Cell separation using tilted-angle standing surface acoustic waves

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Separation of cells is a critical process for studying cell properties, disease diagnostics, and therapeutics. Cell sorting by acoustic waves offers a means to separate cells on the basis of their size and physical properties in a label-free, contactless, and biocompatible manner. The separation sensitivity and efficiency of currently available acoustic-based approaches, however, are limited, thereby restricting their widespread application in research and health diagnostics. In this work, we introduce a unique configuration of tilted-angle standing surface acoustic waves (taSSAW), which are oriented at an optimally designed inclination to the flow direction in the microfluidic channel. We demonstrate that this design significantly improves the efficiency and sensitivity of acoustic separation techniques. To optimize our device design, we carried out systematic simulations of cell trajectories, matching closely with experimental results. Using numerically optimized design of taSSAW, we successfully separated 2- and 10-μm-diameter polystyrene beads with a separation efficiency of ~99%, and separated 7.3- and 9.9-μm-polystyrene beads with an efficiency of ~97%. We illustrate that taSSAW is capable of effectively separating particles—cells of approximately the same size and density but different compressibility. Finally, we demonstrate the effectiveness of the present technique for biological–biomedical applications by sorting MCF-7 human breast cancer cells from non-malignant leukocytes, while preserving the integrity of the separated cells. The method introduced here thus offers a unique route for separating circulating tumor cells, and for label-free cell separation with potential applications in biological research, disease diagnostics, and clinical practice.

Significance

We have developed a unique approach for the separation of particles and biological cells through standing surface acoustic waves oriented at an optimum angle to the fluid flow direction in a microfluidic device. This experimental setup, optimized by systematic analyses, has been used to demonstrate effective separation based on size, compressibility, and mechanical properties of particles and cells. The potential of this method for biological–biomedical applications was demonstrated through the example of isolating MCF-7 breast cancer cells from white blood cells. The method offers a possible route for label-free particle or cell separation for many applications in research, disease diagnosis, and drug-efficacy assessment.


Conflict of interest statement: X.D. and T.J.H. have filed a patent based on a portion of the work outlined in this paper; S.L., P.L., M.D., Z.P., Y.C., X.D., and T.J.H. have filed a patent based on the work presented in this paper. Freely available online through the PNAS open access option.

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Many applications in biology and medicine call for efficient and reliable separation of particles and cells for disease diagnosis, genetic analysis, drug screening, and therapeutics (1–6). Cells can be separated on the basis of their surface molecular markers or physical characteristics such as density, size, stiffness, or electric impedance (7–10). When separating cells with distinct physical properties, using methods that exploit differences in cells’ physical parameters could be advantageous due to their label-free nature and ease of use (11, 12). Many techniques are available to separate cells based on physical properties; they include filtration, centrifugation, acoustic, optical, and dielectrophoresis (13–27). Among these techniques, acoustic-based approaches are advantageous because of their biocompatibility and label-free nature (25, 27–32). The so-called “acoustic tweezers” technologies, which can perform highly precise cell manipulations, are particularly promising for cell-separation applications and offer additional advantages in ease of use and versatility (27, 29). Despite these advantages, acoustic separation has not been widely used in practical cell-separation applications due to their relatively low separation sensitivity and efficiency. An acoustic separation is often achieved by establishing a standing acoustic field within a flow channel. When a standing acoustic field

is present in a fluid medium, particles (or cells) populating the fluid will be pushed toward regions with minimal acoustic radiation pressure (pressure nodes) (25). Particles with different sizes and/or physical properties will experience different acoustic radiation forces and will require different times to migrate to the pressure nodes, thus providing clear identifiers for separation. In all of the existing acoustic separation approaches, the fluid flow direction is parallel to the standing acoustic wave direction (27). With such a configuration, the maximal separation distance is limited to a quarter of the acoustic wavelength. As a result, acoustic separation techniques often have low separation efficiency (i.e., a fraction of the target particles are not separated from the nontarget particles) and low sensitivity (i.e., two sets of particles with small size differences between them cannot be separated from each other). If these limitations could be overcome, acoustic separation could offer a powerful means for label-free separation of cells with many applications in biology research, disease diagnosis, and clinical practice.

In this work, we propose a previously unavailable approach to acoustic separation of particles and cells by using tilted-angle standing surface acoustic waves (taSSAW). Here, the pressure nodal lines induced by the standing surface acoustic wave (SSAW) are inclined at a specific angle to the flow direction, rather than being parallel to each other. With this design, a particle in a fluid...
medium experiences both the acoustic radiation force and the
laminar drag force. The competition between these two forces
determines the position of the particle and defines its movement
along the pressure nodal lines, which lie across the channel at
a particular angle of inclination to the flow. As a result, the
migration distance of the particle along the direction perpendicular
to the flow could be a few times or tens of times the acoustic
wavelength, depending on the geometry of the channel. This
migration distance is significantly higher than that of the tradi-
tional acoustic separation approaches. The ability of taSSAW
to achieve much larger separation distances leads to better
separation sensitivity. In addition, the taSSAW design uses
multiple pressure nodal lines for separation instead of only one
pressure nodal line in the conventional acoustic separation
designs. Because there are many parallel pressure nodal lines
lying across the flow, target particles that escape from one
pressure nodal line can be trapped again by the neighboring
nodal line and be separated from the non-target particles. This
multiple-node design also produces higher separation efficiency.

