

# **Flow control using audio tones in resonant microfluidic networks: towards cell-phone controlled lab-on-a-chip devices**

Reid H. Phillips<sup>1</sup>, Rahil Jain<sup>2</sup>, Yoni Browning<sup>1</sup>, Rachana Shah<sup>1</sup>, Peter Kaufmann<sup>1</sup>, Doan Dinh<sup>1</sup>, Barry R. Lutz<sup>1\*</sup>

<sup>1</sup>*University of Washington, Department of Bioengineering, Seattle, WA 98195*

<sup>2</sup>*University of Washington, Department of Electrical Engineering, Seattle, WA 98195*

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Corresponding author:

Barry Lutz, PhD

Department of Bioengineering

University of Washington

Box 355061, Foegen N530N

3720 15<sup>th</sup> Ave NE

Seattle WA 98195

Phone: (206)685-9891

Email: blutz@uw.edu



# Supplementary Information

## Section 1: Resistance and inductance

Values for the resistance,  $R$ , and inductance,  $L$ , are the real and imaginary components, respectively, of the complex impedance,  $Z$ , given by<sup>1</sup>:

$$\text{Eqn. 1} \quad Z = \frac{ul\pi^2}{32b^4} \left[ \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2 f^2} \left( \frac{a}{b} - \frac{\tanh(f \cdot a / b)}{f} \right) \right]^{-1}, \quad f = \sqrt{\left( ib \sqrt{\frac{w}{\nu}} \right)^2 + \frac{(2n+1)^2 \pi^2}{4}}$$

where  $l$  is the channel length,  $a$  and  $b$  are the half-width and half-height,  $\omega$  is the frequency in radians,  $\mu$  and  $\nu$  are the fluid dynamic and kinematic viscosities. Resistance is a result of fluid-wall interactions and inductance results from fluid momentum.

Matlab code:

```
function [R,L] = RectangularDuctImpedance(w,l,d,f)

% The function calculates the impedance (Z = R + iwL) using equation 14
% from Morris and Forster (2000). It returns R and L.
% w and d are full channel width and depth, l is channel length,
% f is frequency in Hz

alpha = w/d;           % channel aspect ratio
omega = f*2*pi;        % representative frequency point (radians)
u = 1.05e-6;           % fluid dynamic viscosity (kPa*s)
nu = 1;                % fluid kinematic viscosity (mm^2/s)
n = d/2*sqrt(omega/nu); % non-dimensional frequency parameter

a = u*1*pi^2/(32*(d/2)^4);
b = 0;
for j = 0:50           % assumption
    q = sqrt(i*n^2+(2*j+1)^2*pi^2/4);
    b = b + 1/((2*j+1)^2*q^2)*(alpha-tanh(q*alpha)/q);
end

Z = a/b;              % (kg/mm^4/s)

% Calculate Resistance
R = real(Z);          % (kPa*s/mm^3)

% Calculate Inductance
L = imag(Z)/omega;    % (kg/mm^4)
```

## Section 2: Center-to-mean velocity ratio

The center-to-mean velocity ratio for sinusoidal pressure driven flow in rectangular channels was given by O'Brien<sup>2</sup> (note that the original reference contained an error – the second tanh term in the denominator was mistakenly printed as sech – this is corrected below).

$$\frac{W^*(0,0)}{\{W^*\}} = \frac{1 - 2 \sum_{n=0}^{\infty} (-1)^n p_n^{-1} [\operatorname{sech}(\xi_n) + \operatorname{sech}(\mu_n)]}{1 - 2 \sum_{n=0}^{\infty} p_n^{-2} \left[ \frac{\tanh(\xi_n)}{\xi_n} + \frac{\tanh(\mu_n)}{\mu_n} \right]}$$

$$p_n = \frac{2n+1}{2} \pi \quad \xi_n = \sqrt{p_n^2 \left(\frac{a}{b}\right)^2 + \frac{i\omega a^2}{\nu}} \quad \mu_n = \sqrt{p_n^2 \left(\frac{b}{a}\right)^2 + \frac{i\omega b^2}{\nu}}$$

Where  $a$  and  $b$  are the channel half-width and half-height, respectively,  $\omega$  is the frequency in radians, and  $\nu$  is the fluid kinematic viscosity. “C2MR” below is  $V_{cent} / V_{mean}$  from the text.  $V_{cent}$  was calculated from measured particle streak lengths (see text), and the magnitude of AC volumetric flowrate ( $Q$ ) was calculated as  $2a \cdot 2b \cdot V_{mean}$ , which is the fluidic analog to electrical current in the model used here.

