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Opto-combinatorial indexing enables high-content transcriptomics by linking cell images and transcriptome

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Abstract: We introduce a simple integrated analysis method that links cellular phenotypic behaviour with single-cell RNA sequencing (scRNA-seq) by utilizing a combination of optical indices from cells and hydrogel beads. Our method achieves the link reading-out of the combinations, referred to as "joint colour codes" via matching the optical combinations measured by the conventional epi-fluorescence microscopy with the concatenated DNA molecular barcodes created by the cell-hydrogel bead pairs and sequenced by next-generation sequencing. We validated our approach by demonstrating an accurate link between the cell image and scRNA-seq with mixed species experiments, the longitudinal cell tagging by electroporation and lipofection, and gene expression analysis. Furthermore, we extended our approach to multiplexed chemical transcriptomics, which enables us to identify distinct phenotypic behaviours in HeLa cells under various paclitaxel burdens, and uncover corresponding gene regulations associated with the formation of a multipolar spindle.

Introduction

The latest single-cell RNA-seq (scRNA-seq) allows assaying thousands of cells per experiment by combining compartmentalisation of cells with microfluidics and tagging cDNA with cell barcodes to profile gene expression of single cells[1-4]. The tagging approach has been extended for profiling other omics layers including surface proteins[5,6], nuclear proteins[7], and chromatin accessibility[8]. However, most of the omics approaches are still incapable of linking the measured molecular profile to cellular phenotypes, such as morphology and molecular localisation[9,10].

Single cell optical phenotyping and expression (SCOPE-seq and SCOPE-seq2)[11,12] is a method for linking scRNA-seq with live cell imaging. SCOPE-seq co-isolates a single cell and bead bearing barcoded DNA in a microwell, images cellular morphology, and captures mRNA from the single cell on the bead for pooled scRNA-seq. SCOPE-seq links the image of the single cell to the scRNA-seq by optically decoding the barcode of each bead using cyclic hybridisation of fluorescently labelled oligonucleotide probes, followed by fluorescence microscopy.

Herein, we propose a novel and simple approach for optical indexing that leverages the combination of cells and hydrogel beads dual-labelled with optical indices and DNA molecular barcodes (we refer to this dual label as "colour code.") for linking cellular images with scRNA-seq. To link the combinations of optical indices decoded from the imaging to the cell barcodes in scRNA-seq, our approach creates concatenated fragments of barcoded DNA oligos (DNA tags) derived from the cells and barcoded dT primers derived from the hydrogel beads. The concatenated fragments are sequenced with the scRNA-seq library, and provide a look-up table to link the combinations of optical indices and cell barcodes. Our approach is free of automated microfluidic controls and offers fewer on-chip steps, which are advantageous in easily implementing the approach in a standard laboratory setup. We demonstrate our approach with multiplexing up to 256 combinations of colour codes (joint colour codes), using 16 pools of colour-coded cells and 16 pools of colour-coded hydrogel beads, and decoding them with four colours of fluorescence using standard epi-fluorescence microscopy.

Results

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Strategies to link cell images and whole transcriptome by utilizing colour coding

