Shear Stress and Shear Rates for ibidi µ-Slides Based on Numerical Calculations

This application note gives a short introduction and lists all the equations to calculate the wall shear stress (WSS) in ibidi channel slides. For simplicity reasons, the term "shear stress" is used here, always referring to wall shear stress. Further, the shear rate is calculated.

Also included is a general terminology introduction, lists of equations, and points to consider before setting up an experiment.

Due to the standardized Luer adapters, the ibidi channel slides can be easily combined with any flow system (e.g., the ibidi Pump System). The shear stress calculations apply equally to all systems.

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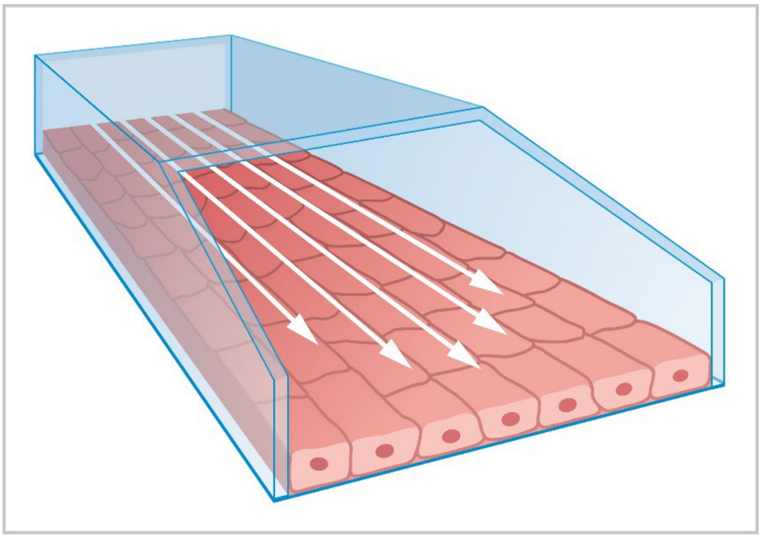


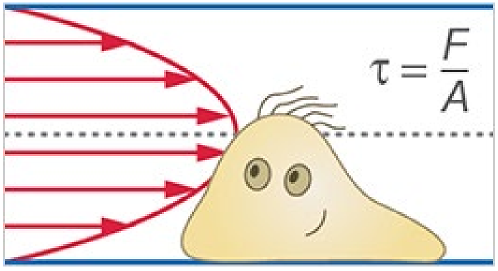
Quick Guide for Shear Stress Calculation in ibidi Channel Slides

Φ	flow rate	ml/min (**µl**/min for µ-Slide VI $^{0.1}$)
τ	shear stress	dyn/cm²
η	dynamical viscosity	dyn·s/cm²

µ-Slide I $^{0.2}$ Luer	$\tau = \eta \cdot 512.9 \cdot \Phi$	
µ-Slide I $^{0.2}$ Luer Glass Bottom	$\tau = \eta \cdot 330.4 \cdot \Phi$	
µ-Slide I $^{0.4}$ Luer	$\tau = \eta \cdot 131.6 \cdot \Phi$	
µ-Slide I $^{0.4}$ Luer Glass Bottom	$\tau = \eta \cdot 104.7 \cdot \Phi$	
µ-Slide I $^{0.6}$ Luer	$\tau = \eta \cdot 60.1 \cdot \Phi$	
µ-Slide I $^{0.6}$ Luer Glass Bottom	$\tau = \eta \cdot 51.5 \cdot \Phi$	
µ-Slide I $^{0.8}$ Luer	$\tau = \eta \cdot 34.7 \cdot \Phi$	
µ-Slide I $^{0.8}$ Luer Glass Bottom	$\tau = \eta \cdot 31.0 \cdot \Phi$	
µ-Slide VI $^{0.4}$	$\tau = \eta \cdot 176.1 \cdot \Phi$	
µ-Slide VI $^{0.5}$ Glass Bottom	$\tau = \eta \cdot 99.1 \cdot \Phi$	
µ-Slide VI $^{0.1}$	$\tau = \eta \cdot 10.7 \cdot \Phi$	*
µ-Slide Membrane ibiPore Flow	$\tau = \eta \cdot 131.6 \cdot \Phi$	
µ-Slide I Luer 3D	$\tau = \eta \cdot 60.1 \cdot \Phi$	
µ-Slide y-shaped		
- single channel	$\tau = \eta \cdot 227.4 \cdot \Phi$	
- branched area	$\tau = \eta \cdot 113.7 \cdot \Phi$	
µ-Slide III ^{3in1}		
- 1 mm channel	$\tau = \eta \cdot 774.1 \cdot \Phi$	
- 3 mm channel	$\tau = \eta \cdot 227.4 \cdot \Phi$	

* Flow rate in µl/min

1 Glossary

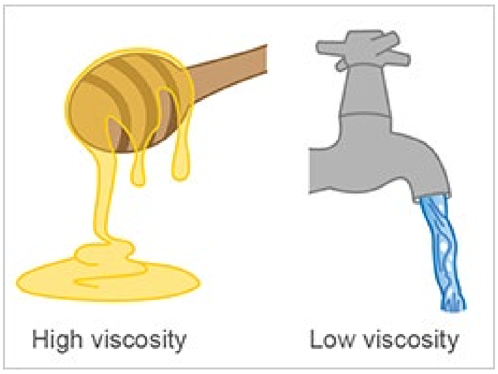


Shear stress is a force that acts on a surface when a solid object is pulled across the surface, or a liquid flows over it. It acts parallel to the surface, in the direction in which the object (or fluid) is moving. Shear stress (τ) is defined as force per area (τ = F/A, where τ = the shear stress, F = the force applied, and A = the cross-sectional area of the material surface).

Shear stress in fluids/flow profile: A fluid flowing through a channel can be seen as a stack of fluid layers moving on top of each other. The shear stress is caused by the friction between the layers, due to the fluid's viscosity. The friction between the layers results in the velocity distribution, the flow profile. The viscosity determines how high the friction between the layers is.

Wall shear stress (WSS) is present directly at the boundary layer from the channel surface to the first liquid layer when liquid flows through a channel. This is the force experienced by the cells and which influences their behavior, morphology, and physiology. WSS is directly related to the viscosity of the fluid and the shear rate.

Shear rate is defined as the change in velocity, at which one fluid moves over an adjacent layer. The shear rate is determined by both the vessel cross-section and the flow rate, measured in reciprocal seconds (s^{-1}). The shear rate is an important parameter in rolling adhesion experiments, as it indicates how fast the cells roll over the surface; or how long the contact time is to the adherent cells.



