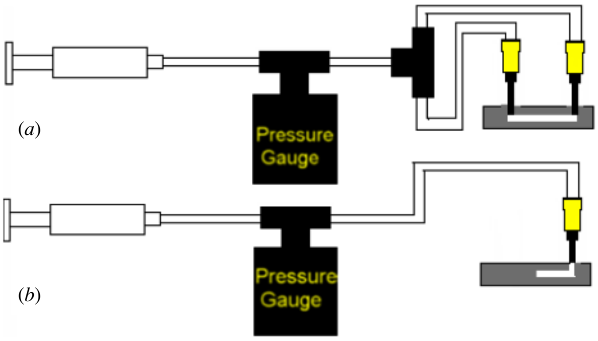

Figure 5. Illustration of the two setups used during pressure testing of the interconnects. Setup (*a*) uses two interconnects and setup (*b*) uses one interconnect and a dead-end channel.

based on observation of the cored holes through a microscope. An interconnect was considered 'poor' if there was vertical tearing. A 'moderate' rating was given if the surface of the PDMS showed some damage, such as spiral tears, but otherwise the interconnect was internally intact. If no tearing or surface damage was present the channel was considered 'good'. Examples of each of these categories are presented in figure 4.

3.4. *Internal pressure limitations and insertion/removal testing*

The ability of the interconnects to withstand pressure was tested using a syringe pump and DI water. The output from a syringe pump (KD Scientific Model 120) was connected to both a pressure gauge and the microchannels via tubing. Two different techniques were used to connect the channels to the pump. The first involved two interconnects at the same pressure created using a 'T' in the tubing. The two interconnects were attached to the same microchannel as shown in figure 5(*a*). The second setup involved only one interconnect leading to a dead-end channel as shown in figure 5(*b*). The pressure gauge (Omega Engineering Inc. PX180-100GV) was accurate to approximately 700 kPa and provided an output voltage in mV that was proportional to the measured pressure. Another pressure gauge (Validyne DP15-46 calibrated to 1400 kPa) was used to test the interconnects at higher pressures. Pressure testing was done on a number of systems that varied in bonding type, hole quality, test setup and PDMS thickness.

One major question regarding the PDMS interconnects revolves around their durability, especially when the interconnects are removed and inserted repeatedly. The ability to remove and insert the needle many times allows repeated use of the channels, customization of the channels, improved prototyping of the channels, and the changing of fluid sources, which may be especially useful for cleaning the channels. Accordingly, after the pressure tests were conducted, one interconnect was tested for the ability to withstand high pressures after multiple connect and disconnect steps by inserting and removing a needle ten times and testing the pressure again. Insertion and removal of the interconnect followed by pressure testing was repeated every ten cycles until the needle had been inserted and removed 100 times.

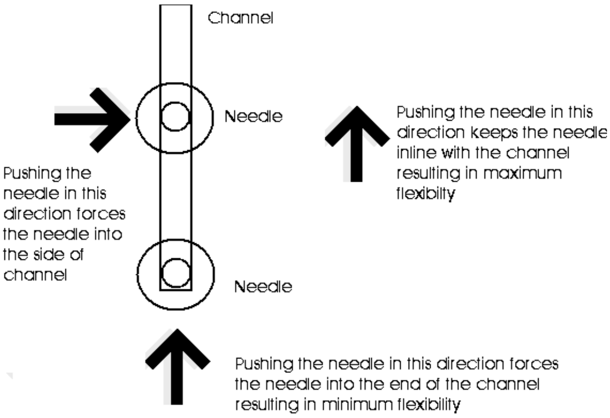

Figure 6. Illustration of flexibility test. After inserting the needle, the top of the needle is pushed in the direction of one of the arrows, as indicated.

3.5. *Flexibility limitations*

One major benefit of PDMS systems is the flexion that the needle can experience without damaging the system. The ability of the interconnect to withstand deflection is especially valuable during the prototyping stage of microfluidic systems, and allows for the simplification of experimental setups and repeated modification of the channel arrangement.

In order to test the interconnect flexibility a PDMS channel was created as described previously with a thickness of 6 mm. The needle was inserted perpendicular to the PDMS into the interconnect and then angled in multiple directions until either the flow stopped or leakage occurred at the interface (see figures 6 and 7). The angle of rotation away from vertical was measured with a protractor using the channel floor as a baseline. These tests were video taped in order to maximize the accuracy of the measurements. Deflection in three directions was tested. First, the needle was angled so that the needle's point was forced into the sidewall of the channel. Next, the needle was angled so that the needle's point was forced in the channel itself. Finally, the needle was angled so that the point was forced into a dead-end. During all experiments a constant flow syringe pump connected to a needle inserted into the system was used to drive fluid through the interconnects and microchannels at a flow rate of 50 ml h^{-1}. The setup was similar to that shown in figure 5(*b*) excluding the pressure gauge.