Matlab code:

```
function [C2MR]=C2M(w,d,f)

% Calculates center to mean velocity ratio based on O'Brien 1975
% w: full channel width (a=w/2), d: full channel depth (b=d/2),
% f: frequency in Hz.
% Code becomes unstable if high stokes number (high frequencies) are
% used or if iterations become too high. Calculations are not accurate
% at lower stokes number.
a = w/2*1e-3;    % half-width (m)
b = d/2*1e-3;    % half-height (m)
v = 1.05e-6;     % Fluid kinematic viscosity (kPa*s)
eta = b*sqrt(f/v); % Stokes Number

sumC = 0;
for n = 0:50
    p = (((2*n+1)*pi)/2);
```

```

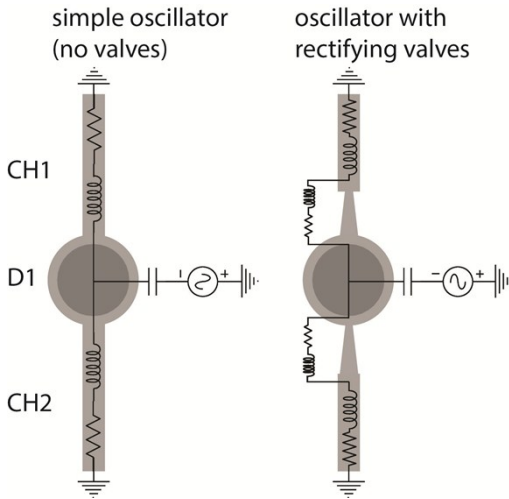
xi = sqrt((p^2)*((a/b)^2)+((i*f*(a^2))/v));
mu = sqrt((p^2)*((b/a)^2)+((i*f*(b^2))/v));
sumC = sumC+((-1)^n)*(p)^-1*(sech(xi)+sech(mu));
end
wC = 1-2*sumC;

sumM = 0;
for n = 0:50
    p = ((2*n+1)*pi)/2;
    xi = sqrt((p^2)*((a/b)^2)+((i*f*(a^2))/v));
    mu = sqrt((p^2)*((b/a)^2)+((i*f*(b^2))/v));
    sumM = sumM+(p)^-2*((tanh(xi)./xi)+(tanh(mu)./mu));
end
wM = 1-2*sumM;

C2MR = abs(wC./wM);
end

```

### Section 3 (main text Figure 3)



Simple oscillator (no valves)	
CH1	$l=20.0\text{mm}, a=0.5\text{mm}, b=0.125\text{mm}$
CH2	$l=20.0\text{mm}, a=0.5\text{mm}, b=0.125\text{mm}$
D1	$d=6.5\text{mm}, \text{PZT } d=6.0\text{mm}$
Oscillator with rectifying valves	
CH1 (main)	$l=13.8\text{mm}, a=0.5\text{mm}, b=0.125\text{mm}$
CH1 (valve)	$l=3.2\text{mm}, b=0.125\text{mm},$ $a=(0.375+0.15)\text{mm}/2=0.2625\text{mm}$
CH2 (main)	$l=13.8\text{mm}, a=0.5\text{mm}, b=0.125\text{mm}$
CH2 (valve)	$l=3.2\text{mm}, b=0.125\text{mm},$ $a=(0.375+0.15)\text{mm}/2=0.2625\text{mm}$
D1	$d=8.0\text{mm}, \text{PZT } d=6.35\text{mm}$

Calculated parameters:

- $R$  and  $L$  based on channel dimensions and **Eqn 1** of the text

Fitted values:

- Diaphragm pressure  $P_{pzt}$  (only affects magnitude, not shape)
- PZT capacitance  $C_{pzt}$  (affects peak location, primary unknown parameter)

Matlab code (devices with no valves):

```
CIRCUIT SOLUTION FOR SIMPLE DEVICES (NO VALVES)
VARIED PARAMETERS: CPZT (C below) and PPZT (V below)
```

```
% Mesh analysis
Vcircuit = [-V, V]';
Z = [(-R1 - s*L1 - 1/(s*C))    (1/(s*C));
     (1/(s*C))                (-1/(s*C) - R2 - s*L2)];
I = Z\Vcircuit;
Imodel(j,1) = abs(I(2));
```

Fitted parameter results for simple devices (no valves):

- Device 1:  $C_{pzt}=0.0017 \text{ mm}^3/\text{kPa}$ ,  $P_{pzt}=0.6408 \text{ kPa}$
- Device 2:  $C_{pzt}=0.0017 \text{ mm}^3/\text{kPa}$ ,  $P_{pzt}=0.8439 \text{ kPa}$
- Device 3:  $C_{pzt}=0.0019 \text{ mm}^3/\text{kPa}$ ,  $P_{pzt}=0.615 \text{ kPa}$
- Device 4:  $C_{pzt}=0.0016 \text{ mm}^3/\text{kPa}$ ,  $P_{pzt}=0.7352 \text{ kPa}$
- Averages:  $C_{pzt}=0.00173\pm 0.00013 \text{ mm}^3/\text{kPa}$  (8%),  $P_{pzt}=0.71\pm 0.10 \text{ kPa}$  (14%)

Parameters from simplified expressions (no valves):

- $R_1=R_2= 0.0154 \text{ kPa}\cdot\text{s}/\text{mm}^3$ ,  $R_{eff} = 1/(1/R_1 + 1/R_2) = 0.0077 \text{ kPa}\cdot\text{s}/\text{mm}^3$ .
- $L_1 = L_2 = 8.27\text{e-}05 \text{ kg}/\text{mm}^4$ ,  $L_{eff} = 1/(1/L_1 + 1/L_2) = 4.13\text{e-}05 \text{ kg}/\text{mm}^4$
- Resonant frequency =  $1/2\pi * 1/(LC)^{1/2} = 595 \text{ Hz}$

Matlab code (devices with valves):