Viscosity (strictly speaking, dynamic viscosity) is the property of liquids that describes their fluidity. It decisively determines how easily liquid layers can slide over each other and is an important parameter for calculating shear stress. Water, for example, has a lower viscosity than honey. In Newtonian fluids (e.g., water, cell culture medium), the viscosity is independent of the flow rate.

Flow rate is the volume flow through a channel in a given time. The flow rate alone does not indicate the force applied to the adherent cells, but it is needed for the shear stress calculation. The flow rate (Φ) is defined as a volume per time (e.g., ml/min).

2 Considerations Before Setting up a Flow Experiment

Before the setup of a successful flow experiment, several parameters must be considered:

- Cell type
- **Shear stress** (tissue- and species-specific)
- Viscosity of the needed medium
- Available amount of medium, supplements, and number of cells
- Duration of the experiment (hours, days, weeks)
- Flow characteristics (continuous, one-way, oscillating…)
- Coating of the surface (cell type-dependent)
- Further experimental details (e.g., addition of substances, time points of measurements, live cell imaging)
- Experimental endpoints (e.g., qPCR, western blot, immunofluorescence staining)

Follow these steps to calculate the necessary flow rate applied by the pump:

1. Define the **shear stress** level to be applied

   Knowing your cell type's physiological shear stress level is essential for every flow experiment. The shear stress required in your experiment will define the choice of the pump, tubing, and channel slides. Then use the required shear stress to calculate the flow rate, which the pump system will apply.

2. Choose the optimal **perfusion system** (pump)

   A range of pump types are designed for various applications, and finding a suitable one depends on the experimental setup (duration, volume, flow characteristics…). For example, for long-term cultivation (e.g., endothelial cell conditioning under flow), we recommend the ibidi Pump System.

3. Determine the **viscosity** of the needed medium (Section 3)

4. Choose the optimal **channel slide and tubing** (see here)

   The ibidi channel slides have different channel geometries, which influence the range of shear stress that can be applied. This range also depends on the flow that the respective pump can generate. Generally, the following rules-of-thumb can be applied:

   - Smaller dimensions channels favor the generation of high shear stress values.
   - Larger dimensions channels favor the generation of low shear stress values.

   Based on the flow rate range of your pump, you can calculate the range of shear stress you will be able to apply. Put in the maximum and minimum flow rate values of your pump into the equation of the respective slide (Sections 4 and 5). This way, you calculate the minimum and maximum possible shear stress and determine whether the selected slide and pump combination will generate the desired shear stress.

5. Once you have followed steps 1–4, you can calculate the exact **flow rate** that is needed to achieve the desired shear stress in the used slide as given by the equations in Section 5.

3 Viscosity of the Perfused Medium

The shear stress in a rectangular channel is dependent on the geometry of the channel, the viscosity, and the flow rate of the perfused medium (Section 4).

Before you start a cell culture experiment, measure the viscosity of your cell culture medium using a viscometer. Several viscometers can be used, such as U-tube viscometers, falling sphere viscometers, vibrational viscometers, rotational viscometers, and others.

Since the viscosity is highly temperature-dependent, take care to measure the viscosity of your medium at the temperature used in your experiment.

Some typical values of dynamical viscosity:

	Temperature	Viscosity in dyn·s/cm²	Viscosity in mPa·s
Water	20°C	0.01	1.002
Water	37°C	0.0068	0.684
Cell culture medium with 10% serum	37°C	~0.0072	~0.72
Cell culture medium with 0.2% methyl cellulose	37°C	~0.03	~3.0

4 Shear Stress Calculation

The **shear stress** in a rectangular channel is dependent on the **flow rate** of the perfused medium. The control of the flow rate depends on the pump type being used. For syringe pumps, the flow rate is set after having defined the syringes; for peristaltic pumps, the flow rate is set when knowing the diameter of the tubing. When using the ibidi Pump System, the flow rate can easily be set within the software.

The shear stress in a rectangular channel is further dependent on the **viscosity** (Section 3) of the perfused medium. To calculate the shear stress in a rectangular channel correctly, you additionally need a **slide-dependent factor**. Please find the slide-dependent factors for all ibidi Channel Slides in Section 5.

The shear stress in a rectangular channel is calculated as follows:

$$\tau = \eta \cdot \text{factor (dependent on slide)} \cdot \Phi$$

τ = shear stress

η = dynamical viscosity

Φ = flow rate

For simplicity reasons, the calculations below include all unit conversions (not shown).

5 Shear Stress Calculation for ibidi Channel Slides

Here you find the slide-dependent factors for all ibidi Channel Slides. To calculate the shear stress correctly, you need to know the viscosity of the perfused medium (Section 3).

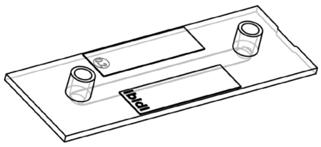
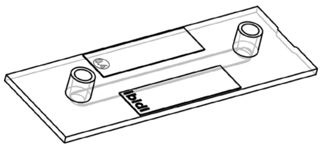
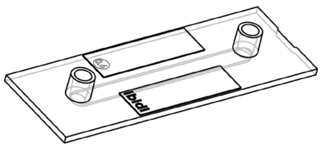
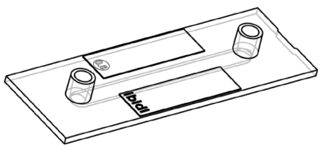
Nomenclature and units:

Φ	flow rate	ml/min (**µl**/min for µ-Slide VI $^{0.1}$)
τ	shear stress	dyn/cm²
η	dynamical viscosity	dyn·s/cm²

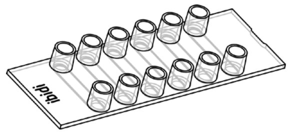
To calculate the shear stress, use the following equations and insert the flow rate and viscosity values in the indicated units. To calculate the flow rate, which is needed to achieve a given shear stress, solve the equation by flow rate.

For simplicity reasons, the calculations include all unit conversions (not shown).

