Supplemental Material

Periodic Flow Purging System for Harvesting Fibers from Screens

Bon Ki Ku[*] [1], Gregory Deye[1] and Leonid A. Turkevich[2]

Centers for Disease Control and Prevention (CDC)

National Institute for Occupational Safety and Health (NIOSH)

[1] Health Effects Laboratory Division (HELD)

[2] Division of Field Studies & Engineering (DFSE)

1090 Tusculum Ave, MS-R7

Cincinnati, Ohio 45226, USA

[*] Author to whom correspondence should be addressed.
Tel.: +1 513 841 4147; fax: +1 513 841 4545.
E-mail address: bku@cdc.gov (B.K. Ku).

Table S1. Statistical parameters for the different cumulative fractions in the fiber/screen experiments.

Screen	Fiber fractions	Geometric mean length (μm)	Geometric standard deviation	Fraction [%] of fibers longer than 20 μm	Mean length (μm)	Standard deviation (μm)
	Total fibers	15	1.56	38.1	23.5	21.5
10	Penetrating	6.5	1.45	10.3	11.3	7.9
10	Backflush—humid air	22	1.43	57.3	35.8	24.3
10	Washed	32.2	1.44	67.8	46.0	34.5
10	Penetrating (run 2)	7.0	1.43	6.4	10.3	7.3
10	Backflush—humid air (run 2)	23	1.63	55.1	45.9	35.0
20	Penetrating	6.3	1.62	11.0	11.0	10.2
20	Backflush--dry air	17.5	1.53	43.8	30.9	23.6
20	Backflush--humid air	26.3	1.68	59.3	45.7	48.0
20	Washed	39.4	1.35	73.5	52.2	32.0
20	Penetrating (run 2)	8.8	1.41	12.7	12.9	8.7
20	Backflush--humid air (run 2)	23.8	1.69	56.0	42.0	44.2

Statistical Analysis

We used the two sample Kolmogorov-Smirnov (K-S) statistical test (the data analysis for this test was generated using the Real Statistics Resource Pack software (Release 7.6). Copyright (2013 – 2021) Charles Zaiontz: Zaiontz, 2020) to quantify the differences in the various cumulative distributions in our experiments. Within the K-S test analysis, the two cumulants are compared, and the maximum difference, D_{max}, between the two cumulant (at a given fiber length) is identified. The critical value, D_α , is determined based on sample size, N, and level α (= 0.05). The null hypothesis (i.e., two cumulative distributions are the same) is rejected at level α if $D_{max} > D_\alpha$.

Table S2 compares the cumulative distributions for one experiment with the 10 μm screen (Fig. 2). All 4 distributions are statistically distinct at level $\alpha = 0.05$.

Table S3 compares the cumulative distributions for one experiment with the 20 μm screen (Fig. 3). All 4 distributions are statistically distinct at level $\alpha = 0.05$.

Table S4 compares the cumulative distributions for the backflushed fibers with the 20 μm screen, using dry vs. humid air for the backflushing (Fig. 3). The dry-air backflush fiber distribution is not statistically different from the distribution of the total (incoming) aerosol; the dry-air and humid-air backflush fiber distributions are statistically different at level $\alpha = 0.05$.

Table S5 compares the cumulative distributions for the penetrating fibers with screens of different mesh sizes (Fig. 4). The distributions of penetrating fibers from the 10 μm and 20 μm

screens are not statistically different; the distributions of penetrating fibers from the 20 μm and 41 μm screens are also not statistically different. However, the K-S test indicates that the distributions of penetrating fibers for the 10 μm and 41 μm screens are statistically different at level $\alpha = 0.05$.

Table S6 compares the cumulative distributions for the washed fibers from screens with different mesh sizes (Fig. 4). The washed fibers from the 10 μm and 20 μm screens are not statistically different; the washed fibers from the 30 μm and 41 μm screens are not statistically different; the washed fibers from the 10 μm and 41 μm screens are not statistically different. However, the K-S test indicates that the washed fibers from the 20 μm and 30 μm screens are statistically different at level $\alpha = 0.05$.