Creating a system of channels that are close together with multiple interconnects is often required in microfluidic systems, but can be challenging to accomplish due to packaging and interconnect limitations. We anticipated that

Figure 7. Picture of flexibility test in progress. After inserting the needle, the top is pushed to test the flexibility, and the angle where failure occurs is measured using the protractor.

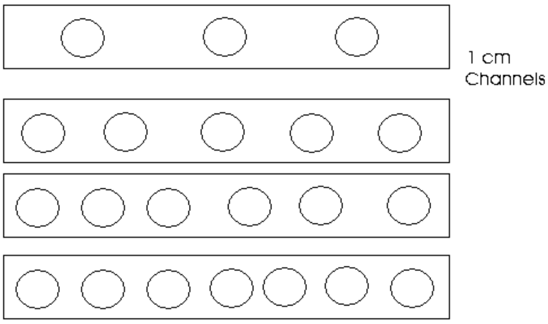

Figure 8. Diagram of interconnect locations in interconnect density test (spacing variation due to hand coring).

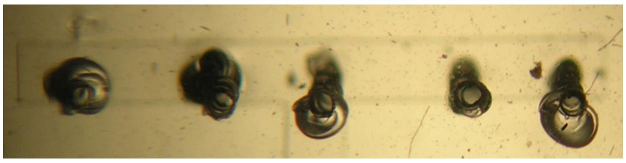

Figure 9. Photograph of experimental test channel with five interconnects in a 1 cm-long channel (hand-cored).

due to the flexibility of the PDMS, a high needle density would be possible in spite of large needle-to-tubing connections. Interconnect density limitations were tested by creating PDMS channels as described previously. These experimental test channels were prepared with three, five, six and seven interconnects over a 1 cm microchannel length as shown in figures 8 and 9. A flow rate of 50 ml h^{-1} was applied and the interconnects were considered to have failed when leaking occurred at the interface.

4. Results and discussion

4.1. Internal pressure limitations and insertion/removal testing

Table 1 presents the results of pressure testing of the interconnects for the PDMS systems. From these results we see that the pressure limits are highly dependent on interconnect quality. Interconnects fabricated by twisting the coring tool by hand seemed less precise but generally successful. The interconnects were difficult to keep straight which made it difficult to put many interconnects close together. The twisting method occasionally made spiral tears in the inside surface of the holes, but the tears did not cause leakage at low pressures. Additionally, this method rarely created vertical tears even when a dull coring tool was used.

The second coring method, pushing the coring tool without twisting through the PDMS, worked well when the coring tool was sharp. When the coring tool was dull, the resulting interconnects had vertical tears inside the holes which leaked at low pressures.

The third coring method, which involved use of a drill press to core the interconnect, produced cored holes with exceptional surface quality where the tool entered (see

Table 1. Pressure testing results.

Test	Maximum pressure (kPa)	Bonding method	Interconnect quality	Test setup (figure 5)	Thickness (mm)	Failure mode	Coring method
1	165.474	PDMS	Good	Two needles	6	Bond	Twisting
2	330.948	PDMS	Good	Two needles	6	Bond	Twisting
3	461.948	PDMS	Good	Two needles	6	Bond	Twisting
4	489.527	PDMS	Good	Two needles	6	Bond	Twisting
5	321.31	O_2/clamped	Moderate	One needle	6	Interconnect	Pushing
6	11.176	O_2/clamped	Poor	Two needles	3	Interconnect	Pushing
7	330	O_2/clamped	Moderate	One needle	6	Interconnect	Pushing
8	386	O_2/clamped	Moderate	One needle	6	Interconnect	Pushing
9	276	O_2/clamped	Moderate	Two needles	6	Interconnect	Pushing
10	700[a]	O_2/clamped	Good	Two needles	6	None[a]	Twisting
11	289	O_2	Good	One needle	6	Bond	Twisting
12	565	O_2	Good	One needle	6	Bond	Twisting
13	700[a]	O_2/clamped	Good	One needle	6	None[a]	Pushing

[a] Pressure gauge limit was 700 kPa.

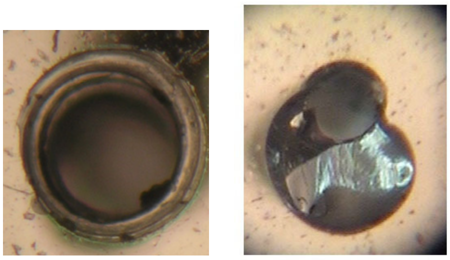
(*a*) (*b*)

Figure 10. Machined cored interconnect: (*a*) shows exceptional entrance quality and (*b*) shows spiral tear where coring device exited.

figure 10(*a*)), but often resulted in small spiral tears at the exit face (such as seen in figure 10(*b*)). These exit flaws (see the figure) could possibly be minimized by adjusting tool rotation speed or by trimming the PDMS specimen to eliminate the surface damage. This type of interconnect was not used in the pressure testing.