5.1 Shear Stress in the µ-Slide I Luer Family

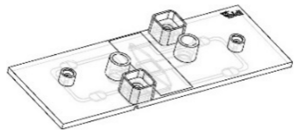
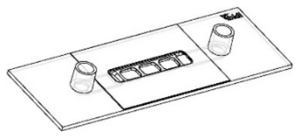
µ-Slide I $^{0.2}$ Luer	$\tau = \eta \cdot 512.9 \cdot \Phi$	
µ-Slide I $^{0.2}$ Luer Glass Bottom	$\tau = \eta \cdot 330.4 \cdot \Phi$	
µ-Slide I $^{0.4}$ Luer	$\tau = \eta \cdot 131.6 \cdot \Phi$	
µ-Slide I $^{0.4}$ Luer Glass Bottom	$\tau = \eta \cdot 104.7 \cdot \Phi$	
µ-Slide I $^{0.6}$ Luer	$\tau = \eta \cdot 60.1 \cdot \Phi$	
µ-Slide I $^{0.6}$ Luer Glass Bottom	$\tau = \eta \cdot 51.5 \cdot \Phi$	
µ-Slide I $^{0.8}$ Luer	$\tau = \eta \cdot 34.7 \cdot \Phi$	
µ-Slide I $^{0.8}$ Luer Glass Bottom	$\tau = \eta \cdot 31.0 \cdot \Phi$	

5.2 Shear Stress in the μ-Slide VI Family

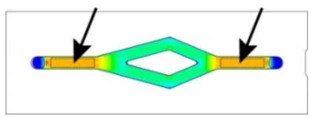
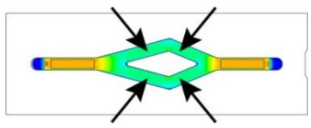
μ-Slide VI $^{0.4}$	$\tau = \eta \cdot 176.1 \cdot \Phi$	
μ-Slide VI $^{0.5}$ Glass Bottom	$\tau = \eta \cdot 99.1 \cdot \Phi$	
μ-Slide VI $^{0.1}$	$\tau = \eta \cdot 10.7 \cdot \Phi$ *	

* Flow rate in µl/min

5.3 Shear Stress in the μ-Slide Membrane ibiPore Flow and μ-Slide I Luer 3D

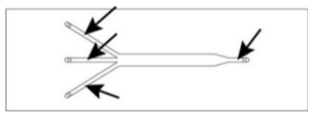
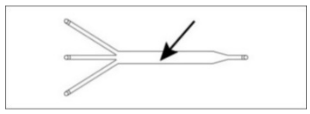
μ-Slide Membrane ibiPore Flow	$\tau = \eta \cdot 131.6 \cdot \Phi$	
μ-Slide I Luer 3D	$\tau = \eta \cdot 60.1 \cdot \Phi$	

5.4 Shear Stress in the μ-Slide y-shaped (Uniform Laminar Flow Regions)

Single channel area	$\tau = \eta \cdot 227.4 \cdot \Phi$	
Branched area	$\tau = \eta \cdot 113.7 \cdot \Phi$	

Numerical simulations of exact shear stress values at the branching points can be found in Application Note 18 "Shear Stress and Shear Rates in µ-Slide µ-Shaped".

5.5 Shear Stress in the μ-Slide III ^{3in1}

1 mm channels	$\tau = \eta \cdot 774.1 \cdot \Phi$	
3 mm channel	$\tau = \eta \cdot 227.4 \cdot \Phi$	

6 Shear Rate Calculations for ibidi Channel Slides

Do not confuse shear stress and shear rate!

The shear stress is the force acting on the cell layer on the wall. The shear rate describes the velocity profile of the perfused medium.

The following equation relates shear stress and shear rate:

$$\boxed{\tau = \eta \cdot \gamma}$$

Φ	flow rate	ml/min (**µl**/min for µ-Slide VI 0.1)
τ	shear stress	dyn/cm²
γ	shear rate	1/s
η	dynamical viscosity	dyn·s/cm²

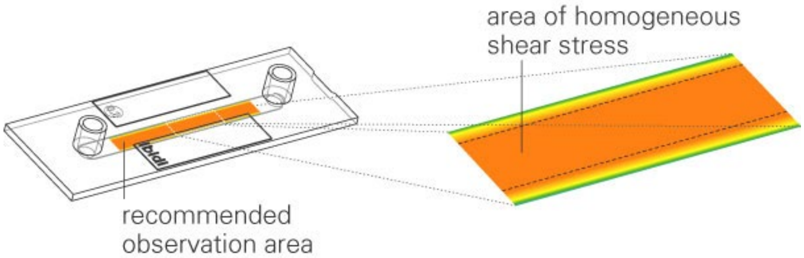
The shear rate γ (1/s) at the wall of the channels can be defined with the following equation:

µ-Slide I 0.2 Luer	$\gamma = 512.9 \cdot \Phi$	Φ in ml/min
µ-Slide I 0.2 Luer Glass Bottom	$\gamma = 330.4 \cdot \Phi$	Φ in ml/min
µ-Slide I 0.4 Luer	$\gamma = 131.6 \cdot \Phi$	Φ in ml/min
µ-Slide I 0.4 Luer Glass Bottom	$\gamma = 104.7 \cdot \Phi$	Φ in ml/min
µ-Slide I 0.6 Luer	$\gamma = 60.1 \cdot \Phi$	Φ in ml/min
µ-Slide I 0.6 Luer Glass Bottom	$\gamma = 51.5 \cdot \Phi$	Φ in ml/min
µ-Slide I 0.8 Luer	$\gamma = 34.7 \cdot \Phi$	Φ in ml/min
µ-Slide I 0.8 Luer Glass Bottom	$\gamma = 31.0 \cdot \Phi$	Φ in ml/min
µ-Slide VI 0.4	$\gamma = 176.1 \cdot \Phi$	Φ in ml/min
µ-Slide VI 0.5 Glass Bottom	$\gamma = 99.1 \cdot \Phi$	Φ in ml/min
µ-Slide VI 0.1	$\gamma = 10.7 \cdot \Phi$	Φ in **µl**/min
µ-Slide Membrane ibiPore Flow	$\gamma = 131.6 \cdot \Phi$	Φ in ml/min
µ-Slide I Luer 3D	$\gamma = 60.1 \cdot \Phi$	Φ in ml/min
µ-Slide y-shaped (uniform laminar flow regions)		
- single channel	$\gamma = 227.4 \cdot \Phi$	Φ in ml/min
- branched area	$\gamma = 113.7 \cdot \Phi$	Φ in ml/min
µ-Slide III 3in1		
- 1 mm channel	$\gamma = 774.1 \cdot \Phi$	Φ in ml/min
- 3 mm channel	$\gamma = 227.4 \cdot \Phi$	Φ in ml/min