To develop a robust scientific basis for optimizing the design
of this taSSAW method and to guide our experiments, we have
developed computational simulations of particle–cell trajectories
in a taSSAW field. In this article we present comprehensive
numerical simulations and parametric analyses to predict parti-
cle trajectories in continuous flow. These parametric analyses
examined the specific effects of key variables, such as cell size
and properties, tilt angle of the pressure nodal lines with respect
to the flow direction, flow rate, and input power, on separation
efficiency. The predictions of the numerical simulations were
also systematically validated with results from control experi-
ments. The computational models developed here thus provide
a general framework to systematically assess the complex in-
terplay among various geometrical, rheological, and physical
properties of the components of taSSAW device for cell sepa-
ration in a wide variety of applications in a manner that cannot
be accomplished solely by experiments.

We also demonstrate the ability of the taSSAW method for
human cancer diagnostics by accurately separating MCF-7 breast
cancer cells from normal human leukocytes (white blood cells,
WBCs). This result points to the potential of this technique as a
label-free, biocompatible assay to separate circulating tumor cells,
and thereby, to distinguish different lineages of healthy human
cells from pathological ones for a wide array of disease
diagnostics.

Results

Design and Characterization. Fig. 1 illustrates the structure and
the working mechanism of the taSSAW separation device. A poly-
dimethylsiloxane (PDMS) microfluidic channel was bonded in
between a pair of identical interdigital transducers (IDTs) coated
on a piezoelectric substrate. The microfluidic channel consists of
three inlets and two outlets. The pair of IDTs were deposited in
a parallel arrangement with respect to each other, and aligned at
a specific angle with respect to the channel and flow direction.
A radio frequency (RF) signal was imposed at each IDT to generate
two identical surface acoustic waves (SAWs). These two SAWs
propagate toward each other and interfere to form an SSAW in
between the IDTs located within the PDMS microchannel. Such
an SSAW generates parallel pressure nodal and antinodal lines at
a particular angle to the flow direction, and is termed ‘taSSAW.’
Details about the device fabrication and experimental setup are
listed in SI Text, Device Fabrication and Experimental Setup.

The acoustic radiation force, generated from the pressure
distribution within the microfluidic channel, pushes the sus-
pended particles toward the pressure nodal or antinodal lines
in the taSSAW field, depending on the physical properties (such
as volume, compressibility, and density) of particles and medium.
Particles were first injected through the center inlet channel and
then were hydrodynamically focused in the main channel by two
sheath flows before entering the taSSAW working region.

When a particle enters the SSAW working region, it experiences
an acoustic radiation force, a drag force, a gravitational force, and
a buoyancy force. With the small dimensions of the microfluidic
channels, the gravitational and the buoyancy forces have similar
magnitude but opposite direction, and are almost balanced. Thus,
the behavior of particles in the microfluidic channel can be char-
acterized by examining the drag force ($F_d$) and the acoustic radi-
ation force ($F_a$). The acoustic radiation force tends to confine
particles at the pressure nodal lines whereas the drag force induced
by the flowing fluid pushes particles forward along the flow di-
rection. When a mixture of particles with various sizes passes
through the taSSAW region, they all experience acoustic radiation
force and drag force. The acoustic radiation force dominates over
the drag force for larger particles and results in a lateral dis-
placement. Conversely, the drag force dominates over the acoustic
force for smaller particles, resulting in little lateral displacement.

Using the taSSAW approach, we demonstrate separation of
10- and 2-μm polystyrene beads with 99% separation efficiency.
The separation process can be found in the stacked images in
Fig. 1 B and C, where the large particles (10 μm) were collected
in the upper outlet channel whereas the small ones (2 μm) ac-
cumulated in the lower outlet. In our current device, a number of
pressure nodal lines fall within the channel at 30° to the flow di-
rection, as depicted in Fig. 1 B. Whereas the small particles tend
to traverse those multiple pressure nodal lines, the large particles
will be confined within the nodal lines and migrate along a path line
at 30° with respect to the flow of the smaller particles. Because
the velocity of each individual particle varies, some larger particles
may escape from the first pressure node; however, they would eventu-
ally be captured at subsequent neighboring nodes and continue
to migrate across the channel. The multiple pressure nodal lines
along the path of the particle stream significantly improved the
separation efficiency and sensitivity compared with the previously
demonstrated SSAW-based particle separator (27), in which there
was only one pressure nodal (or antinodal) line in the channel.
Note that the keys for high-efficiency separation in the taSSAW
mechanism are the angle between pressure nodal lines and the flow, as well as the device operation power, which will be explored in the following two sections.

With the taSSAW design, separation of particles with small size differences also becomes feasible. Next we demonstrate high-efficiency separation of 7.3- and 9.9-μm particles. An aqueous solution with fluorescent polystyrene beads with diameters of 9.9 μm (red) and 7.3 μm (green) was injected into the main channel of the device at a flow velocity of ~1.5 mm/s. The angle between the SSAW pressure nodal lines and the flow direction is set at 15° for this particular experiment. The length of the overlapping IDT electrode fingers is designed to be 4 mm, corresponding to the period of the IDT fingers, which is 200 μm. The main channel is 75 μm high and 1,000 μm wide. The mixed beads were focused upstream before entering the SSAW working region in the channel (Fig. 2). The input power was set at 25 dBm. The fluorescence intensity of beads was profiled near the outlet channel to indicate the mean distribution of the bead positions. Downstream of the SSAW working region, the 9.9-μm beads had a lateral migration of ~130 μm more than the 7.3-μm beads. By splitting the outlet channel near the center of the green peak and red peak (at about ~220 μm of the lateral position in Fig. 2B), we could achieve a separation efficiency of ~100% for 9.9-μm beads and ~97% for 7.3-μm beads. The two peaks in distribution of the smaller beads could be caused by the parabolic velocity distribution of the fluid in the vertical direction and imperfect particle focusing before entering the SSAW working region.