CIRCUIT SOLUTION FOR SIMPLE DEVICES (WITH VALVES)  
 VARIED PARAMETERS:  $C_{PZT}$  (C below) and  $P_{PZT}$ (V below)

```
diffuser(3), diffuser(1), f);
R1 = Rch1 + Rd;
L1 = Lch1 + Ld;
R2 = Rch2 + Rd;
L2 = Lch2 + Ld;

% Mesh analysis
Vcircuit = [-V, V]';
Z = [(-R1 - s*L1 - 1/(s*C))    (1/(s*C));
     (1/(s*C))                (-1/(s*C) - R2 - s*L2)];
I = Z\Vcircuit;
Imodel(j,1) = abs(I(2));
```

Fitted parameter results for pump devices (with valves):

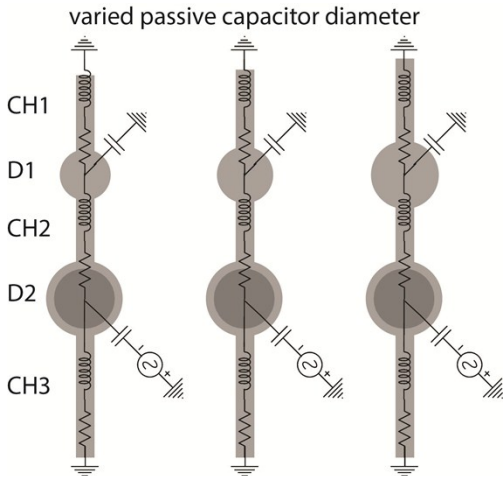
- Device 1:  $C_{pzt}=0.0016 \text{ mm}^3/\text{kPa}$ ,  $P_{pzt}=1.8057 \text{ kPa}$
- Device 2:  $C_{pzt}=0.0016 \text{ mm}^3/\text{kPa}$ ,  $P_{pzt}=1.1214 \text{ kPa}$
- Device 3:  $C_{pzt}=0.0016 \text{ mm}^3/\text{kPa}$ ,  $P_{pzt}=0.7263 \text{ kPa}$
- Averages:  $C_{pzt}=0.0016\pm 0.0 \text{ mm}^3/\text{kPa}$  (0%),  $P_{pzt}=1.22\pm 0.55 \text{ kPa}$  (45%)

Parameters from simplified expressions (with valves):

- $R_1 = R_2 = 0.0153 \text{ kPa}\cdot\text{s}/\text{mm}^3$ ,  $R_{eff} = 1/(1/R_1 + 1/R_2) = 0.0076 \text{ kPa}\cdot\text{s}/\text{mm}^3$
- $L_1 = L_2 = 8.22\text{e-}05 \text{ kg}/\text{mm}^4$ ,  $L_{eff} = 1/(1/L_1 + 1/L_2) = 4.11\text{e-}05 \text{ kg}/\text{mm}^4$
- Resonant frequency =  $1/2\pi * 1/(LC)^{1/2} = 620 \text{ Hz}$ .



## Section 4 (main text Figure 4)



Simple oscillator (no valves)	
CH1	$l=12.0\text{mm}$ , $a=0.5\text{mm}$ , $b=0.125\text{mm}$
CH2	$l=10.0\text{mm}$ , $a=0.5\text{mm}$ , $b=0.125\text{mm}$
CH3	$l=10.0\text{mm}$ , $a=0.5\text{mm}$ , $b=0.125\text{mm}$
D1	$d=4.5\text{mm}$ , $d=5.0\text{mm}$ , or $d=6.0\text{mm}$
D2	$d=8.0\text{mm}$ , PZT $d=6.35\text{mm}$

Calculated parameters:

- $R$  and  $L$  based on channel dimensions and **Eqn 1** of the text

Fitted values:

- Diaphragm pressure  $P_{pzt}$  (only affects magnitude, not shape)
- PZT capacitance  $C_{pzt}$  (below compared to expected values from **Fig. 3**)
- Diaphragm capacitances  $C$  (primary new parameter)

Matlab code:

CIRCUIT SOLUTION FOR SINGLE-CHANNEL DEVICES (4.5, 5.0, 6.0 MM DIAPHRAGMS)  
 VARIED PARAMETERS:  $C_{PZT}$  (C1 below),  $P_{PZT}$  (V below), and  $C$  (C2 below)

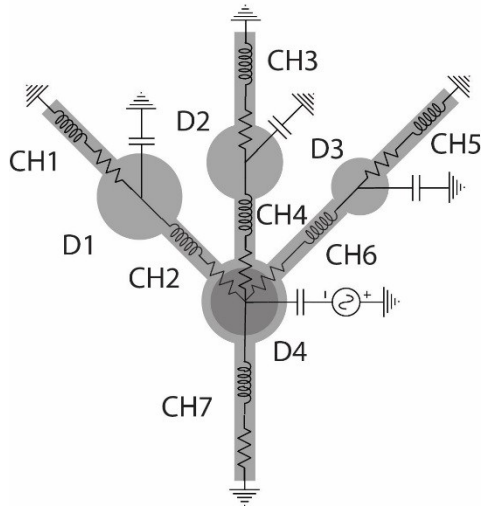
```
% Mesh analysis
Vcircuit = [0, V, -V]';
Z = [(1/(s*C2)+R2+s*L2), -R2-s*L2, 0; ...
     -R2-s*L2, s*L2+R2+s*L1+R1+1/(s*C1), -1/(s*C1); ...
     0, -1/(s*C1), 1/(s*C1)+R3+s*L3];
I = Z\Vcircuit;
Iupstream(j,1) = abs(I(2));
Idownstream(j,1) = abs(I(1)-I(2));
```