7 Area of Homogeneous Shear Stress

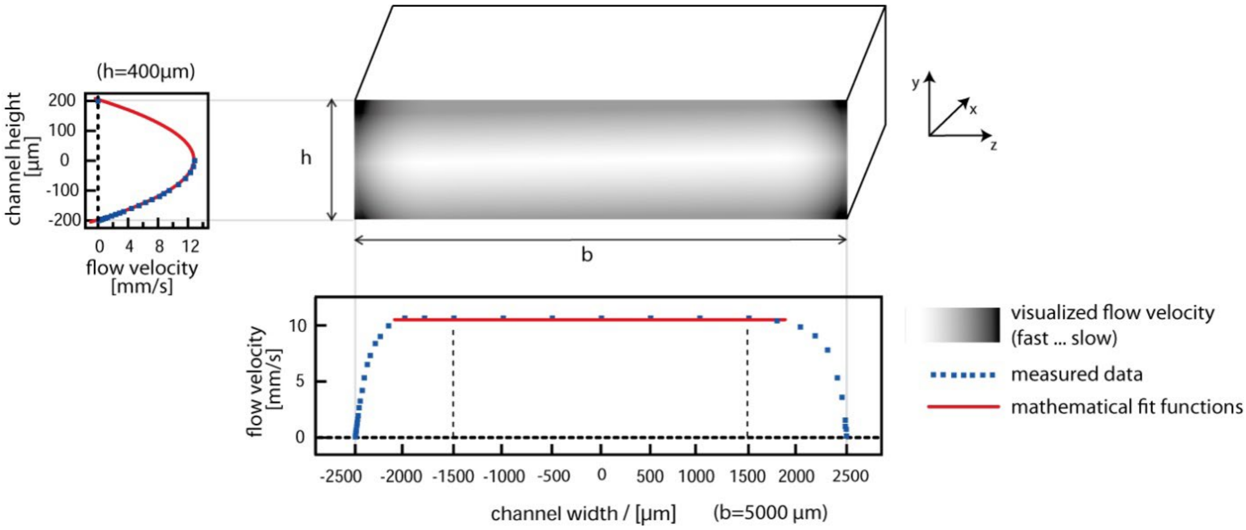
All shear stress calculations are only valid in regions away from the slide walls (see orange area below). Side effects near the wall are ignored. Observations should be done in a distance away from the walls comparable to the channel height.

For example, if the channel has a height of 400 µm, the observation area showing a homogeneous flow profile will be about 400 µm from the side walls in the center region of the channel (orange area).



8 Flow Profile in y-Direction

All ibidi channel slides are characterized by parabola-shaped flow profiles in the y-direction. An example of the flow profile inside µ-Slide I $^{0.4}$ Luer is shown below.



9 Background Information

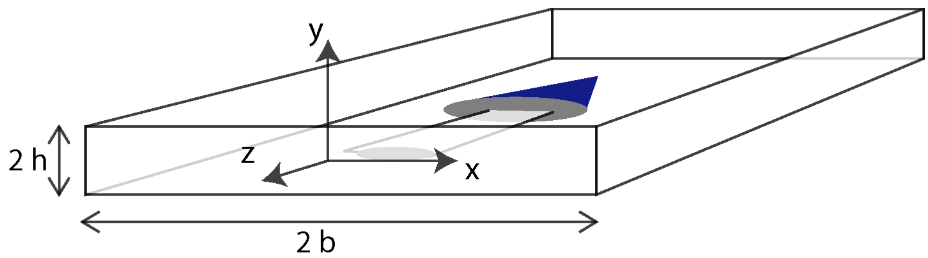
The local flow velocity v(x,y) is calculated as follows[1]:

$$v(x,y) = -\frac{1}{\eta}\frac{dp}{dz}\left\{\frac{b^2}{2} - \frac{x^2}{2} - \sum_{n=0}^{\infty}\frac{(-1)^n(2b^2)}{(2n+1)^3}\left(\frac{2}{\pi}\right)^3 \frac{\cosh\left[(2n+1)\left(\frac{\pi y}{2b}\right)\right]}{\cosh\left[(2n+1)\left(\frac{\pi h}{2b}\right)\right]}\cos\left[\frac{(2n+1)\pi x}{2b}\right]\right\}$$

The total flow Φ through the channel is calculated as follows[1]:

$$\Phi = -\frac{1}{\eta}\frac{dp}{dz}\left\{\frac{4}{3}hb^3 - 8b^4\left(\frac{2}{\pi}\right)^5 \sum_{n=0}^{\infty}\frac{1}{(2n+1)^5}\tanh\left[\frac{(2n+1)\pi h}{2b}\right]\right\}$$

2 h is the height of the channel in direction of the y-axis, 2 b is the width of the channel in direction of the x-axis, the z-axis is in direction of the flow. $\frac{dp}{dz}$ is the change of pressure along the channel.



Coordinate conventions: The coordinate cross is in the center of the channel. The y-axis is in the vertical direction, the x-axis in the horizontal direction and perpendicular to the flow direction. The z-axis is parallel to the flow direction.

$\frac{dp}{dz}$ is eliminated as follows:

$$\Phi = -\frac{1}{\eta}\frac{dp}{dz}\underbrace{\left\{\frac{4}{3}hb^3 - 8b^4\left(\frac{2}{\pi}\right)^5 \sum_{n=0}^{\infty}\frac{1}{(2n+1)^5}\tanh\left[\frac{(2n+1)\pi h}{2b}\right]\right\}}_{q}$$

$$\frac{dp}{dz} = -\eta\frac{\Phi}{q}$$

Cornish, R. J. (1928). "Flow in a Pipe of Rectangular Cross-Section." Proc. R. Soc. A **12o**(786): 691-700

Shear stress is calculated using the relation:

$$\tau(x,y) = \eta \frac{\partial v(x,y)}{\partial y}\bigg|_{y=-h} = \eta \left(-\frac{1}{\eta}\frac{dp}{dz} \sum_{n=0}^{\infty} \frac{(-1)^n\, b\pi}{(2n+1)^2} \left(\frac{2}{\pi}\right)^3 \frac{\sinh\left[(2n+1)\frac{\pi y}{2b}\right]}{\cosh\left[(2n+1)\frac{\pi h}{2b}\right]} \cos\left[\frac{(2n+1)\pi x}{2b}\right] \right)\Bigg|_{y=-h}$$

Elimination of $\frac{dp}{dz}$ gives:

$$\tau(x,y) = \eta \left(-\frac{1}{\eta}\left(-\eta\frac{\Phi}{q}\right) \sum_{n=0}^{\infty} \frac{(-1)^n\, b\pi}{(2n+1)^2} \left(\frac{2}{\pi}\right)^3 \frac{\sinh\left[(2n+1)\frac{\pi y}{2b}\right]}{\cosh\left[(2n+1)\frac{\pi h}{2b}\right]} \cos\left[\frac{(2n+1)\pi x}{2b}\right] \right)\Bigg|_{y=-h} =$$

$$= \eta \frac{\Phi}{q} \sum_{n=0}^{\infty} \frac{(-1)^n\, b\pi}{(2n+1)^2} \left(\frac{2}{\pi}\right)^3 \frac{\sinh\left[(2n+1)\frac{\pi y}{2b}\right]}{\cosh\left[(2n+1)\frac{\pi h}{2b}\right]} \cos\left[\frac{(2n+1)\pi x}{2b}\right] \Bigg|_{y=-h}$$

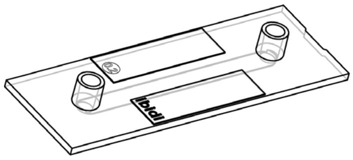
The cells typically attach to the bottom of the channel. The wall shear stress τ at the bottom of the channel (y = -h) and the center of the channel (x = 0) is:

$$\tau(x=0, y=-h) = \eta \frac{\Phi}{q} \left\{ \sum_{n=0}^{\infty} \frac{(-1)^n\, b\pi}{(2n+1)^2} \left(\frac{2}{\pi}\right)^3 \tanh\left[(2n+1)\frac{\pi h}{2b}\right] \right\}$$

10 Reference Tables for Shear Stress Values

These tables are suitable for quickly determining the required flow rate for the desired shear stress in the ibidi Channel Slides. The shear stress is calculated for medium at 37°C (viscosity of 0.0072 dyn·s/cm²).