Numerical Simulation of Particle Separation. Parametric studies of the key variables in the design of the device would improve the efficiency of separating microbeads of similar sizes and isolating cancer cells from normal cells. To better understand the mechanism of taSSAW-based particle separation, we performed an analysis of the trajectory of a particle in a rectangular channel flow under an acoustic radiation force field using numerical simulations. In particular, we studied the effects of acoustic power, particle size, and particle compressibility on particle trajectory, and compared the numerical results with corresponding experimental results. Details are listed in SI Text, Details About Numerical Simulation of Particle Separation.

First, we studied the particle size effect and considered three different diameters: 15, 10, and 4 μm. A comparison between the simulation data and the experimental results is shown in Fig. 3A. The particle separation process was captured digitally (10 frames/s) and is presented as stacked images in Fig. 3A (also see Movie S1). The black dots are trajectories of particles with different sizes. The areas with different colors are trajectory ranges predicted by numerical simulations for three different particle sizes [15 μm (red), 10 μm (blue), and 4 μm (green)]. The initial positions of particles ahead of the taSSAW working region are distributed in a range of 60 μm in the Y direction. For all three different particle sizes, the predicted trajectories in simulations match well with the experiment. For particles with a diameter of...
15 μm, they only lie in one pressure nodal line and form a single line (the red line in Fig. 3A). This is because the acoustic radiation force for 15-μm particles is very strong and overcomes the initial disturbed vertical positions of particles. For diameter of 10 μm, particles cross two pressure nodal lines. In the transition between pressure nodal lines, the simulations show spread areas, whereas between these transitions, the particle trajectories converge to narrow lines, which are the pressure nodal lines as shown by the blue area in Fig. 3A. For diameter of 4 μm, because the acoustic radiation force is much weaker than flow-induced drag force, the particles almost follow the original undisturbed streamlines as shown by the green area in Fig. 3A.

Second, we studied the particle trajectories under different acoustic powers (19, 23, 27, and 31 dBm), and the diameter of the bead was chosen for this purpose to be 15 μm. The simulation results (areas with different colors in Fig. 3B) are consistent with the experimental results (black dots in Fig. 3B). For an input power of 31 dBm, the particles only stay in one pressure nodal line (red area); for input powers of 27, 23, and 19 dBm the particles cross two, three, and five pressure nodal lines, respectively (blue, purple, and green in Fig. 3B). The simulation results again match well with experimental results. We also carried out a series of tests to explore the overall effects of size and power on the particle trajectories. The trajectories of particles with various sizes under different powers are shown in Fig. S1.

Finally, we studied the influence of the particle compressibility. Particle separation has been demonstrated by applying magnetic, dielectrophoretic, optical, and hydrodynamic forces (6, 7, 19, 20). None of these methods, however, is capable of effectively separating particles on the basis of their compressibility difference. To explore the unique capability of our taSAW-based method, we carried out particle separation based on differences in compressibility. HL-60 is a human promyelocytic leukemia cell line with average diameter, density, and compressibility of ∼15 μm, 1.075 kg m$^{-3}$, and 4 × 10$^{-10}$ Pa$^{-1}$, respectively. Polystyrene beads (∼15 μm in diameter, with density ∼1.05 kg m$^{-3}$, and compressibility ∼2.16 × 10$^{-10}$ Pa$^{-1}$) were mixed with HL-60 cells in a ratio of 1:4. They have similar densities and sizes but different compressibilities. In this case, inclination angle, θ = 30°, an SAW wavelength λ = 300 μm, and flow rate = 9 μL/min were used. Fig. 3C shows that the simulation results once again closely match the experimentally observed particle trajectories. The small black dots in Fig. 3C are the trajectory of polystyrene beads in experiments, whereas the large gray dots are HL-60 cells. The red and blue areas in Fig. 3C are the trajectories for polystyrene beads and HL-60 cells, respectively, as predicted by numerical simulations.

**Optimization of the Angle of Inclination by Numerical Simulations.** To further improve the separation efficiency, we studied its dependence on the angle of inclination θ by numerical simulations. For example, to achieve the maximum separation distance ΔY in the Y direction between two microbeads with diameters of 10 and 4 μm at the outlet, we plot ΔY as a function of θ at different power levels (Fig. 4A). It shows that ΔY increases almost linearly when θ increases from 0° to a higher value (depending on power levels) between 10° and 15°, and it drops significantly when θ increases to 45°. In addition, there are small oscillations in the dependence of ΔY on θ due to the increasing number of pressure nodal lines in the path of particles. For the power of 30 dBm, the separation distance ΔY (∼500 μm) with an inclined angle of 15° is twice that (∼250 μm) with an inclined angle of 10°. For different power levels, the initial increases of ΔY with θ overlap, and the maximum separation distance increases linearly with the power magnitude.