Fitted parameter results:

- Large diaphragm, 6.0 mm diameter ( $n=3$ ):  $C_{pzt} = 0.0019 \pm 0.0002 \text{ mm}^3/\text{kPa}$  (8%),  $P_{pzt} = 0.76 \pm 0.08 \text{ kPa}$  (5%),  $C_{6.0} = 0.0019 \pm 0.00001 \text{ mm}^3/\text{kPa}$  (5%).
- Medium diaphragm, 5.0 mm diameter ( $n=3$ ):  $C_{pzt} = 0.0021 \pm 0.0004 \text{ mm}^3/\text{kPa}$  (18%),  $P_{pzt} = 0.71 \pm 0.23 \text{ kPa}$  (32%),  $C_{5.0} = 0.00093 \pm 0.00002 \text{ mm}^3/\text{kPa}$  (17%).
- Small diaphragm, 4.5 mm diameter ( $n=3$ ):  $C_{pzt} = 0.0023 \pm 0.0006 \text{ mm}^3/\text{kPa}$  (27%),  $P_{pzt} = 0.68 \pm 0.20 \text{ kPa}$  (30%),  $C_{4.5} = 0.00058 \pm 0.00005 \text{ mm}^3/\text{kPa}$  (9%).

## Section 5 (main text Figure 5)

network with varied capacitor diameters



Simple oscillator (no valves)	
CH1	$l=10.0\text{mm}$ , $a=0.325\text{mm}$ , $b=0.125\text{mm}$
CH2	$l=5.0\text{mm}$ , $a=0.325\text{mm}$ , $b=0.125\text{mm}$
CH3	$l=10.0\text{mm}$ , $a=0.325\text{mm}$ , $b=0.125\text{mm}$
CH4	$l=5.0\text{mm}$ , $a=0.325\text{mm}$ , $b=0.125\text{mm}$
CH5	$l=8.0\text{mm}$ , $a=0.325\text{mm}$ , $b=0.125\text{mm}$
CH6	$l=5.0\text{mm}$ , $a=0.325\text{mm}$ , $b=0.125\text{mm}$
CH7	$l=20.0\text{mm}$ , $a=0.325\text{mm}$ , $b=0.125\text{mm}$
D1	$d=6.5\text{mm}$ (larger than previous)
D2	$d=5.0\text{mm}$
D3	$d=4.5\text{mm}$
D4	$d=8.0\text{mm}$ , PZT $d=6.35\text{mm}$

Calculated parameters:

- $R$  and  $L$  based on channel dimensions and **Eqn 1** of the text
- $C_{pzt}=0.0017 \text{ mm}^3/\text{kPa}$  (from **Fig. 3**)

Fitted values:

- Diaphragm pressure  $P_{pzt}$  (only affects magnitude, not shape)
- Diaphragm capacitances ( $C$ ) (compared to expected values)

Fitted parameters results (manual fitting):

- $P_{pzt}=0.85 \text{ kPa}$
- $C_{6.5}=0.0048 \text{ mm}^3/\text{kPa}$  (not measured independently, but value checked below)
- $C_{5.0}=0.00093 \text{ mm}^3/\text{kPa}$  (compared to  $C_{5.0}=0.00093\pm 0.00002 \text{ mm}^3/\text{kPa}$  from **Fig. 4**)
- $C_{4.5}=0.00052 \text{ mm}^3/\text{kPa}$  (compared to  $C_{5.0}=0.00058\pm 0.00005 \text{ mm}^3/\text{kPa}$  from **Fig. 4**)