Our strategy to link a single-cell image and gene expression leverages joint colour code created by co-isolated single cell and hydrogel bead (Fig.1A). The cells and hydrogel beads are respectively labelled by fluorescence dye and corresponding DNA molecular barcodes (Fig.1B, S1, S2) that are read out by epi-fluorescence microscopy (Fig.1C) and next-generation sequencing. The joint colour codes increase the possible unique codes by the combination and enable linking single-cell images and gene expression profiles in the two data pools (Fig.1D). In our demonstration, we designed 16 colour codes, which were bright or dim combinations of four fluorescence dyes (2^4 = 16), and which also corresponded to 16 different sequences of DNA barcodes, respectively for cells and hydrogel beads (see Methods); thus, a maximum of 256 joint colour codes (16×16) could be registered. The expected number of cell–bead pairs with unique joint colour codes per experimental run was predicted to attain a maximum of approximately 94 when assaying 256 single cells on the basis of Poisson distribution excluding the cells with duplicated joint colour codes (Fig.1E). To demonstrate our protocol, we performed mixed-species experiments using HeLa cells (human) and NIH/3T3 cells (mouse) (Fig.S3). We prepared a pool of 16 differently colour-coded cells (eight sub-pools each of HeLa and NIH/3T3 cells) that were respectively labelled with a combination of four different dyes (CellTrace Violet, CFSE, Yellow, and Far Red from Thermo Fisher Scientific) (Fig.1B, S1) and corresponding DNA tags, which contained 8 nt barcode, poly A sequence, and a PCR handle (Table S2), via electroporation. We then isolated the single cells out of the pool of 16 colour codes in microwells to image them by epi-fluorescence and a bright field. The hydrogel beads bearing barcoded primers with colour codes (Fig.1B, S2) were subsequently isolated in the microwells to capture mRNA and DNA tags. To retain the molecules released from the cells within the microwells, we sealed the microwells with a track-etched membrane with nanopores of 10 nm in diameter, chemically lysed the cells in microwells, and captured the mRNA and DNA tags by the hydrogel beads via hybridisation. After peeling off the track-etched membrane, we imaged the fluorescence of the hydrogel beads in the microwells to read out the colour codes. We registered the images of the single cells with the joint colour codes by integrating the microscopic images of cells and hydrogel beads. We finally transferred the hydrogel beads to a standard PCR tube to synthesise libraries of the scRNA-seq and DNA tag by off-chip reactions (see Methods). The latter library yielded a look-up table that linked the cell barcodes in the cDNA fragments and joint colour codes by creating concatenated fragments of colour codes of hydrogel beads and cells (Fig.S4).

Our microwell chip, which had 2511 wells per chip, captured approximately 149 ± 70 cells and 1326 ± 462 hydrogel beads per run (n = 13), and created approximately 137 ± 64 pairs of single cells and hydrogel beads on average. The image-based decoding of the joint colour codes showed that the number of unique joint colour codes matched the theoretical prediction (Fig.1E).

Linking single-cell images to scRNA-seq

The sequence reads with the same cell barcode were dominantly mapped either to the homosapiens genome (GRCh38.p12) or Mus musculus genome (GRCm38.p6), supporting the successful RNA-seq at single-cell resolution (Fig. 2A). The scRNA-seq detected approximately 1296 ± 586 genes per cell (i.e., approximately 2839 ± 1829 unique molecular identifiers (UMIs) per cell) and approximately 1203 ± 541 genes per cell (i.e., approximately 2633 ± 1716 UMIs per cell), respectively for HeLa and NIH/3T3 cells (sequence read per cell was 30,865 on average). Of the 360 unique joint colour codes identified by fluorescence microscopy in six experimental runs, 137 were also identified in the DNA tag library and successfully linked to the scRNA-seq data. Of those, 122 cells, i.e., 89.1%, were consistent for the species (Fig.2A-C).

To link the cell barcode in scRNA-seq to single-cell images via joint colour codes, we devised a framework that optimises pairs of cell barcode and single-cell image by maximizing the sum of the similarity between the decoded colour code from the images and counts of DNA tag (Fig.2D, E). We benchmarked the framework in terms of the accuracy and number of linked datasets using the mixed-species data, computing with various metrics of similarity and normalisation approaches for the DNA tag counts. The result showed that the cosine similarity in combination with the centred log ratio (CLR per feature) for normalisation of DNA tags performed the best among those tested (Fig.2F). The framework with the cosine similarity and CLR yielded a consistency of 91% for species at a threshold of 0.5 for the cosine similarity (Fig.2A). We employed the same framework throughout this study.