Table 1 also indicates that pressure is often more limited by the bonding technique than the interconnect itself. Tests 1–4 all displayed good interconnect qualities, but failed at the bond. O_2 plasma bonding also showed limitations with bonding in tests 11 and 12. However, when the O_2 plasma bonding was combined with clamping much, higher pressures were possible and we were able to test the interconnects rather than the bonding method.

It is important to note that even though interconnects created by pushing without twisting often resulted in moderate quality interconnects, these systems still reached pressures high above that required for most microfluidic systems [16]. Interconnects of good quality demonstrated exceptional resistance to elevated static pressures. With stronger bonding or combinations of bonding and modifications in PDMS thickness and needle size, it is probable that these systems could handle pressures required for complex, high-pressure systems [1]. A slight modification to the interconnect fabrication method involving the use of a smaller needle as the coring tool may also make it capable of handling higher pressures. The smaller cored hole would increase the circumferential pressure on the needle and should allow for higher internal pressures in the system. Increasing the thickness of the PDMS to equal the length of the needle could be another method that might increase the pressure resistance of the interconnects. Experiments of this type have not yet been conducted.

Another test to determine the interconnects response to repeated assembly and disassembly was conducted by measuring static pressure limits after multiple removals and insertions of the needles. The same interconnect used in test 13 in table 1 was used. The needle removals and insertions were done rather roughly to simulate actual use. During each of the ten measurements static pressure reached 700 kPa. From these results it was found that the PDMS interconnect is quite durable and resilient to repeated insertion and removal. The ability to remove and insert the needle so many times demonstrates that this interconnect method will allow repeated disassembly and reassembly. This quality is especially valuable during the prototyping phase of microfluidic systems, and may allow for better quality assessment and control in a manufacturing environment. Although a system like this is often intended to be disposable due to its low cost, there is also a possibility that interconnects could be repaired in the event of ripping damage to microfluidic systems designed for long-term use. These repairs typically require only the application of uncured PDMS, or can involve adhesives if desired.

Table 2. Interconnect flexibility results using 6 mm-thick PDMS.

Test number	Failure mode	Direction of rotation	Maximum angle (°)
1	Stop of flow	Into sidewall	50
2	Stop of flow	Into sidewall	48
3	Stop of flow/interconnect	Into channel	60
4	Stop of flow/interconnect	Into channel	62
5	Stop of flow	Into channel, dead-end	30
6	Stop of flow	Into sidewall	45
7	Stop of flow	Into sidewall	50

4.2. Interconnect flexibility testing results

Table 2 shows the results from the interconnect flexibility tests. From table 2 it can be seen that the interconnect flexibility is largest in the direction of the channel; however, when taken to its limits, deflection in this direction also is most prone to leaking at the interface. These results demonstrate two benefits. First, the results show that the interconnects are very practical for many systems, including those that may experience rough handling, such as those for the consumer market or those in a rapid prototyping lab. Second, the results provide help in designing microfluidic systems. For example, because flow stops after a mild interconnect deflection of 30° into the end of a channel, it may be best to place the interconnect so that it is not at the end of a channel if high flexibility and continued flow are important. Placing the interconnect some distance from the end of a microchannel can increase the flexibility by up to 15°. Although the flow of fluid stops after a 45°–60° interconnect deflection, the needle can be rotated to nearly 80° before tearing occurs. Thinner specimens suffer from early tearing due to the fact that internal tears are so near the surface. Thinner specimens also tend to exhibit poor sealing because the contact area between the needle and PDMS is relatively small. Thicker specimens have similar flexibility properties but were not tested extensively.

4.3. Interconnect density testing results

The results of the interconnect density testing are presented in table 3. In test 5, which included seven interconnects in a 1 cm channel length, failure occurred between two of the interconnects, while the remainder continued to function. Using a machine to core these interconnects could possibly increase the interconnect density due to the better quality of the cored holes and the higher precision of the interconnect locations. Another method to potentially increase needle density would be to use smaller needles, such as 32 gauge needles.

Table 3. Interconnect density test results in a 1 cm-long channel, tests 1–5.

Number of interconnects	Result
2	Successful
4	Successful
5	Successful
6	Successful
7	Failure at interconnect

5. Conclusion

The characteristics of PDMS press-fit microfluidic interconnects make these types of interconnects practical for low-pressure microfluidics and a possibility for high-pressure microfluidic systems. The flexible nature of the PDMS press-fit interconnects, both with regard to physical deflections and the ability to reassemble the interconnects multiple times, makes PDMS ideal for research systems where the setup is constantly being adjusted and multiple cleaning cycles are necessary. The flexibility characteristics also make it possible for many interconnects to be placed close together in order to minimize the dimensions of complex systems that require many interconnects. These results suggest that this technique will reduce the size and cost of packaging microfluidic systems as well as simplifying the fabrication and modification of microfluidic systems. Thus, these interconnects will aid in overcoming one of the greatest challenges in the development and commercialization of microfluidic systems [5, 6].

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