Matlab code:

```

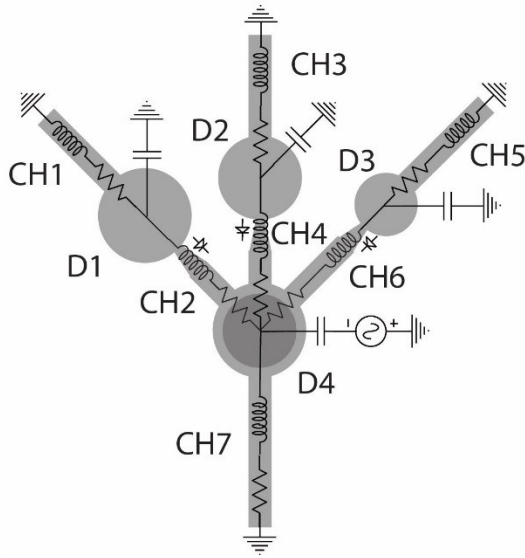
% CIRCUIT SOLUTION FOR 3-CHANNEL DEVICE
% PZT VALUES CPZT=0.0017 (FROM FIG 3) AND PPZT=0.85 (VPZT below)
% "B" CURRENTS ARE THE ONLY RELEVANT ONES (AT THE DIODE)

% Solve Circuit
A = [1/(Rout + s*Lout) + s*Cpzt + 1/(Rin1b + s*Lin1b) + 1/(Rin2b + s*Lin2b) + 1/(Rin3b + s*Lin3b)
(-1)/(Rin1b + s*Lin1b) (-1)/(Rin2b + s*Lin2b) (-1)/(Rin3b + s*Lin3b);
(-1)/(Rin1b + s*Lin1b) 0 1/(Rin1b + s*Lin1b) +
s*C1 + 1/(Rin1a + s*Lin1a) 0 0;
(-1)/(Rin2b + s*Lin2b) 0 0
1/(Rin2b + s*Lin2b) + s*C2 + 1/(Rin2a + s*Lin2a) 0;
(-1)/(Rin3b + s*Lin3b) 0
0 1/(Rin3b + s*Lin3b) + s*C3 + 1/(Rin3a + s*Lin3a)];
B = [Vpzt*s*Cpzt 0 0 0]';
V = A\B;
% Record Voltage Data
F((f - lowf + step)/step) = f;
V0((f - lowf + step)/step) = V(1);
V1((f - lowf + step)/step) = V(2);
V2((f - lowf + step)/step) = V(3);
V3((f - lowf + step)/step) = V(4);
% Record Current Data
% Input Channel 1
Iin1b((f - lowf + step)/step) = (V(2) - V(1))/(Rin1b + s*Lin1b);
Iin1a((f - lowf + step)/step) = V(2)/(Rin1a + s*Lin1a);
% Input Channel 2
Iin2b((f - lowf + step)/step) = (V(3) - V(1))/(Rin2b + s*Lin2b);
Iin2a((f - lowf + step)/step) = V(3)/(Rin2a + s*Lin2a);
% Input Channel 3
Iin3b((f - lowf + step)/step) = (V(4) - V(1))/(Rin3b + s*Lin3b);
Iin3a((f - lowf + step)/step) = V(4)/(Rin3a + s*Lin3a);

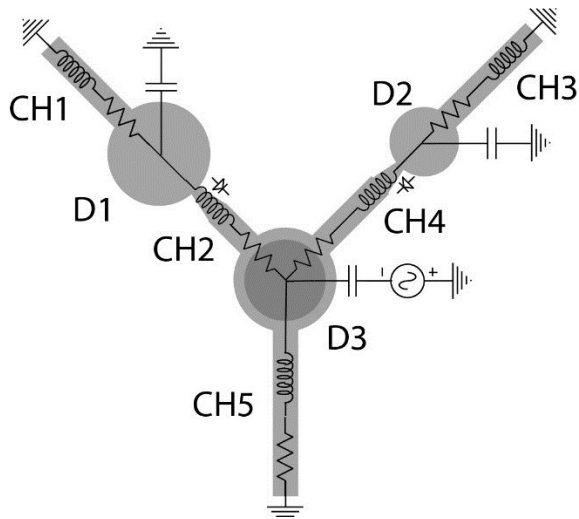
```

## Section 6 (main text Figure 6)

network with varied capacitor diameters



Simple oscillator (no valves)	
CH1	$l=10.0\text{mm}$ , $a=0.325\text{mm}$ , $d=0.125\text{mm}$
CH2 (main)	$l=1.9\text{mm}$ , $a=0.7\text{mm}$ , $b=0.125\text{mm}$
CH2 (diode)	$l=3.2\text{mm}$ , $b=0.125\text{mm}$ , $a=(0.375+0.15)\text{mm}/2=0.2625\text{mm}$
CH3	$l=10.0\text{mm}$ , $a=0.325\text{mm}$ , $b=0.125\text{mm}$
CH4 (main)	$l=1.9\text{mm}$ , $a=0.7\text{mm}$ , $b=0.125\text{mm}$
CH4 (diode)	$l=3.2\text{mm}$ , $b=0.125\text{mm}$ , $a=(0.375+0.15)\text{mm}/2=0.2625\text{mm}$
CH5	$l=8.0\text{mm}$ , $a=0.325\text{mm}$ , $b=0.125\text{mm}$
CH6 (main)	$l=1.9\text{mm}$ , $a=0.7\text{mm}$ , $b=0.125\text{mm}$
CH6 (diode)	$l=3.2\text{mm}$ , $b=0.125\text{mm}$ , $a=(0.375+0.15)\text{mm}/2=0.2625\text{mm}$
CH7	$l=20.0\text{mm}$ , $a=0.325\text{mm}$ , $b=0.125\text{mm}$
D1	$d=6.5\text{mm}$ (larger than previous)
D2	$d=5.0\text{mm}$
D3	$d=4.5\text{mm}$
D4	$d=8.0\text{mm}$ , PZT $d=6.35\text{mm}$