Labelling cells with DNA tags

Next, we benchmarked two different approaches, electroporation and lipofection for labelling cells with DNA tags using fluorescently labelled DNA tags and flow cytometry (Fig.3A, B). The data revealed that lipofection outperformed in delivering more DNA tags to cells than electroporation, while the amount of DNA tags resulted in a relatively large cell-to-cell variation. Furthermore, lipofection was less efficient for NIH/3T3 cells than for HeLa cells. To gain a similar sensitivity in detecting the DNA tags from HeLa and NIH/3T3 cells, we employed electroporation in the experiments with mixed species. Alternatively, modulating the concentration of DNA tags for lipofection could tune the sensitivity (Fig.3A, B). We employed lipofection in the other experiments with a cell line.

We also assessed the durability of the DNA tags within the cells by quantifying their presence over time (see Fig.3C). Remarkably, even after 48 h of labelling, the DNA tags remained detectable, indicating the potential for combining our approach with longitudinal live-cell imaging. Notably, the linking rate, a metric representing the fraction of cell images linked to scRNA-seq among those identified from the cell images, exhibited no degradation over time (Fig.3D). Interestingly, the linking rate associated with the electroporation labelling increased over time. We hypothesise that this trend may be attributed to a

selection bias in favour of healthy cells within the electroporated cell population. Furthermore, we conducted additional analyses to confirm the integration of labelled cells with the unlabelled ones in the transcriptomic space (Fig.3E, F). These data serve as a clear benchmark for cell tagging achieved through DNA delivery via electroporation and lipofection.

Exploring chemical perturbation with high-content transcriptomics

Next, we sought to determine if our approach could enhance the insights gained from chemical screening. Specifically, we investigated the cell-to-cell heterogeneity in the response of HeLa cells to the chemical impact of paclitaxel, which is a chemotherapy drug used in the clinical treatment of lung, ovarian, and breast cancer; it inhibits the growth of cancer cells by blocking cell division. Traditionally, it was believed to induce cell death through mitotic arrest. However, recent studies have suggested that tumour regression is not solely dependent on the mitotic arrest, but is influenced by multipolar spindle formation,[13] leading to cell death.[14] In our study, we aimed to dissect the nuclear phenotype associated with multipolar spindles induced by paclitaxel and its underlying transcriptomic basis.

To understand the intricate relationship between the phenotypic and transcriptomic responses at the single-cell level, we subjected the DNA-tagged and colour-coded HeLa cells to paclitaxel treatment at eight distinct concentrations, ranging from 0.5 to 500 nM, over a 24-h period. Subsequently, we analysed the combined samples using our established approach. Specifically, we utilised a single fluorescence channel to monitor the emergence of multipolar spindles as a phenotypic response to paclitaxel by staining the DNA with Hoechst 33342. The colour-decoded images of individual cells revealed that the occurrence of multipolar spindles became more prevalent at higher concentrations of paclitaxel. Notably, even at identical concentrations of paclitaxel, the number of spindles exhibited considerable heterogeneity across the cells (Fig.4A, B). These observations aligned with the findings from non-pooled assays conducted in separate dishes (Fig.S5E, F).

To uncover the mechanism underlying the heterogeneous cellular response, we leveraged the transcriptomic data linked to the phenotypic responses. The transcriptomic data showed approximately 1364 ± 350 genes per cell (i.e., approximately 4357 ± 2366 UMIs per cell, with 106,119 sequence read per cell on average). The integrated multimodal data by weighted nearest neighbour analysis enabled inferring two distinct trajectories, related to the formation of multipolar spindles, or lack thereof, in response to paclitaxel burden within the transcriptomic data (Fig.4C-E). Gene set enrichment analysis (GSEA) revealed that the genes associated with the mitosis (*mitotic cell cycle, mitotic cell cycle process, cell cycle process, cell cycle G2/M phase transition, cell cycle phase transition, G2/M transition of mitotic cell cycle, and regulation of cell cycle*) were down-regulated with increasing paclitaxel concentration, irrespective of the presence of multipolar spindle formation (Fig.4F); the genes included in the GO terms consistently exhibited the down-regulation (Fig.4G). Subsequently, in trajectory 1 (no multipolar spindle formation), GSEA highlighted the induction of endoplasmic reticulum (ER) stress, which, if sustained or is severe, can potentially trigger apoptosis (Fig.4H).[15] Conversely, in trajectory 2, characterised by multipolar spindle formation, the *RFC4* gene, known for its role in DNA replication and repair,[16] consistently exhibited up-regulation in response to increasing paclitaxel exposure. These findings underscore the remarkable power of integrated multimodal data analysis, effectively distinguishing the gene regulations between the two trajectories associated with distinct phenotypic outcomes.