10.1 µ-Slide I $^{0.2}$ Luer



Viscosity η = 0.0072 dyn·s/cm²

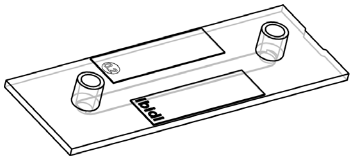
$\tau = \eta \cdot 512.9 \cdot \Phi$

τ [dyn/cm²]	Φ [ml/min]
0.1	0.03
0.2	0.05
0.3	0.08
0.4	0.11
0.5	0.14
0.6	0.16
0.7	0.19
0.8	0.22
0.9	0.24
1	0.27
1.2	0.32
1.4	0.38
1.6	0.43
1.8	0.49
2	0.54
2.2	0.60
2.4	0.65
2.6	0.70
2.8	0.76
3	0.81

τ [dyn/cm²]	Φ [ml/min]
3.5	0.95
4	1.08
4.5	1.22
5	1.35
5.5	1.49
6	1.62
7	1.90
8	2.17
9	2.44
10	2.71
11	2.98
12	3.25
13	3.52
14	3.79
15	4.06
16	4.33
18	4.87
20	5.42
22	5.96
24	6.50

τ [dyn/cm²]	Φ [ml/min]
25	6.77
30	8.12
35	9.48
40	10.83
45	12.19
50	13.54
55	14.89
60	16.25
65	17.60
70	18.96
75	20.31
80	21.66
85	23.02
90	24.37
95	25.73
100	27.08
105	28.43
110	29.79
115	31.14
120	32.49

10.2 µ-Slide I 0.2 Luer Glass Bottom



Viscosity η = 0.0072 dyn·s/cm²

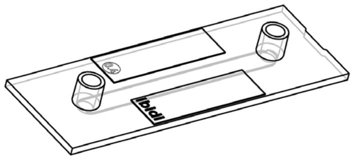
$$\tau = \eta \cdot 330.4 \cdot \Phi$$

τ [dyn/cm²]	Φ [ml/min]
0.1	0.04
0.2	0.08
0.3	0.13
0.4	0.17
0.5	0.21
0.6	0.25
0.7	0.29
0.8	0.34
0.9	0.38
1	0.42
1.2	0.50
1.4	0.59
1.6	0.67
1.8	0.76
2	0.84
2.2	0.92
2.4	1.01
2.6	1.09
2.8	1.18
3	1.26

τ [dyn/cm²]	Φ [ml/min]
3.5	1.47
4	1.68
4.5	1.89
5	2.10
5.5	2.31
6	2.52
7	2.94
8	3.36
9	3.78
10	4.20
11	4.62
12	5.04
13	5.46
14	5.89
15	6.31
16	6.73
18	7.57
20	8.41
22	9.25
24	10.09

τ [dyn/cm²]	Φ [ml/min]
25	10.51
30	12.61
35	14.71
40	16.81
45	18.92
50	21.02
55	23.12
60	25.22
65	27.32
70	29.43
75	31.53
80	33.63
85	35.73
90	37.83
95	39.93
100	42.04
105	44.14
110	46.24
115	48.34
120	50.44

10.3 µ-Slide I $^{0.4}$ Luer



Viscosity η = 0.0072 dyn·s/cm²

$\tau = \eta \cdot 131.6 \cdot \Phi$

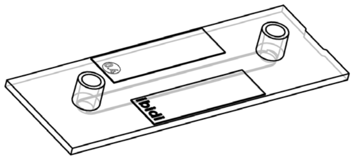
τ [dyn/cm²]	Φ [ml/min]
0.1	0.11
0.2	0.21
0.3	0.32
0.4	0.42
0.5	0.53
0.6	0.63
0.7	0.74
0.8	0.84
0.9	0.95
1	1.06
1.2	1.27
1.4	1.48
1.6	1.69
1.8	1.90
2	2.11
2.2	2.32
2.4	2.53
2.6	2.74
2.8	2.96
3	3.17

τ [dyn/cm²]	Φ [ml/min]
3.5	3.69
4	4.22
4.5	4.75
5	5.28
5.5	5.80
6	6.33
7	7.39
8	8.44
9	9.50
10	10.55
11	11.61
12	12.66
13	13.72
14	14.78
15	15.83
16	16.89
18	19.00
20	21.11
22	23.22
24	25.33

τ [dyn/cm²]	Φ [ml/min]
25	26.38
30	31.66
35	36.94
40	42.22
45	47.49
50	52.77
55	58.05
60	63.32
65	68.60
70	73.88
75	79.15
80	84.43
85	89.71
90	94.98
95	100.26
100	105.54
105	110.82
110	116.09
115	121.37
120	126.65

cells in focus ibidi

10.4 μ-Slide I 0.4 Luer Glass Bottom



Viscosity $\eta = 0.0072$ dyn·s/cm²

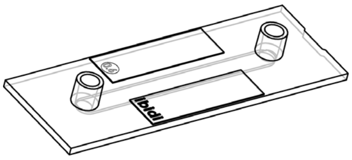
$\tau = \eta \cdot 104.7 \cdot \Phi$

τ [dyn/cm²]	Φ [ml/min]
0.1	0.13
0.2	0.27
0.3	0.40
0.4	0.53
0.5	0.66
0.6	0.80
0.7	0.93
0.8	1.06
0.9	1.19
1	1.33
1.2	1.59
1.4	1.86
1.6	2.12
1.8	2.39
2	2.65
2.2	2.92
2.4	3.18
2.6	3.45
2.8	3.71
3	3.98

τ [dyn/cm²]	Φ [ml/min]
3.5	4.64
4	5.31
4.5	5.97
5	6.63
5.5	7.30
6	7.96
7	9.29
8	10.61
9	11.94
10	13.27
11	14.59
12	15.92
13	17.25
14	18.57
15	19.90
16	21.22
18	23.88
20	26.53
22	29.18
24	31.84