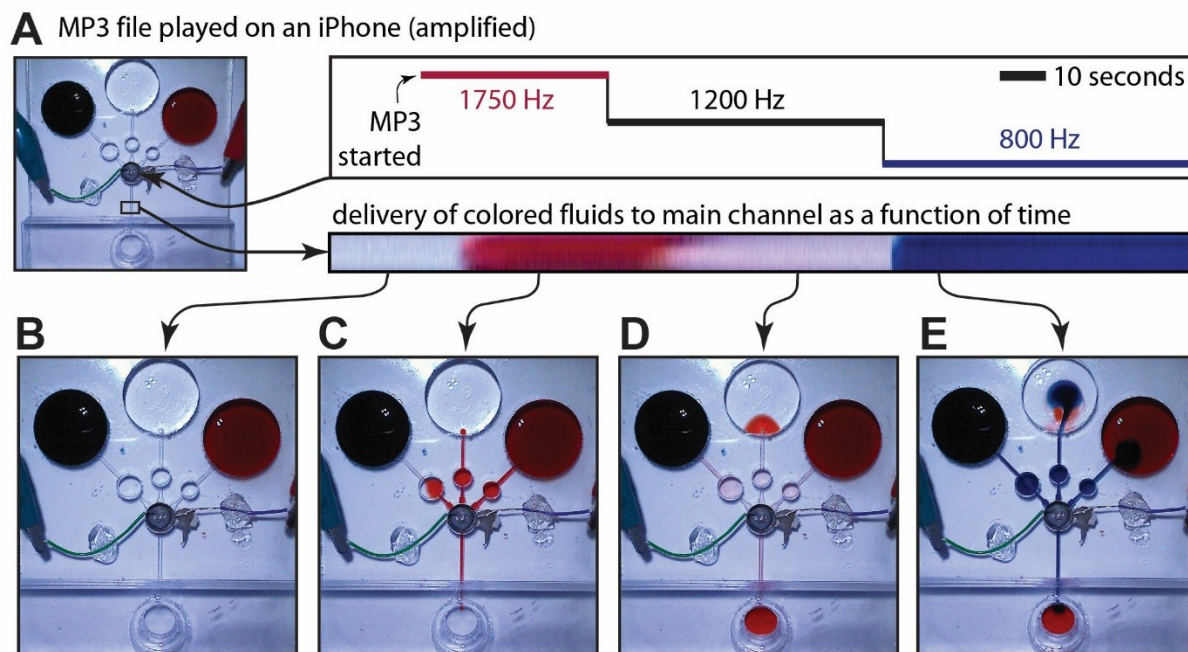
Simple oscillator (no valves)	
CH1	$l=12.0\text{mm}$ , $a=0.325\text{mm}$ , $d=0.125\text{mm}$
CH2 (main)	$l=1.9\text{mm}$ , $a=0.7\text{mm}$ , $b=0.125\text{mm}$
CH2 (diode)	$l=3.2\text{mm}$ , $b=0.125\text{mm}$ , $a=(0.375+0.15)\text{mm}/2=0.2625\text{mm}$
CH3	$l=12.0\text{mm}$ , $a=0.325\text{mm}$ , $b=0.125\text{mm}$
CH4 (main)	$l=1.9\text{mm}$ , $a=0.7\text{mm}$ , $b=0.125\text{mm}$
CH4 (diode)	$l=3.2\text{mm}$ , $b=0.125\text{mm}$ , $a=(0.375+0.15)\text{mm}/2=0.2625\text{mm}$
CH5	$l=25.0\text{mm}$ , $a=0.325\text{mm}$ , $b=0.125\text{mm}$
D1	$d=8.0\text{mm}$
D2	$d=5.5\text{mm}$
D3	$d=8.0\text{mm}$ , PZT $d=6.35\text{mm}$

**Section 7: Summary of fitted parameters for all devices (pressure unit kPa, capacitance unit mm<sup>3</sup>/kPa)**

	<b>Fig. 3, no valve (n=4)</b>	<b>Fig. 3, valves (n=3)</b>	<b>Fig. 4, large (n=3)</b>	<b>Fig. 4, med (n=3)</b>	<b>Fig. 4, small (n=3)</b>	<b>Fig. 5</b>
$P_{pzt}$	0.71+/-0.10	1.22+/-0.55	0.76+/-0.08	0.71+/-0.23	0.68+/-0.20	0.85
$C_{pzt}$	0.00173+/-0.00013	0.0016+/-0.0	0.0019+/-0.0002	0.0021+/-0.0004	0.0023+/-0.0006	[0.0017, fixed]
$C_{6.5mm}$						0.0048
$C_{6mm}$			0.0019+/-0.00001			
$C_{5mm}$				0.00093+/-0.00002		0.00093
$C_{4.5mm}$					0.00058+/-0.00005	0.00052

**Section 8: backflow through diffuser valves**

The diffuser valves used here had no “check-valve” function, which led to back-flow through the valves when neighboring pumps were activated. **Figure S1** shows images during delivery of fluids from each pump. **Fig. S1B** shows the initial device filled with colorless fluid and three fluids (blue, colorless, and red) loaded into source reservoirs before pumps were activated. **Fig. S1C** shows backflow of red fluid into neighboring reservoirs during activation of the red pump. **Fig. S1D** shows delivery of colorless fluid and remaining red fluid in its source reservoir. **Fig. S1E** shows backflow of blue fluid into both neighboring channels. This backflow could be eliminated by using more conventional valves with “check-valve” function, such as those developed by Collino, *et. al.*<sup>3</sup>. In addition, the diffuser valves used here had low rectification efficiency, which required large driving voltages to the piezo and limited the accessible frequency range (since higher frequencies require more power). Conventional valves with higher efficiency would allow lower driving voltages, potentially directly from the cell phone audio port, and access to a wider frequency range for added pump channels.