Discussion

Multiplex chemical transcriptomics provides mechanistic insights into the cellular responses to the chemical perturbations at the molecular level and offers a comprehensive understanding across pooled conditions, suppressing the batch effect.[17,18] Cellular tagging is a key to demultiplex genetically identical cells, extending its applicability to study chemical-dependent or dose-dependent responses. However, transcriptomics-based screening still faces difficulty in linking molecular responses to key phenotypic expression, such as cell proliferation and morphological change, which are typically profiled by quantitative optical microscopy. The integration of microscopical phenotyping and molecular profiling provides a unique opportunity to dissect the molecular cascades that cause the specific phenotypic expression.[19,20]

There are two major strategies for the integrated phenotypic and transcriptomics analysis. The first is the optical decoding of the barcode sequence by sequential fluorescence in situ hybridisation, and the second is physical isolation of the interested cell and indexing by known barcode tags. SCOPE-seq2 employs the former strategy, decoding the cell barcode of the hydrogel beads by performing cyclic hybridisation and readout with automated microfluidic control and microscopic imaging.[12] As an example of the latter strategy, an automated cell picking system was employed to isolate single cells into 96 well plates and then process them for scRNA-seq[21]. In contrast to these methods, to link the cellular phenotype and transcriptomics, our approach uses a combination of colour codes of cells and hydrogel beads to optically index pairs of single cells and hydrogel beads. Our approach is free of automated microfluidic controls and robotic systems, has fewer on-chip steps, and is compatible with standard epi-fluorescence microscopy, which are advantageous features to be implemented in a standard laboratory.

As demonstrated in our experiments for the paclitaxel burden on HeLa cells, the cell colour code also works as cell hashing for multiplex chemical screening. Our analysis revealed two distinct trajectories in transcriptomic response by paclitaxel treatment, which correspond to distinct phenotypic reactions. The trajectory that involved no multipolar spindle formation showed up-regulation of ER stress response. Prolonged and severe ER stress may induce apoptosis, otherwise leading to the acquisition of drug resistance[22] through the activation of unfolded protein response (UPR), a signalling pathway involved in both adaptive and apoptotic response[23]. The second trajectory exhibited generations of multipolar spindles, leading to chromosome missegregation and cell

death[14].

Our approach has the potential to be extended to the integrated analysis of dynamic phenotyping and transcriptomics using longitudinal live-cell imaging. The DNA tags were retained within the cells even after 48 h of labelling. For instance, the integration of our approach with longitudinal imaging of leukocytes at the sites of active inflammation can potentially classify leukocytes by spatio-temporal behaviours[24] and uncover the molecular background. Furthermore, our approach can be readily integrated with the profiling of surface protein via CITE-seq[6] thereby enabling the analysis to couple with another omics layer. The proposed opto-combinatorial indexing is also compatible with cell-hashing using DNA-tagged antibodies[25] or lipids[26]. The transfection-based approaches (electroporation or lipofection) used in our demonstration are robust and cost-effective, for instance, when assaying cells from non-model organisms.