Table S2. Statistics of two sample Kolmogorov-Smirnov statistical test comparing the cumulative distributions in the experiment with 10 µm screen (Fig. 2).

	10 µm screen Cumulative fraction					
Fiber length (µm)	Penetrating fibers	Total	Total	Backflushed fibers	Backflushed fibers	Washed fibers
1.18	0.000	0.000	0.000	0.000	0.000	0.000
1.66	0.000	0.000	0.000	0.000	0.000	0.000
2.32	0.063	0.011	0.011	0.000	0.000	0.000
3.25	0.188	0.070	0.070	0.012	0.012	0.006
4.55	0.286	0.149	0.149	0.047	0.047	0.044
6.36	0.448	0.256	0.256	0.086	0.086	0.082
8.91	0.625	0.320	0.320	0.165	0.165	0.145
12.47	0.797	0.421	0.421	0.273	0.273	0.208
17.46	0.880	0.579	0.579	0.390	0.390	0.283
24.45	0.927	0.691	0.691	0.523	0.523	0.390
34.23	0.969	0.820	0.820	0.668	0.668	0.528
47.92	1.000	0.941	0.941	0.798	0.798	0.698
67.08	1.000	0.941	0.980	0.887	0.887	0.843
93.91	1.000	0.994	0.994	0.936	0.936	0.956
131.48	1.000	1.000	1.000	0.966	0.966	0.975
184.07	1.000	1.000	1.000	0.985	0.985	1.000
257.70	1.000	1.000	1.000	1.000	1.000	1.000
360.78	1.000	1.000	1.000	1.000	1.000	1.000
505.09	1.000	1.000	1.000	1.000	1.000	1.000
D_{max}	0.376		0.211		0.175	
Critical value D_α	0.120		0.114		0.139	
Significantly different	Yes		Yes		Yes	

Null Hypothesis: F(x) = G(y)
Alternative Hypothesis: F(x) < > G(y)

At the 0.05 level, the two distributions are significantly different if $D_{max} > D_\alpha$

Table S3. Statistics of two sample Kolmogorov-Smirnov statistical test comparing the cumulative distributions in the experiment with 20 µm screen (Fig. 3).

	20 µm screen Cumulative fraction					
Fiber length (µm)	Penetrating fibers	Total	Total	Backflushed fibers	Backflushed fibers	Washed fibers
1.18	0.000	0.000	0.000	0.000	0.000	0.000
1.66	0.000	0.000	0.000	0.000	0.000	0.000
2.32	0.036	0.000	0.000	0.007	0.007	0.000
3.25	0.158	0.004	0.004	0.034	0.034	0.027
4.55	0.320	0.065	0.065	0.041	0.041	0.066
6.36	0.509	0.143	0.143	0.095	0.095	0.115
8.91	0.635	0.229	0.229	0.155	0.155	0.159
12.47	0.761	0.364	0.364	0.236	0.236	0.221
17.46	0.860	0.485	0.485	0.365	0.365	0.239
24.45	0.941	0.623	0.623	0.480	0.480	0.310
34.23	0.991	0.771	0.771	0.588	0.588	0.420
47.92	1.000	0.857	0.857	0.689	0.689	0.633
67.08	1.000	0.918	0.918	0.811	0.811	0.827
93.91	1.000	0.965	0.965	0.919	0.919	0.907
131.48	1.000	0.987	0.987	0.980	0.980	0.973
184.07	1.000	1.000	1.000	1.000	1.000	0.996
257.70	1.000	1.000	1.000	1.000	1.000	1.000
360.78	1.000	1.000	1.000	1.000	1.000	1.000
505.09	1.000	1.000	1.000	1.000	1.000	1.000
D_{max}	0.376		0.183		0.170	
Critical value D_α	0.126		0.141		0.142	
Significantly different	Yes		Yes		Yes	

Null Hypothesis: F(x) = G(y)
Alternative Hypothesis: F(x) < > G(y)

At the 0.05 level, the two distributions are significantly different if $D_{max} > D_\alpha$

Table S4. Statistics of two sample Kolmogorov-Smirnov statistical test comparing the cumulative distributions of two backflushed samples in (Fig. 3).