To demonstrate the ability of this method to successfully separate cancer cells from healthy human WBCs, we also carried out numerical simulations to find the optimal angle of inclination to maximize the separation efficiency between these two types of cells with different sizes (20 μm vs. 12 μm), different compressibilities (4.22 × 10$^{-10}$ Pa$^{-1}$ vs. 3.99 × 10$^{-10}$ Pa$^{-1}$), and different densities (1.068 kg m$^{-3}$ vs. 1.019 kg m$^{-3}$). Because ΔY increases with increasing power, we found that for the maximal operating power (45 dBm), the maximal separation ΔY can be achieved at an inclination angle of 15°. In distinct contrast with the case of the microbeads (Fig. 4A), cell separation leads to a noticeably different response: the initial increase of ΔY is slow when θ is small, and there is an abrupt increase after θ reaches...
a certain value, as shown in Fig. 4B. In addition, the initial parts of the curves are quite different at different power levels, whereas they are almost the same for the microbeads (Fig. 4A). After \( \theta \) reaches the optimal angle, \( \Delta \theta \) decreases significantly when \( \theta \) increases to 45\(^\circ\).

**Separation of Cancer Cells from Human Healthy WBCs.** As a crucial step in isolating and analyzing circulating tumor cells for cancer diagnosis, we used the taSSAW device to separate MCF-7 cancer cells from normal leukocytes (WBCs) using an optimized design, guided by the numerical simulation, with an angle of inclination of 15\(^\circ\). In this set of experiments, 1 mL human whole blood (Zen-bio) was lysed using a red blood cell (RBC) lysis buffer (eBioscience), and the concentration of the collected leukocytes was measured to be \( \sim 3 \times 10^6/mL \). One mL of such erythrocyte-lysed blood sample was then mixed with 100 \( \mu \)L of cancer cells \( (3 \times 10^6 \text{ cells/mL}) \) to achieve a cancer cell concentration of \( \sim 10\% \). Here the MCF-7 cell (a human breast cancer epithelial cell line) was used as the cancer cell model. The mixed sample of fluorescently stained MCF-7 cells and normal leukocytes was then delivered into the taSSAW separation device through a syringe pump. Because MCF-7 cells are usually larger than leukocytes (as shown in Fig. 5), when the cells entered the taSSAW working region, the \( \sim 20\text{-}\mu \text{m}-diameter \) MCF-7 cells were separated from the \( \sim 12\text{-}\mu \text{m}-diameter \) leukocytes (Movie S2). The process of isolating one MCF-7 cell (red circle) from the leukocytes (green circles) is shown in Fig. 5A, in which a series of time-lapsed images shows the position of one MCF-7 cell. As shown in Fig. 5A, the cell trajectories predicted by our numerical simulations match well with those obtained from the experiments. The simulation results also indicate that the compressibility difference between MCF-7 cells and leukocytes works against the size-difference-mediated separation. Specifically, the separation distance at the outlet is about 95 \( \mu \text{m} \) with both compressibility and size differences considered, but it is increased to 260 \( \mu \text{m} \) if the compressibility difference is removed in the numerical simulations by setting the compressibility of MCF-7 cells from 4.22 \( \times 10^{-10} \text{ Pa}^{-1} \) to the same value of normal leukocytes (3.99 \( \times 10^{-10} \text{ Pa}^{-1} \)). These results indicate that a small difference in compressibility can result in a significant increase of separation distance. Cancer cells and leukocytes were eventually collected at different outlets for subsequent identification. Fig. 5B and C shows fluorescence images of stained cells illustrating the cell distributions before and after separation. Here EpCAM (red), CD45 surface markers (green), and a nuclear stain (DAPI, blue) were used to determine the purity of the isolated MCF-7 cells. Epithelial cancer cells such as MCF-7 are positive to EpCAM (red) and DAPI (blue) and negative to CD45, whereas leukocytes are positive to CD45 (green) and DAPI (blue), and negative to EpCAM. Fig. 5D–F shows the fluorescence images of MCF-7 after exposure to EpCam, CD45, and DAPI, respectively. Fig. 5G is a composite of the three fluorescence images. To quantitatively evaluate the capability of our device, we investigated the recovery rate and purity of cancer cell isolation. The recovery rate (\%) and purity (\%) for cell isolation are defined as the percentage of the number of isolated cancer cells over the number of spiked cancer cells, and that of the number of isolated cancer cells over the total number of collected cells, respectively. Under our current experimental conditions, we achieved a recovery rate of 71\% and a purity of 84\%, as shown in Fig. 5H. The flow fraction at the collection outlet (the upper outlet channel) significantly influences the purity and recovery. Logically, a higher fraction of flow into the collection stream results in a monotonic increase in the recovery rate and decrease in purity. For instance, additional experiments show that a 45\% flow fraction into the collection stream yielded a purity of \( \sim 98\% \) and a recovery rate of \( \sim 20\% \). However, a 60\% flow fraction into the collection stream yielded a purity of \( \sim 84\% \) but increased the recovery rate to \( \sim 71\% \).

**Tests on Cell Viability and Proliferation.** We conducted viability and proliferation assays to verify that our device is safe to biological cells for the duration of the experiment. The water-soluble tetrazolium salt cell viability test (Roche) and the BrdU Cell Proliferation ELISA (Roche) were used to test the cells’ viability and proliferation, respectively. MCF-7 cells were delivered into the device at a flow rate of 2 \( \mu \text{L/min} \) with an input power of 25 dBm (\( \sim 2 \text{ W/cm}^2 \)). Cell tests were then carried out immediately after collecting them from the outlet. Cells that were not processed in the device and those flowing through the device with SAWS turned off were also tested as control experiments. Cell viability and proliferation were examined by measuring cell metabolic activity and DNA synthesis, as shown in Fig. S2A and B. Direct staining of cell viability, as shown in Fig. S2 C–E, indicates that no significant damage was found in the physiological properties of the processed cells as a consequence of the taSSAW experiment.