τ [dyn/cm²]	Φ [ml/min]
25	33.16
30	39.80
35	46.43
40	53.06
45	59.69
50	66.33
55	72.96
60	79.59
65	86.23
70	92.86
75	99.49
80	106.12
85	112.76
90	119.39
95	126.02
100	132.65
105	139.29
110	145.92
115	152.55
120	159.18

10.5 μ-Slide I $^{0.6}$ Luer

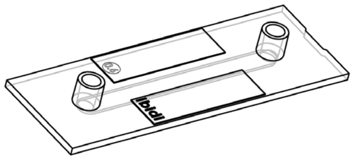


Viscosity η = 0.0072 dyn·s/cm²

$\tau = \eta \cdot 60.1 \cdot \Phi$

τ [dyn/cm²]	Φ [ml/min]	τ [dyn/cm²]	Φ [ml/min]	τ [dyn/cm²]	Φ [ml/min]
0.1	0.23	3.5	8.09	25	57.77
0.2	0.46	4	9.24	30	69.33
0.3	0.69	4.5	10.40	35	80.88
0.4	0.92	5	11.55	40	92.44
0.5	1.16	5.5	12.71	45	103.99
0.6	1.39	6	13.87	50	115.55
0.7	1.62	7	16.18	55	127.10
0.8	1.85	8	18.49	60	138.66
0.9	2.08	9	20.80	65	150.21
1	2.31	10	23.11	70	161.77
1.2	2.77	11	25.42	75	173.32
1.4	3.24	12	27.73	80	184.88
1.6	3.70	13	30.04	85	196.43
1.8	4.16	14	32.35	90	207.99
2	4.62	15	34.66	95	219.54
2.2	5.08	16	36.98	100	231.10
2.4	5.55	18	41.60	105	242.65
2.6	6.01	20	46.22	110	254.21
2.8	6.47	22	50.84	115	265.76
3	6.93	24	55.46	120	277.32

10.6 µ-Slide I $^{0.6}$ Luer Glass Bottom



Viscosity $\eta = 0.0072$ dyn·s/cm²

$$\tau = \eta \cdot 51.5 \cdot \Phi$$

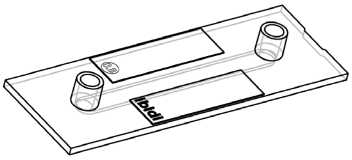
τ [dyn/cm²]	Φ [ml/min]
0.1	0.27
0.2	0.54
0.3	0.81
0.4	1.08
0.5	1.35
0.6	1.62
0.7	1.89
0.8	2.16
0.9	2.43
1	2.70
1.2	3.24
1.4	3.78
1.6	4.31
1.8	4.85
2	5.39
2.2	5.93
2.4	6.47
2.6	7.01
2.8	7.55
3	8.09

τ [dyn/cm²]	Φ [ml/min]
3.5	9.44
4	10.79
4.5	12.14
5	13.48
5.5	14.83
6	16.18
7	18.88
8	21.57
9	24.27
10	26.97
11	29.67
12	32.36
13	35.06
14	37.76
15	40.45
16	43.15
18	48.54
20	53.94
22	59.33
24	64.72

τ [dyn/cm²]	Φ [ml/min]
25	67.42
30	80.91
35	94.39
40	107.87
45	121.36
50	134.84
55	148.33
60	161.81
65	175.30
70	188.78
75	202.27
80	215.75
85	229.23
90	242.72
95	256.20
100	269.69
105	283.17
110	296.66
115	310.14
120	323.62

cells in focus ibidi

10.7 µ-Slide I $^{0.8}$ Luer



Viscosity η = 0.0072 dyn·s/cm²

$\tau = \eta \cdot 34.7 \cdot \Phi$

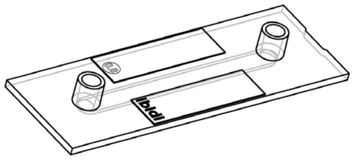
τ [dyn/cm²]	Φ [ml/min]
0.1	0.40
0.2	0.80
0.3	1.20
0.4	1.60
0.5	2.00
0.6	2.40
0.7	2.80
0.8	3.20
0.9	3.60
1	4.00
1.2	4.80
1.4	5.60
1.6	6.40
1.8	7.20
2	8.01
2.2	8.81
2.4	9.61
2.6	10.41
2.8	11.21
3	12.01

τ [dyn/cm²]	Φ [ml/min]
3.5	14.01
4	16.01
4.5	18.01
5	20.01
5.5	22.01
6	24.02
7	28.02
8	32.02
9	36.02
10	40.03
11	44.03
12	48.03
13	52.03
14	56.04
15	60.04
16	64.04
18	72.05
20	80.05
22	88.06
24	96.06

τ [dyn/cm²]	Φ [ml/min]
25	100.06
30	120.08
35	140.09
40	160.10
45	180.12
50	200.13
55	220.14
60	240.15
65	260.17
70	280.18
75	300.19
80	320.20
85	340.22
90	360.23
95	380.24
100	400.26
105	420.27
110	440.28
115	460.29
120	480.31

cells in focus ibidi

10.8 µ-Slide I 0.8 Luer Glass Bottom



Viscosity η = 0.0072 dyn·s/cm²

$\tau = \eta \cdot 31 \cdot \Phi$

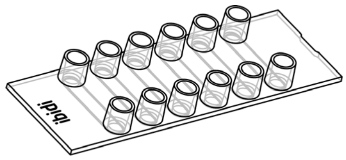
τ [dyn/cm²]	Φ [ml/min]
0.1	0.45
0.2	0.90
0.3	1.34
0.4	1.79
0.5	2.24
0.6	2.69
0.7	3.14
0.8	3.58
0.9	4.03
1	4.48
1.2	5.38
1.4	6.27
1.6	7.17
1.8	8.06
2	8.96
2.2	9.86
2.4	10.75
2.6	11.65
2.8	12.54
3	13.44

τ [dyn/cm²]	Φ [ml/min]
3.5	15.68
4	17.92
4.5	20.16
5	22.40
5.5	24.64
6	26.88
7	31.36
8	35.84
9	40.32
10	44.80
11	49.28
12	53.76
13	58.24
14	62.72
15	67.20
16	71.68
18	80.65
20	89.61
22	98.57
24	107.53

τ [dyn/cm²]	Φ [ml/min]
25	112.01
30	134.41
35	156.81
40	179.21
45	201.61
50	224.01
55	246.42
60	268.82
65	291.22
70	313.62
75	336.02
80	358.42
85	380.82
90	403.23
95	425.63
100	448.03
105	470.43
110	492.83
115	515.23
120	537.63

cells in focus ibidi

10.9 µ-Slide VI [0.4]