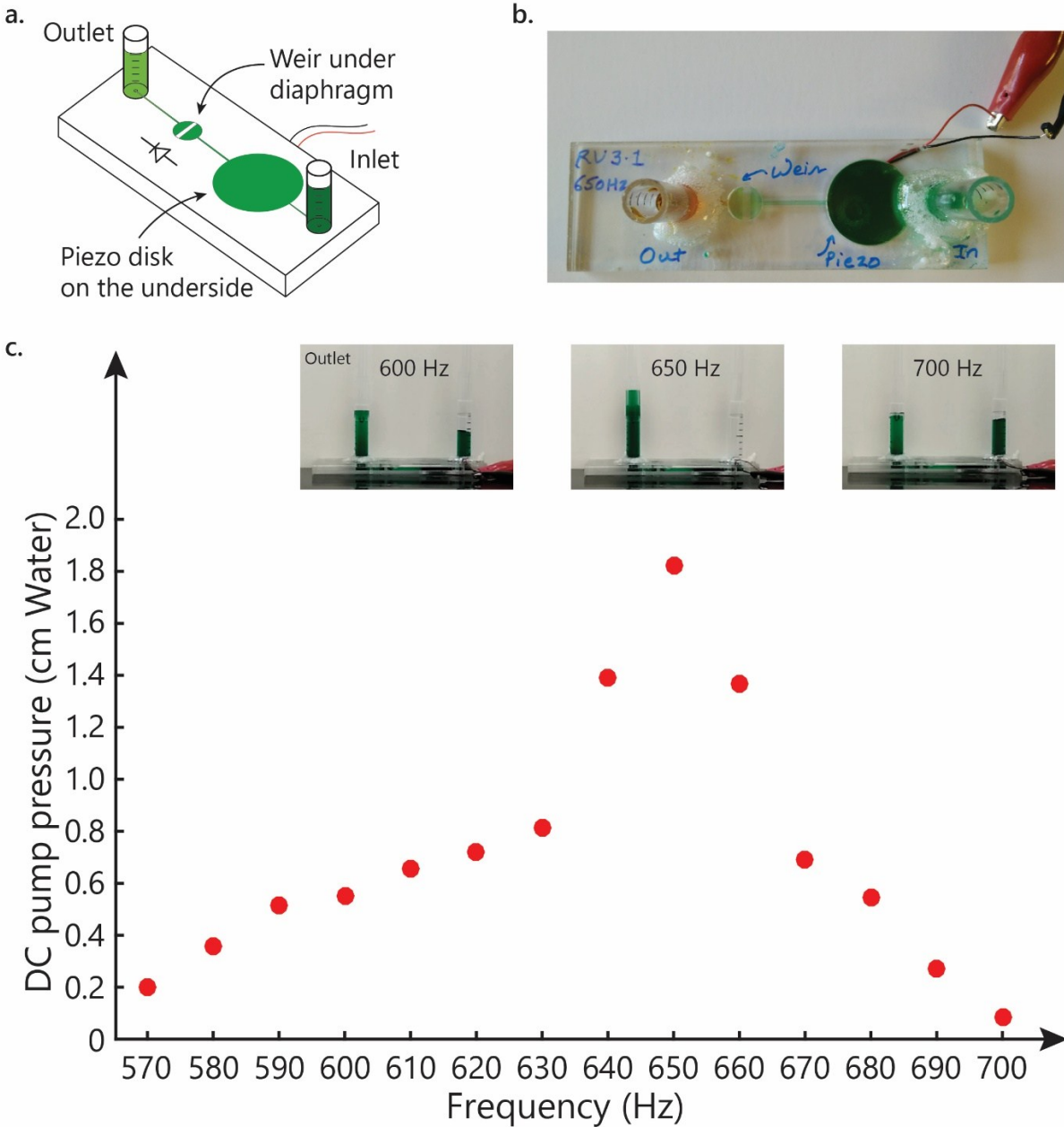


**Figure S1. Images of the 3-channel device from Figure 5 during the pumping timecourse.** Operation of one pump caused backflow through other pump channels, since diffuser valves do not have check valve function. This backflow would be a problem for operation of analytical devices, and improved valves with check valve function should be used. Despite this backflow, pumps were able to deliver fluids to the main channel based on the frequency of the audio tone.

### Section 9: demonstration of conventional valves designed for audible-frequency tones

Conventional valve designs can prevent backflow and increase pumping efficiency but the contribution of the valve itself must be included in the circuit description. To determine whether conventional valves could be driven with audible-frequency tones, we created valves similar to Collino, *et al* by adding a weir under the diaphragm. Device showed peak DC pumping at 650 Hz (**Fig. S2**). In Collino, *et al*, the diaphragm provided flow rectification without contributing to circuit behavior, and resonance was controlled by the off-chip fluid connection<sup>3</sup>. In **Fig. S2**, the diaphragm served as both the flow rectification component and also as the frequency tuning component. Thus, diaphragm valves can be fabricated for resonant excitation by audible frequency tones. Video of the demonstration is included in the Supplementary (Video SV1).