**Discussion**

We have developed a taSSAW-based, label-free, cell-separation device that can achieve relatively high separation efficiency, high sensitivity, and high biocompatibility simultaneously compared with existing methods. By aligning the SAWA-induced pressure nodal lines at an inclined angle to the fluid direction, we covered the microchannel with the cells of pressure nodal lines, a design feature that significantly improved the cell-separation efficiency and sensitivity over previous acoustic cell separators.

Acoustic radiation force \( F_r \) is a sinusoidal function of space (as shown in Eq. S1) rather than a constant, so that if the acoustic radiation force is orthogonal to the fluid direction, particles on different sides of the nodal lines will experience forces with opposite signs, and they will eventually converge to a nodal line, leading to no separation. However, in the tilted-angle case, smaller particles will experience smaller acoustic forces and be pushed by the flow field to cross multiple nodal lines, leading to separation from larger particles. If all particles are subjected to large acoustic forces, they will converge to a single nodal line even in the tilted-angle case. Thus, in the case of \( \theta = 90\° \) (acoustic force is orthogonal to fluid field), there will be no separation if the channel is long enough for particles to converge. On the other hand, if \( \theta = 0\° \) and the acoustic force is in the same direction with the fluid field, there is no lateral motion of particles so that there is no separation either. Therefore, an optimal separation is only achieved for \( 0\° < \theta < 90\° \), as clearly shown by our simulation results in Fig. 4.

Using the taSSAW approach, we were able to separate 10- and 2-\( \mu \text{m} \)-diameter polystyrene beads with a 99\% separation efficiency (Fig. 1B and C). With the taSSAW design, separation of particles with small size differences was also achieved: separation of particles with diameter of 7.3 from 9.9-\( \mu \text{m}\)-diameter particles with a 97\% separation efficiency.

The successful separation of three different particles of 4-, 10-, and 15-\( \mu \text{m}\)-diameter in one step demonstrates the potential of the method presented here to simultaneously separate multiple components of a sample. Such a capability could be applied to achieve separation of plasma, platelets, RBCs, and WBCs in human blood in a single step. The ability to distinguish cells–particles with different mechanical properties (such as compressibility) offers unique avenues for cell separation for disease diagnostics (e.g., distinguishing between RBCs invaded by malaria-inducing *Plasmodium falciparum* versus *Plasmodium vivax* parasites) and for elucidating the underlying mechanistic processes.

Our method is able to separate cancer cells from normal WBCs, thereby providing a unique approach for the isolation and detection of circulating tumor cells and addressing an important challenge in cancer biology. Under our current experimental conditions, we achieved a recovery rate of 71\% and a purity of 84\%, as shown in Fig. 5H. We could further improve the device...
performance by optimizing device-operating parameters (such as channel dimensions, input power, and inclination angle) and/or hardware (such as electronics and piezoelectric substrate). The taSSAW technology, with future enhancements, has the potential to address one of the significant challenges in cancer research and diagnostics: isolating a small number of leukemia cells from normal leukocytes, which may have similar size but different compressibility (33). Our simulation results (Fig. S3), for the power and inclination angle of 30 dBm and 8°, respectively, suggest that a small difference in compressibility (from the normal value of $3.99 \times 10^{-10}$ Pa$^{-1}$ to $3.75 \times 10^{-10}$ Pa$^{-1}$) is sufficient for effective separation of these softer cells from normal leukocytes. These results show that the taSSAW technology is very sensitive to cell compressibility, which provides an alternative route for cell separation. This route would be suitable for applications involving cells with similar size, but different compressibility.

Furthermore, the acoustic power intensity and frequency used in our taSSAW separation methods are in a similar range to those used in ultrasonic imaging, which has proven to be extremely safe for health monitoring, even during pregnancy. At these power intensities and frequencies, acoustic waves tend to be gentle to biological cells. As a result, cell integrity is likely to be preserved during the acoustic separation process. The biocompatible nature of our approach was partially validated by cell viability and proliferation assays, in which no significant damage was found in the cell populations. These results show that the taSSAW technology is very effective for separation of these softer cells from normal leukocytes. These results show that the taSSAW technology is very sensitive to cell compressibility, which provides an alternative route for cell separation. This route would be suitable for applications involving cells with similar size, but different compressibility.

To maintain high separation sensitivity and efficiency, the taSSAW device was found to work best at a throughput of $\approx 2 \mu$m/min for cells ($10,000–20,000$ cells/min) and $\approx 20 \mu$m/min for polystyrene beads. This throughput might be sufficient for many medical diagnostic systems, and it provides proof of concept for other applications such as identifying circulating tumor cells. However, this requires significant further improvement in cell-separation throughput for cancer detection in clinical practice (e.g., isolation of a small number of circulating tumor cells in a large population of cells) or therapeutics applications (e.g., transfection).

Finally, the taSSAW-based device is compact and inexpensive. SAW devices have been used extensively in many microelectronics industries, including the cell phone industry. This industrial base for SAW devices and associated accessories has dramatically lowered the cost and improved the reliability of these components. The simple design, low cost, and standard fabrication process of the device outlined here allows for easy integration with other laboratory-on-a-chip technologies and small RF power supplies to further develop a fully integrated cell separation and analysis system. With its advantages in biocompatibility, efficiency, sensitivity, and simplicity, the taSSAW-based method presented here thus provides potential new avenues for furthering acoustic tweezers technologies and for many biological studies and clinical applications.