	20 µm screen Cumulative fractions			
Fiber length (µm)	Total	Backflushed (dry)	Backflushed (dry)	Backflushed (humid)
1.18	0.000	0.000	0.000	0.000
1.66	0.000	0.000	0.000	0.000
2.32	0.000	0.000	0.000	0.007
3.25	0.004	0.000	0.000	0.034
4.55	0.065	0.066	0.066	0.041
6.36	0.143	0.115	0.115	0.095
8.91	0.229	0.238	0.238	0.155
12.47	0.364	0.393	0.393	0.236
17.46	0.485	0.508	0.508	0.365
24.45	0.623	0.656	0.656	0.480
34.23	0.771	0.779	0.779	0.588
47.92	0.857	0.902	0.902	0.689
67.08	0.918	0.934	0.934	0.811
93.91	0.965	0.951	0.951	0.919
131.48	0.987	0.975	0.975	0.980
184.07	1.000	1.000	1.000	1.000
257.70	1.000	1.000	1.000	1.000
360.78	1.000	1.000	1.000	1.000
505.09	1.000	1.000	1.000	1.000
D_{max}	0.045		0.212	
Critical value D_α	0.150		0.163	
Significantly different	No		Yes	

Null Hypothesis: $F(x) = G(y)$
Alternative Hypothesis: $F(x) <> G(y)$

At the 0.05 level, the two distributions are significantly different if $D_{max} > D_\alpha$

Table S5. Statistics of two sample Kolmogorov-Smirnov statistical test comparing the cumulative distributions of different penetrating fiber samples (Fig. 4).

	Penetrating fibers Cumulative fractions					
Fiber length (µm)	10 µm screen	20 µm screen	20 µm screen	41 µm screen	10 µm screen	41 µm screen
1.18	0.000	0.000	0.000	0.000	0.000	0.000
1.66	0.000	0.000	0.000	0.003	0.000	0.003
2.32	0.038	0.036	0.036	0.028	0.038	0.028
3.25	0.201	0.158	0.158	0.146	0.201	0.146
4.55	0.418	0.320	0.320	0.272	0.418	0.272
6.36	0.582	0.509	0.509	0.443	0.582	0.443
8.91	0.753	0.635	0.635	0.587	0.753	0.587
12.47	0.874	0.761	0.761	0.741	0.874	0.741
17.46	0.950	0.860	0.860	0.869	0.950	0.869
24.45	0.987	0.941	0.941	0.924	0.987	0.924
34.23	1.000	0.991	0.991	0.975	1.000	0.975
47.92	1.000	1.000	1.000	0.995	1.000	0.995
67.08	1.000	1.000	1.000	1.000	1.000	1.000
93.91	1.000	1.000	1.000	1.000	1.000	1.000
131.48	1.000	1.000	1.000	1.000	1.000	1.000
184.07	1.000	1.000	1.000	1.000	1.000	1.000
257.70	1.000	1.000	1.000	1.000	1.000	1.000
360.78	1.000	1.000	1.000	1.000	1.000	1.000
505.09	1.000	1.000	1.000	1.000	1.000	1.000
D_{max}	0.118		0.066		0.166	
Critical value D_α	0.125		0.113		0.110	
Significantly different	No		No		Yes	

Null Hypothesis: F(x) = G(y)
Alternative Hypothesis: F(x) < > G(y)

At the 0.05 level, the two distributions are significantly different if $D_{max} > D_\alpha$

Table S6. Statistics of two sample Kolmogorov-Smirnov statistical test comparing the cumulative distributions of different washed fiber samples (Fig. 4).