Device fabrication: Diaphragm valve devices were fabricated by stacking laser-cut 1.5 mm acrylic sheets (McMaster Part# 8560K171). Channels are defined as features in the sheet and make up the resistive and inductive parts of the fluidic circuit. Rohaglas film 0.254 mm thick (Sabic Polymershapes Seattle WA, Part#76017130-C) was used as the deformable material to make diaphragms. A piezo buzzer (10 mm radius, Mouser Part# 81-7BB-20-6L0) sticking to a diaphragm connected to channel(s) served as the on-chip harmonic pressure source. Fluid ports (cut pieces of 5.6 mm diameter 5mL serological pipette) were glued to the device to form pump inlet and outlet. The size of ports was sufficiently large so as to not impact the frequency response of the underlying microfluidic network.



**Figure S2: Resonant fluidic pump with a diaphragm valve for flow rectification.** (a,b) Schematic and picture of the diaphragm-valve device. The valve design was similar to that of Collino, et al, except that stiffer diaphragm material (Rohaglas) was used to shift the resonant frequency to the audible frequency range. Weir was symmetrically placed under the diaphragm. Weir width was 2mm and height was same as the channels (1.5mm). (c) DC pump pressure as a function of driving frequency. DC pump pressure was measured under stopped flow conditions (inset images for 600 Hz, 650 Hz and 700 Hz). Maximum pump pressure was noted at 650 Hz and was comparable to DC pump pressure observed for the devices in the text. DC Flow below 570 Hz and above 700 Hz were below the threshold of detection. **Device dimensions.** Channels: 1.5 mm tall, 0.8 mm wide. Outlet channel (left): 8 mm long. Valve-piezo channel (middle): 14 mm long. Outlet channel (right): 2 mm long. Valve diaphragm: radius 4 mm radius, thickness 0.25 mm ( $C_d = 0.0156 \text{ mm}^3/\text{kPa}$ ). Valve weir: 2 mm wide, full channel height, full diaphragm width.



## Section 10: Power draw and valve efficiency estimate.

We measured the AC electrical current consumed by the piezo when driven under conditions used for experiments (100-2000 Hz, filled with density-matched fluid). The valve efficiency was estimated from a pump device by measuring the DC flowrate pumping against a moderate DC pressure head for a device of the Figure 3 design (also see supplementary video SV3).

### Instantaneous input power calculation (electrical)

- Peak-to-Peak AC input Voltage:  $V_{in} = 30\sqrt{2}$  V
- Peak-to-Peak AC input Current:  $I_{in} = 10\sqrt{2}$   $\mu$ A (@650 Hz)
- Total instantaneous input power:  $P_{in} = V_{in} * I_{in} = 600$   $\mu$ W

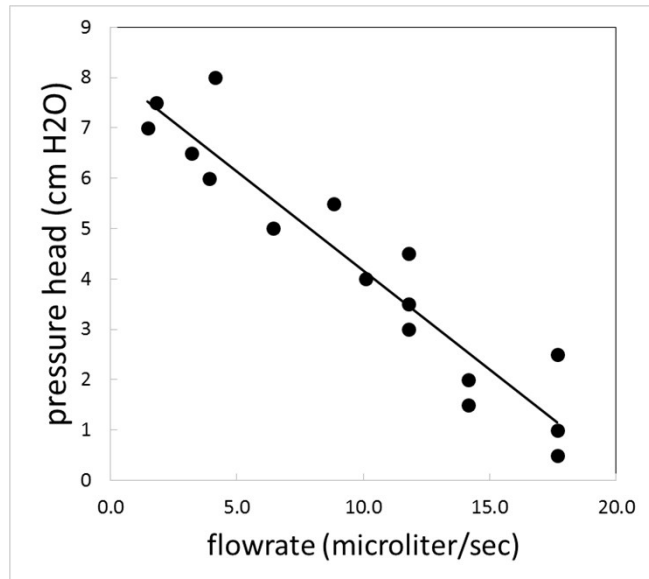
### Instantaneous output power calculation (fluidic)

- DC pressure:  $P_{DC, out} = 4$  cm H<sub>2</sub>O = 400 Pa
- DC flowrate:  $Q_{DC, out} = 10$   $\mu$ L/s
- Instantaneous output power:

$$\begin{aligned} \text{Power}_{out} &= P_{DC, out} * Q_{DC, out} \\ &= 400 \text{ Pa} * 10 \text{ } \mu\text{L/s} \\ &= 400 \text{ (kg.m}^{-1}\text{.s}^{-2}\text{)} * 10 * 10^{-6} \text{ L/s} * 10^{-3} \text{ m}^3/\text{L} \\ &= 4 \text{ } \mu\text{W} \end{aligned}$$

### Pump efficiency estimate

- Efficiency:  $\eta = \text{Power}_{out}/\text{Power}_{in} = 4/600 * 100 = 0.7\%$



**Figure S3.** Pump curve for a device from **Fig. 3** in the text. Flowrate and pressure head were measured from the resting state (no pressure difference) to near the no-flow condition at the resonant pump frequency (~600 Hz). For estimation of the fluidic power output, the mid-point condition of the pump curve was chosen (flowrate 10  $\mu\text{L}/\text{second}$ , pressure head 4 cm  $\text{H}_2\text{O}$ ).

## References

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