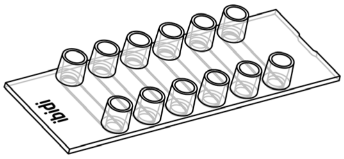


Viscosity $\eta = 0.0072$ dyn·s/cm²

$$\tau = \eta \cdot 176.1 \cdot \Phi$$

τ [dyn/cm²]	Φ [ml/min]	τ [dyn/cm²]	Φ [ml/min]	τ [dyn/cm²]	Φ [ml/min]
0.1	0.08	3.5	2.76	25	19.72
0.2	0.16	4	3.15	30	23.66
0.3	0.24	4.5	3.55	35	27.60
0.4	0.32	5	3.94	40	31.55
0.5	0.39	5.5	4.34	45	35.49
0.6	0.47	6	4.73	50	39.43
0.7	0.55	7	5.52	55	43.38
0.8	0.63	8	6.31	60	47.32
0.9	0.71	9	7.10	65	51.27
1	0.79	10	7.89	70	55.21
1.2	0.95	11	8.68	75	59.15
1.4	1.10	12	9.46	80	63.10
1.6	1.26	13	10.25	85	67.04
1.8	1.42	14	11.04	90	70.98
2	1.58	15	11.83	95	74.93
2.2	1.74	16	12.62	100	78.87
2.4	1.89	18	14.20	105	82.81
2.6	2.05	20	15.77	110	86.76
2.8	2.21	22	17.35	115	90.70
3	2.37	24	18.93	120	94.64

10.10 µ-Slide VI $^{0.5}$ Glass Bottom



Viscosity η = 0.0072 dyn·s/cm²

$\tau = \eta \cdot 99.1 \cdot \Phi$

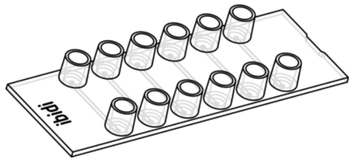
τ [dyn/cm²]	Φ [ml/min]
0.1	0.14
0.2	0.28
0.3	0.42
0.4	0.55
0.5	0.70
0.6	0.84
0.7	0.98
0.8	1.12
0.9	1.26
1	1.40
1.2	1.68
1.4	1.96
1.6	2.24
1.8	2.52
2	2.80
2.2	3.08
2.4	3.36
2.6	3.64
2.8	3.92
3	4.20

τ [dyn/cm²]	Φ [ml/min]
3.5	4.91
4	5.61
4.5	6.31
5	7.01
5.5	7.71
6	8.41
7	9.81
8	11.21
9	12.61
10	14.02
11	15.42
12	16.82
13	18.22
14	19.62
15	21.02
16	22.42
18	25.23
20	28.03
22	30.83
24	33.64

τ [dyn/cm²]	Φ [ml/min]
25	35.04
30	42.05
35	49.05
40	56.06
45	63.07
50	70.08
55	77.08
60	84.09
65	91.10
70	98.11
75	105.11
80	112.12
85	119.13
90	126.14
95	133.14
100	140.15
105	147.16
110	154.17
115	161.17
120	168.18

cells in focus ibidi

10.11 µ-Slide VI [0.1]



Viscosity η = 0.0072 dyn·s/cm²

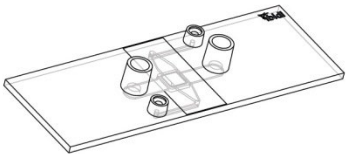
$\tau = \eta \cdot 10.7 \cdot \Phi$

τ [dyn/cm²]	Φ [µl/min]
0.1	1.30
0.2	2.60
0.3	3.89
0.4	5.19
0.5	6.49
0.6	7.79
0.7	9.09
0.8	10.38
0.9	11.68
1	12.98
1.2	15.58
1.4	18.17
1.6	20.77
1.8	23.36
2	25.96
2.2	28.56
2.4	31.15
2.6	33.75
2.8	36.34
3	38.94

τ [dyn/cm²]	Φ [µl/min]
3.5	45.43
4	51.92
4.5	58.41
5	64.90
5.5	71.39
6	77.88
7	90.86
8	103.84
9	116.82
10	129.80
11	142.78
12	155.76
13	168.74
14	181.72
15	194.70
16	207.68
18	233.64
20	259.61
22	285.57
24	311.53

τ [dyn/cm²]	Φ [µl/min]
25	324.51
30	389.41
35	454.31
40	519.21
45	584.11
50	649.01
55	713.91
60	778.82
65	843.72
70	908.62
75	973.52
80	1038.42
85	1103.32
90	1168.22
95	1233.13
100	1298.03
105	1362.93
110	1427.83
115	1492.73
120	1557.63

10.12 µ-Slide Membrane ibiPore Flow



Viscosity η = 0.0072 dyn·s/cm²

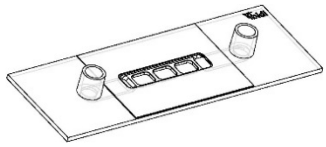
$$\tau = \eta \cdot 131.6 \cdot \Phi$$

τ [dyn/cm²]	Φ [ml/min]
0.1	0.11
0.2	0.21
0.3	0.32
0.4	0.42
0.5	0.53
0.6	0.63
0.7	0.74
0.8	0.84
0.9	0.95
1	1.06
1.2	1.27
1.4	1.48
1.6	1.69
1.8	1.90
2	2.11
2.2	2.32
2.4	2.53
2.6	2.74
2.8	2.96
3	3.17

τ [dyn/cm²]	Φ [ml/min]
3.5	3.69
4	4.22
4.5	4.75
5	5.28
5.5	5.80
6	6.33
7	7.39
8	8.44
9	9.50
10	10.55
11	11.61
12	12.66
13	13.72
14	14.78
15	15.83
16	16.89
18	19.00
20	21.11
22	23.22
24	25.33

τ [dyn/cm²]	Φ [ml/min]
25	26.38
30	31.66
35	36.94
40	42.22
45	47.49
50	52.77
55	58.05
60	63.32
65	68.60
70	73.88
75	79.15
80	84.43
85	89.71
90	94.98
95	100.26
100	105.54
105	110.82
110	116.09
115	121.37
120	126.65

10.13 µ-Slide I Luer 3D



Viscosity η = 0.0072 dyn·s/cm²

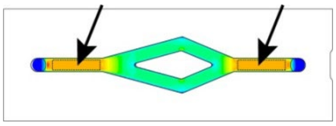
$$\tau = \eta \cdot 60.1 \cdot \Phi$$

τ [dyn/cm²]	Φ [ml/min]
0.1	0.23
0.2	0.46
0.3	0.69
0.4	0.92
0.5	1.16
0.6	1.39
0.7	1.62
0.8	1.85
0.9	2.08
1	2.31
1.2	2.77
1.4	3.24
1.6	3.70
1.8	4.16
2	4.62
2.2	5.08
2.4	5.55
2.6	6.01
2.8	6.47
3	6.93