Materials and Methods

Device Fabrication and Experimental Setup. The fabrication of the taSSAW microfluidic device and experimental setup were described previously (27).

Cell Preparation and Cell Staining. Standard protocols and procedures are used to prepare human WBCs and MCF-7 cells for the experiments. The details can be found in SI Text, Cell Preparation and Cell Staining.

Cell Viability and Proliferation Tests. Postseparation evaluations of viability and proliferation on taSSAW-treated live MCF-7 cells were conducted. For more details please refer to SI Text, Cell Viability and Proliferation Tests.

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Supporting Information
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SI Text

Device Fabrication and Experimental Setup

The fabrication of the tilted-angle standing acoustic waves (taSSAW) microfluidic device involves three major steps: (i) the fabrication of interdigital transducers (IDTs) on a lithium niobate (LiNbO_3) piezoelectric substrate, (ii) the fabrication of polymethylsiloxane (PDMS) microchannel, and (iii) bonding of the PDMS channel onto the LiNbO_3 piezoelectric substrate with IDTs. The fabrication of IDTs consists of photolithography, metal deposition, and lift-off process. One layer of photoresist (SPR3012, MicroChem) was first spin-coated on a Y with IDTs. The fabrication of IDTs consists of photolithography, metal deposition, and lift-off process. Subsequently a lift-off process was followed to remove the photoresist and to form the IDTs. The PDMS microchannels were fabricated using standard photolithography and mold-replica techniques. Photolithography was used to pattern the silicon substrate using photoresist (SU-8, MicroChem), followed by a post-exposure baking at 150 °C for 30 min. Sylgard 184 Silicone Elastomer Curing Agent (Dow Corning) and Sylgard 184 Silicone Elastomer Base were mixed at 1:10 weight ratio, cast on top of the silicon mold, and cured at 65 °C for 30 min. Finally, the IDT substrate and the PDMS microchannel were both treated with oxygen plasma and bonded together, and connected with polyethylene tubing (inner diameter: 280 μm).

During the experiments, a taSSAW microfluidic device was mounted on the stage of an inverted microscope (Nikon TE2000U). IDTs were electrically connected to a function generator (Agilent E4422B) through an amplifier (AR 250A100). PDMS channel inlet and outlet were connected to syringes driven by Nemesys syringe pumps (Cetoni GmbH). A CCD camera (CoolSNAP HQ2, Photometrics) and a high-speed camera (Fastcam SA4, Photron) were connected to the microscope to record the separation process.

Details About Numerical Simulation of Particle Separation

The behavior of particles in the microfluidic channel can be characterized by examining the drag force and the acoustic radiation force. The acoustic radiation force \( F_d \) and the drag force \( F_d \) are expressed as

\[
F_r = -\left( \frac{\pi \rho_p V_p \beta_p}{2 \lambda} \right) \phi(\beta, \rho) \sin(2ky), \quad [S1]
\]

\[
\phi(\beta, \rho) = \frac{5 \rho_p - 2 \rho_m}{2 \rho_p + \rho_m} \beta_p - \beta_m,
\]

\[
F_d = -6\pi \mu R_d u_r, \quad [S3]
\]

where \( \rho_0, \lambda, V_p, \rho_m, \beta_p, \beta_m, \mu, R_d, \) and \( u_r \) are the acoustic pressure, acoustic wavelength, volume of the particle, density of the medium, density of the particle, compressibility of the medium, compressibility of the particle, viscosity of the medium, radius of the particle, and relative velocity of the particle, respectively. In Eq. S1, \( y \) is the coordinate as shown in Fig. 1B and \( k \) is the wavenumber of the standing acoustic wave. From these equations, we see that the magnitude of the acoustic radiation force acting on a particle is a function of its volume, density, compressibility, and the power of radio frequency signal applied to device. Hence, particles with differences in these properties will experience varying radiation force, and can be separated in a standing surface acoustic wave (SSAW) device.

We first illustrate the working mechanism using size-based particle separation. Eq. S2 describes the acoustic contrast factor \( \phi \), which determines whether a particle moves to a pressure nodal or an antinodal line: the particles will aggregate at pressure nodal lines when \( \phi \) is positive and at pressure antinodal lines when \( \phi \) is negative. Most solid particles and cells in aqueous solution have a positive \( \phi \), and move toward pressure nodal lines in an SSAW field. Eqs. S1–S5 indicate that the drag force is proportional to the radius of the particle or cell and the acoustic radiation force is proportional to the volume. The acoustic radiation force tends to confine particles at the pressure nodal lines whereas the drag force induced by the flowing fluid pushes particles forward along the flow direction. When a mixture of particles with various sizes passes through the taSSAW region, those particles all experience acoustic radiation force and drag force. The acoustic radiation force dominates over the drag force for larger particles and results in a lateral displacement. Conversely, the drag force dominates over the acoustic force for smaller particles, resulting in little lateral displacement.

In our taSSAW design, the pressure nodal lines align with the flow direction at an angle \( \theta \) as shown in Fig. 1B. Because the flow field is a linear Stokes flow in this length scale, the velocity of the particle can be decomposed into an undisturbed channel flow velocity \( u_f \) and a velocity \( u_r \) due to the acoustic radiation force. The position of the particle in the coordinate system \( \{x, y, z\} \), as shown in Fig. 1B, at the center plane of the height \( \lambda = 0 \) is described by the following ordinary differential equations (ODEs):

\[
\frac{dX}{dt} = u_f \cos \theta, \quad [S4]
\]

\[
\frac{dY}{dt} = u_f \sin \theta + u_r, \quad [S5]
\]

where \( u_f \) is the fluid velocity in an infinitely long channel with a rectangular section (width \( a \), height \( b \)), \( u_r \) is the velocity of the particle due to the acoustic radiation force imposed by the standing surface acoustic wave, and \( t \) is time.