	Washed fibers Cumulative fractions							
Fiber length (μm)	10 μm screen	20 μm screen	20 μm screen	30 μm screen	30 μm screen	41 μm screen	10 μm screen	41 μm screen
1.18	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.66	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2.32	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.003
3.25	0.006	0.027	0.027	0.033	0.033	0.033	0.006	0.033
4.55	0.044	0.066	0.066	0.090	0.090	0.092	0.044	0.092
6.36	0.082	0.115	0.115	0.135	0.135	0.132	0.082	0.132
8.91	0.145	0.159	0.159	0.204	0.204	0.211	0.145	0.211
12.47	0.208	0.221	0.221	0.270	0.270	0.244	0.208	0.244
17.46	0.283	0.239	0.239	0.342	0.342	0.307	0.283	0.307
24.45	0.390	0.310	0.310	0.453	0.453	0.403	0.390	0.403
34.23	0.528	0.420	0.420	0.553	0.553	0.531	0.528	0.531
47.92	0.698	0.633	0.633	0.700	0.700	0.680	0.698	0.680
67.08	0.843	0.827	0.827	0.820	0.820	0.848	0.843	0.848
93.91	0.956	0.907	0.907	0.919	0.919	0.947	0.956	0.947
131.48	0.975	0.973	0.973	0.979	0.979	0.974	0.975	0.974
184.07	1.000	0.996	0.996	0.997	0.997	1.000	1.000	1.000
257.70	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
360.78	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
505.09	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
D_{max}	0.108		0.144		0.051		0.067	
Critical value D_α	0.116		0.107		0.077		0.131	
Significantly different	No		Yes		No		No	

Null Hypothesis: F(x) = G(y)
Alternative Hypothesis: F(x) < > G(y)

At the 0.05 level, the two distributions are significantly different if $D_{max} > D_\alpha$

Throughput of the Current System and Relevance for Toxicological Studies

While at the present time, we do not have an operational instrument that can prepare total mass M ~ 0.1 g of sample (the typical quantity required for an inhalation toxicology experiment), we are evaluating whether this screen flow purging system can be used for length separation of fibers in large quantity. The estimates below indicate that the technique has the potential to separate fibers in sufficient quantity.

The number fluxes, dN/dt, of original, penetrating, and back-flushed fibers may be estimated from the optical microscope images. In each field there are about 30-40 fibers for the original test fibers (20 penetrating fibers and 10 back-flushed fibers), which depends on initial batch amount of fiber powder (typical batch amount ~ 0.1 g in this study). The MCE filter has approximately 5800 fields per filter. This gives a number flux dN/dt ~ 1290 and 483 fibers/s for penetrating and back-flushed fibers, respectively. A typical fiber (diameter ~ 1 μm, length ~ 10 μm) has a mass of ~ 20 pg. The number flux of penetrating and back-flushed fibers corresponds to a mass flux dM/dt ~ 2.58×10^{-8} g/s and 9.66×10^{-9} g/s, respectively. The time to collect 0.1 g of material is t ~ 1100 hr (~ 138 days) and 2800 hr (350 days) for penetrating and back-flushed fibers, respectively.

If we increase the initial batch amount of fiber powder from 0.1 g to 1.0 g, as we showed in the previous study (Ku *et al.,* 2013), the number concentration of aerosolized fibers increases from 200-300 particles/cm^3 to 2000-3000 particles/cm^3; this reduces the collection time for each fiber sample to 110 hr (~ 14 days) and 280 hr (35 days), respectively.

For comparison, the Baron fiber length classifier (Baron *et al.,* 1994) has a mass flux of 2.26 x 10^{-9} g/s; the time to collect 0.1 g of material is t ~ 12,300 hr (~1500 days). Thus, our flow purging system has an order of magnitude higher mass throughput than the Baron fiber length classifier.