τ [dyn/cm²]	Φ [ml/min]
3.5	8.09
4	9.24
4.5	10.40
5	11.55
5.5	12.71
6	13.87
7	16.18
8	18.49
9	20.80
10	23.11
11	25.42
12	27.73
13	30.04
14	32.35
15	34.66
16	36.98
18	41.60
20	46.22
22	50.84
24	55.46

τ [dyn/cm²]	Φ [ml/min]
25	57.77
30	69.33
35	80.88
40	92.44
45	103.99
50	115.55
55	127.10
60	138.66
65	150.21
70	161.77
75	173.32
80	184.88
85	196.43
90	207.99
95	219.54
100	231.10
105	242.65
110	254.21
115	265.76
120	277.32

10.14 µ-Slide y-shaped (Single Channel Area)



Uniform laminar flow regions, viscosity η = 0.0072 dyn·s/cm²

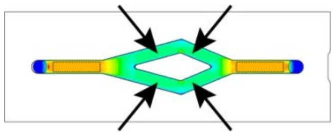
$$\tau = \eta \cdot 227.4 \cdot \Phi$$

τ [dyn/cm²]	Φ [ml/min]
0.1	0.06
0.2	0.12
0.3	0.18
0.4	0.24
0.5	0.31
0.6	0.37
0.7	0.43
0.8	0.49
0.9	0.55
1	0.61
1.2	0.73
1.4	0.86
1.6	0.98
1.8	1.10
2	1.22
2.2	1.34
2.4	1.47
2.6	1.59
2.8	1.71
3	1.83

τ [dyn/cm²]	Φ [ml/min]
3.5	2.14
4	2.44
4.5	2.75
5	3.05
5.5	3.36
6	3.66
7	4.28
8	4.89
9	5.50
10	6.11
11	6.72
12	7.33
13	7.94
14	8.55
15	9.16
16	9.77
18	10.99
20	12.22
22	13.44
24	14.66

τ [dyn/cm²]	Φ [ml/min]
25	15.27
30	18.32
35	21.38
40	24.43
45	27.48
50	30.54
55	33.59
60	36.65
65	39.70
70	42.75
75	45.81
80	48.86
85	51.92
90	54.97
95	58.02
100	61.08
105	64.13
110	67.18
115	70.24
120	73.29

10.15 µ-Slide y-shaped (Branched Channel Area)



Uniform laminar flow regions, viscosity η = 0.0072 dyn·s/cm²

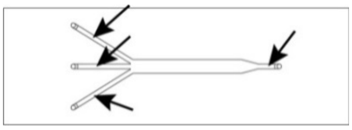
$$\tau = \eta \cdot 113.7 \cdot \Phi$$

τ [dyn/cm²]	Φ [ml/min]
0.1	0.12
0.2	0.24
0.3	0.37
0.4	0.49
0.5	0.61
0.6	0.73
0.7	0.86
0.8	0.98
0.9	1.10
1	1.22
1.2	1.47
1.4	1.71
1.6	1.95
1.8	2.20
2	2.44
2.2	2.69
2.4	2.93
2.6	3.18
2.8	3.42
3	3.66

τ [dyn/cm²]	Φ [ml/min]
3.5	4.28
4	4.89
4.5	5.50
5	6.11
5.5	6.72
6	7.33
7	8.55
8	9.77
9	10.99
10	12.22
11	13.44
12	14.66
13	15.88
14	17.10
15	18.32
16	19.54
18	21.99
20	24.43
22	26.87
24	29.32

τ [dyn/cm²]	Φ [ml/min]
25	30.54
30	36.65
35	42.75
40	48.86
45	54.97
50	61.08
55	67.18
60	73.29
65	79.40
70	85.51
75	91.62
80	97.72
85	103.83
90	109.94
95	116.05
100	122.15
105	128.26
110	134.37
115	140.48
120	146.58

10.16 µ-Slide III ^{3in1} (1 mm Channels)



Viscosity $\eta = 0.0072$ dyn·s/cm²

$$\tau = \eta \cdot 774.1 \cdot \Phi$$

τ [dyn/cm²]	Φ [ml/min]
0.1	0.02
0.2	0.04
0.3	0.05
0.4	0.07
0.5	0.09
0.6	0.11
0.7	0.13
0.8	0.14
0.9	0.16
1	0.18
1.2	0.22
1.4	0.25
1.6	0.29
1.8	0.32
2	0.36
2.2	0.39
2.4	0.43
2.6	0.47
2.8	0.50
3	0.54

τ [dyn/cm²]	Φ [ml/min]
3.5	0.63
4	0.72
4.5	0.81
5	0.90
5.5	0.99
6	1.08
7	1.26
8	1.44
9	1.61
10	1.79
11	1.97
12	2.15
13	2.33
14	2.51
15	2.69
16	2.87
18	3.23
20	3.59
22	3.95
24	4.31

τ [dyn/cm²]	Φ [ml/min]
25	4.49
30	5.38
35	6.28
40	7.18
45	8.07
50	8.97
55	9.87
60	10.77
65	11.66
70	12.56
75	13.46
80	14.35
85	15.25
90	16.15
95	17.04
100	17.94
105	18.84
110	19.74
115	20.63
120	21.53

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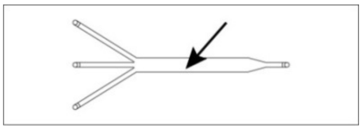
10.17 µ-Slide III 3in1 (3 mm Channel)



Viscosity η = 0.0072 dyn·s/cm²

$$\tau = \eta \cdot 227.4 \cdot \Phi$$

τ [dyn/cm²]	Φ [ml/min]
0.1	0.06
0.2	0.12
0.3	0.18
0.4	0.24
0.5	0.31
0.6	0.37
0.7	0.43
0.8	0.49
0.9	0.55
1	0.61
1.2	0.73
1.4	0.86
1.6	0.98
1.8	1.10
2	1.22
2.2	1.34
2.4	1.47
2.6	1.59
2.8	1.71
3	1.83

τ [dyn/cm²]	Φ [ml/min]
3.5	2.14
4	2.44
4.5	2.75
5	3.05
5.5	3.36
6	3.66
7	4.28
8	4.89
9	5.50
10	6.11
11	6.72
12	7.33
13	7.94
14	8.55
15	9.16
16	9.77
18	10.99
20	12.22
22	13.44
24	14.66

τ [dyn/cm²]	Φ [ml/min]
25	15.27
30	18.32
35	21.38
40	24.43
45	27.48
50	30.54
55	33.59
60	36.65
65	39.70
70	42.75
75	45.81
80	48.86
85	51.92
90	54.97
95	58.02
100	61.08
105	64.13
110	67.18
115	70.24
120	73.29