It is well known that the fluid velocity \( u_f \) in a rectangular channel with width \( a \) and height \( b \) is given by

\[
u_r = \frac{\nabla P}{\mu b} + \frac{4}{\pi b^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{a_n^2} \cosh \left( \frac{a_n \alpha}{b} \right) \cos \left( \frac{b \alpha}{b} \right) \cosh \left( \frac{a_n \alpha}{b} \right) \cos \left( \frac{b \alpha}{b} \right) \right], \quad [S6]
\]

where \( Z \) is the coordinate in the channel height direction and \( Y \) is the coordinate in the width direction in the \( \{X, Y, Z\} \) coordinate system aligned with flow direction as shown in Fig. 1B, \( \mu \) is the fluid viscosity, \( VP \) is the pressure gradient, and \( a_n = (n - (1/2)) \pi \). The coordinates in two different systems \( \{X, Y, Z\} \) and \( \{x, y, z\} \) can be converted by a rotational transformation with an angle \( \theta \).

The velocity of the particle due to the acoustic radiation force \( u_r \) in Eq. S5 can be obtained based on the balance between acoustic radiation force \( F_r \) and viscous drag force \( F_d \), which is a function of
\( u_t \). The viscous drag force is given by Stokes law as shown in Eq. S5, and the acoustic radiation force is given by Eq. S1. Due to force balance \( F_t = F_d \), the velocity of the particle due to the acoustic radiation force \( u_t \) in Eq. S5 is given by

\[
\begin{aligned}
  u_t &= \frac{\pi R^2 \mu_0}{2 \mu} \phi(\beta, \rho) \sin(2\gamma y).
\end{aligned}
\]  

We assume that the particle is in the center of the channel in the vertical direction so that \( Z = z = 0 \). Combining Eqs. S4–S7, we can predict the trajectory of the particle in \((x, y)\) coordinate system by integrating the ODEs numerically (using, for example, MATLAB, Mathworks) with initial particle positions of \( x_0 \) and \( y_0 \). We then obtain the trajectory of the particle in \((x, y)\) coordinate system by a rotation transformation of an angle \( \theta \).

The dimensions of the channel used in the simulation were \( L \) (length) \( = 4,000 \mu \text{m} \), \( W \) (width) \( = 1,000 \mu \text{m} \), and \( H \) (height) \( = 75 \mu \text{m} \). The default angle of inclination was \( \theta = 15^\circ \), the default wave length \( \lambda = 200 \mu \text{m} \), and the default flow rate \( = 11 \mu \text{L/min} \). At room temperature, the compressibility of water \( = 4.6 \times 10^{-10} \text{Pa}^{-1} \) and the compressibility of the beads \( = 2.16 \times 10^{-10} \text{Pa}^{-1} \). The density of the water \( = 997 \text{ kg/m}^3 \), the viscosity of water \( = 0.001 \text{ Pa} \cdot \text{s} \), the density of the beads \( = 1,050 \text{ kg/m}^3 \), and the density of the substrate \( = 4,650 \text{ kg/m}^3 \). The sound speed of the substrate \( = 1,050 \text{ kg/m}^3 \times 4.65 \text{ m/s} \). The frequency \( (f) \) of the wave is \( \sim 20 \text{ MHz} \). The initial position of the particle was varied about \( 50-60 \mu \text{m} \) in the experiments in the \( Y \) direction, so that we consider a variation of \( 60 \mu \text{m} \) for \( Y_0 \) in our simulations. The acoustic pressure was evaluated as \( p_0 = \sqrt{a \beta} \rho c_x / \rho \), where \( \beta \) is the pressure of the IDTs, \( \rho \) (taken to be \( 4,650 \text{ kg/m}^3 \) in this study) and \( c_x \) (taken to be \( 3,997 \text{ m/s} \)) are the density and the sound speed of the substrate, respectively, \( A_w \) is the working area given as the channel length multiplied by the distance between IDTs \( = 4,000 \mu \text{m} \times 2,600 \mu \text{m} = 1.04 \times 10^{-2} \text{ m}^2 \) in this study), and \( a \) is the power conversion efficiency in which the power of the IDTs converts to the acoustic pressure in the fluids. Because the power conversion efficiency is influenced by several factors, such as energy dissipation in the IDTs, in the substrate, and in the fluid, \( a \) had to be calibrated for each microfluidic device by matching the simulated particle trajectory with the experiment. Once calibrated, the same \( a \) was used for all simulations of the experiments done on this particular microfluidic device setup. The calibrated power conversion efficiency \( a \) in our experiments is \( 10-20\% \). We use the default parameters indicated in this section and in the Design and Characterization section in the main text unless noted otherwise.

**Cell Preparation and Cell Staining**

Fresh human whole blood with acid citrate dextrose as an anticoagulant was purchased from Zen-bio. To lyse the red blood cells (RBCs), \( 1 \) mL whole blood was mixed with \( 10 \) mL \( 1\times \) RBC lysis buffer (eBioscience) and incubated for \( 10-15 \) min at room temperature. After centrifugation at \( 400 \times g \) for \( 5 \) min to remove the supernatant, white blood cells (WBCs) were resuspended in \( 1 \) mL \( 4% \) formaldehyde in PBS (Santa Cruz Biotechnology) and fixed at room temperature for \( 10 \) min. After cell counting with a hemacytometer to determine the cell concentration, the fixed WBCs were centrifuged and resuspended in PBS before use.