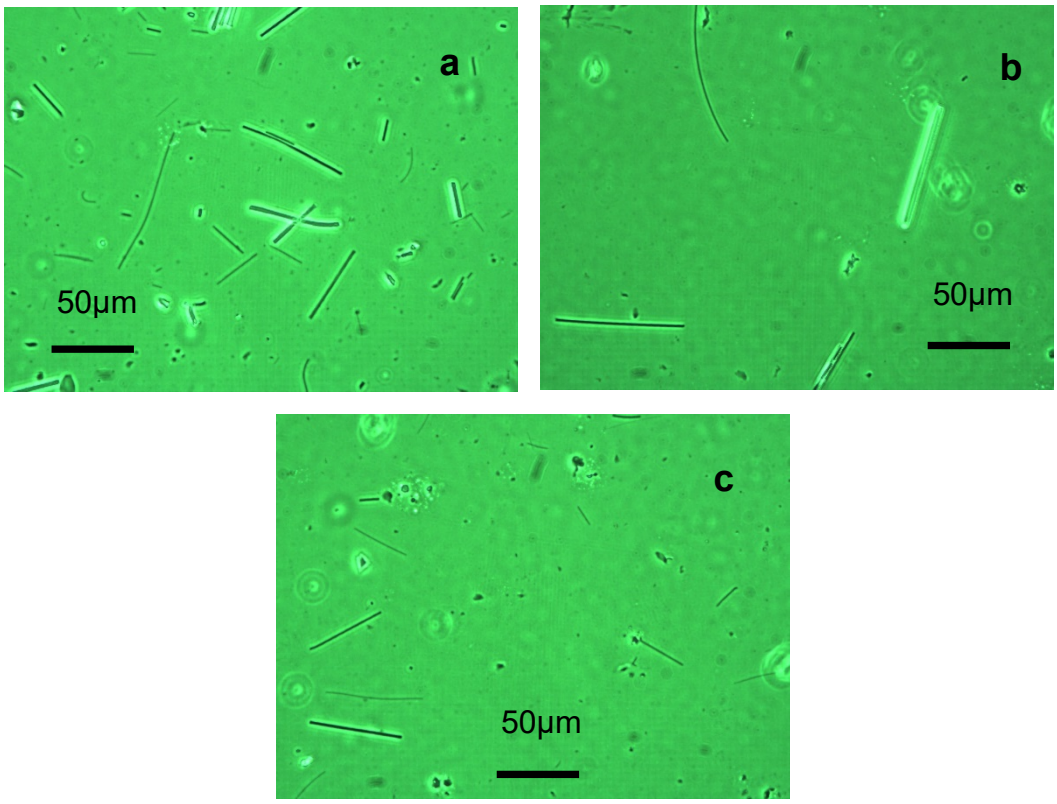

Fig. S1 Typical images of fibers taken by phase contrast microscope. Aerosolized glass fibers collected on MCE filter (a) without screen, (b) harvested from 10 μm screen by back-flushing purge, and (c) harvested from 20 μm screen by back-flushing purge.

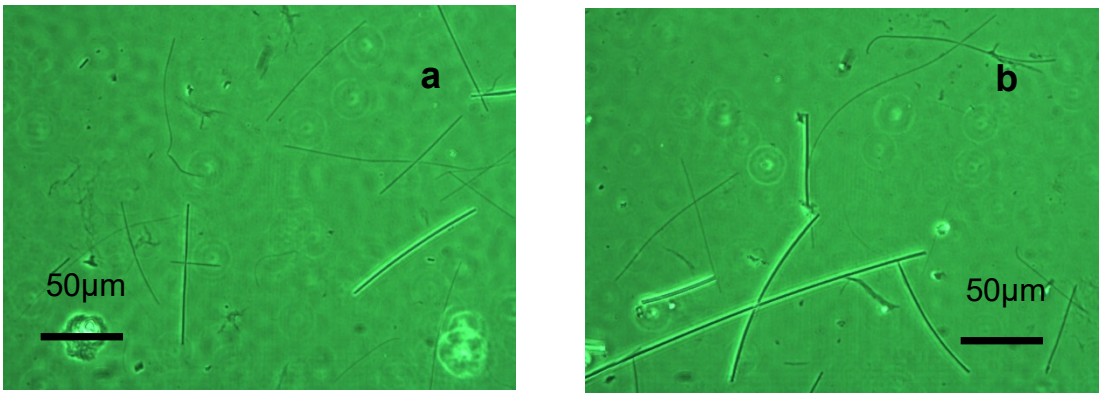

Fig. S2 Typical images of fibers collected on a screen and harvested by washing screen (a) 10 μm and (b) 20 μm.

References

Baron, P.A., Deye, G.J., Fernback, J. (1994). Length separation of fibers. *Aerosol Sci. Technol. 21*: 179-192.

Ku, B.K., Deye, G., Turkevich, L.A. (2013). Characterization of a Vortex Shaking Method for Aerosolizing Fibers. *Aerosol Sci Technol* 47, 1293-301.

Zaiontz, C. (2020). Real Statistics Using Excel. www.real-statistics.com