MCF-7 breast cancer cells were cultured in Dulbecco’s modified Eagle medium, (DMEM)-F12 medium (Life Technologies), with \( 10\% \) FBS (Life Technologies), penicillin (100 U/mL), and \( 100 \mu \text{g/mL} \) streptomycin (Mediatech) to about \( 90\% \) confluence. Then the MCF-7 cells were trypsinized (Trypsin + 0.05% EDTA, Life Technologies), centrifuged, and resuspended in \( 4\% \) formaldehyde in PBS (Santa Cruz Biotechnology) for cell fixation. After cell counting with a hemacytometer to determine the cell concentration, the fixed MCF-7 cells were centrifuged and resuspended in PBS before use.

After the MCF-7 cells were spiked into the WBCs at desired ratios, these cells were centrifuged and resuspended in \( 500 \mu \text{L} \) PBS with \( 5 \mu \text{L} \) of \( 300 \text{nM} \) DAPI in PBS (Life Technologies) added for staining of cell nuclei at room temperature for \( 10 \) min. Then the cells were washed with PBS, centrifuged, and resuspended in \( 200 \mu \text{L} \) PBS, after which \( 5 \mu \text{L} \) FITC-conjugated anti-CD45 antibody (Life Technologies) was added to stain the surface of WBCs for \( 10 \) min at room temperature. After another wash with PBS and centrifugation, the cells were again resuspended in \( 200 \mu \text{L} \) PBS with \( 5 \mu \text{L} \) Phycocerythrin-conjugated anti-EpCAM antibody (eBioscience) added to stain the surface of MCF-7 cells for \( 10 \) min at room temperature. After all of the staining steps, the cells were washed and suspended in PBS.

**Cell Viability and Proliferation Tests**

Postseparation evaluations of viability and proliferation on tSSAW-treated live MCF-7 cells were conducted. Live MFC-7 cells suspended in fresh medium were introduced into the microchannel and collected at the outlet either with SAW applied (“SAW on” group) or without SAW (“SAW off” group). Live MCF-7 cells without any treatment were used as positive control.

The viability of MCF-7 cells was first measured using live–dead cell staining. MCF-7 cells in each group were counted with a hemacytometer and seeded into 35-mm tissue culture dishes at seeding density of \( 4 \times 10^5 \) cells per dish. After culture for \( 24 \) h, the cell monolayers were stained with \( 500 \text{ ng/mL} \) Calcein AM (live cell staining) (Life Technologies) and \( 1 \mu \text{M} \) SYTOX Orange (dead cell staining) (Life Technologies) to evaluate the number of apoptotic cells in each group under epifluorescence imaging.

For cell viability and proliferation assays, cells in each group were first counted with a hemacytometer and diluted with fresh medium to \( 4 \times 10^5 \) cells/mL, and then seeded in a Costar 96-well black clear-bottom plate (Corning Life Sciences) with cell seeding density of \( 2 \times 10^4 \) cells per well within a \( 100-\mu \text{L} \) culture medium. For each group, five repeat wells were seeded. MCF-7 cells were then cultured in an incubator at \( 37^\circ \text{C} \) and \( 5\% \) CO\(_2\) for \( 20 \) h when we added \( 10 \mu \text{L} \) BrdU labeling solution (Roche Applied Science) into each well. After \( 2 \) h of incubation, we added \( 10 \mu \text{L} \) water-soluble tetrazolium salt (WST-1, Roche Applied Science) into each well. After another \( 2 \) h of incubation, we measured the absorbance of each well at \( 450 \) and \( 690 \) nm (reference wavelength) using a microplate reader (BioTek) to assess cell viability. Cell proliferation was then measured by characterizing BrdU incorporation using Cell Proliferation ELISA, BrdU (colorimetric) (Roche Applied Science). We measured the absorbance of each well at \( 370 \) and \( 492 \) nm (reference wavelength) after finishing the standard ELISA procedure.
Fig. S1. Separation distance as a function of particle size and input power. Lateral migration of particles of distinct sizes are investigated under different input power. Each data point represents five repeats.

![Graph](image_url)

Fig. S2. Cell viability and proliferation assays. Experimental results for MCF-7 Cell (A) viability and (B) proliferation tests for four different samples: (i) positive control (no SAW treatment), (ii) cells passing through the device with SAW off, (iii) cells passing through the device with SAW on, and (iv) negative control. Cell viability imaging was also carried out for (C) positive control, (D) cells passing through the device with SAW off, and (E) cells passing through the device with SAW on.

![Images](image_url)

Fig. S3. Simulation of cell separation based on compressibility. Computed trajectories of leukemia cells (assuming a softer compressibility of $3.75 \times 10^{-10} \cdot \text{Pa}^{-1}$) versus normal leukocytes (with a normal compressibility of $3.99 \times 10^{-10} \cdot \text{Pa}^{-1}$), with the same cell size (12 μm).

![Simulation](image_url)
Movie S1. Single-step separation of multiple-size particles. This movie corresponds to the data presented in Fig. 3A of the main text. Here, polystyrene beads with diameters of 15, 10, and 4 μm are separated at one step. The movie is in real time.

Movie S2. Separation of human cancer cell from blood cells. The movie demonstrates the separation process of MCF-7 (human breast cancer cell) from leukocytes, and corresponding data are given in Fig. 5A. The movie is in real time.