In analysing the drug response of HeLa cells to paclitaxel, we labelled nuclei with a fluorescent dye (Hoechst 33342) to observe the nuclear morphology, resulting in a reduction in the number of cell colour codes. We envision that increasing the number of fluorescence channels by quantitatively demultiplexing the fluorophores with spectral overlap is the key to both improving scalability and increasing observable phenotypic parameters. In future, we hope to demonstrate high-content and improved multiplexing by increasing the fluorescence channels and using unmixing approaches[27].

In conclusion, opto-combinatorial indexing provides a simplified strategy to analyse the image and gene expressions simultaneously from single cells, and effectively dissect the molecular background of distinct phenotypic behaviours by integrating cellular phenotype and transcriptomics data.

Methods

Synthesis of colour-coded hydrogel beads.

To allow optical readout of the bead colour codes, we designed the branched DNA that hybridises with the bead colour code and converts the nucleotide sequence to a bright or dim combination of four fluorophores by hybridising four readout oligos with or without fluorophores, creating 2^4=16 different colour combinations (Table S1). This approach minimizes the number of readout oligos labelled with fluorophores and significantly reduces the cost of synthesizing them. We synthesized the polyacrylamide hydrogel beads with poly(dT) sequences through two rounds of split-pool ligation[28]. Briefly, we generated droplets of acrylamide premix with 50 μM acrydited primer (5’-Acryd/AAGCAGTGGTATCAACGCAGAGTACGACGCTCTT-3’) using a simple coflow microfluidic device. The final bead size was ~40 μm. We then ligated the first barcode fragments containing the bead colour code and the first part of the cell barcode (Table S1, Stem_CC00_ID01–Stem_CC15_ID25). In the second round of ligation, we added fragments with the second part of the cell barcode, UMI and poly(T) (NNNNNNNNTTTTTTTTTTTTTTTTTTTTTTTTTTTTVN) (Table S1, ID00_dT–ID32_dT). The combination of the first and second parts of the cell barcode created 6400 unique barcodes.

To stain beads with colour codes, we pooled the beads with cell barcodes in a single tube and combined 3×10^4 beads, a mixture of 6 μM branch oligos (Table S1, Branch_00_NNNN–Branch_15_BGPR), a mixture of 12 μM readout oligos (with Alexa 488, Alexa 555, Alexa 647, and Alexa 750, Table S1, Readout_Alexa647–Readout_Alexa750), 12 μM oligo without fluorophore (Table S1, Readout_R0–Readout_B0 to fill the sequence in branch oligo for dim beads) and 0.1 mg/mL salmon sperm DNA in hybridisation buffer (5 mM Tris-HCl (pH 8.0), 1 M KCl, 5 mM EDTA, 0.05% (vol/vol) Tween-20). We incubated the mixture at 94˚C for 5 min and cooled it by 5˚C every 5 min to 25˚C and then kept it at 4˚C. Excess probes were washed three times with an ice-cold hybridisation buffer.

We reasoned the hybridisation-based staining of hydrogel beads has an insignificant effect on the synthesis of cDNA and the amplification with PCR, because the branch oligo hybridises downstream of the cDNA extension during reverse transcription, and the concentration of the branch oligo in PCR is estimated at 3.52 nM per colour code while that of the PCR primer is at 240 nM. Further, the melting temperature of the branch oligo is lower at 66.4˚C than that of the PCR primer at 77.5˚C (under conditions of 50 mM Na^+ and 3 mM Mg^{2+} as an example), while the annealing temperature for PCR is at 65˚C.

Colour-corded cell preparation

We cultured HeLa (RCB0007, RIKEN BRC) and NIH/3T3 cells (RCB2767, RIKEN BRC) cells in Dulbecco’s Modified Eagle Medium (DMEM, 08456-65, Nacalai Tesque) containing 10% fetal bovine serum (FBS, 26140-079, gibco) and 1% penicillin-streptomycin (P/S, P4333-100ML, Sigma-Aldrich).

For the species-mixing experiment, we respectively seeded the HeLa cells and NIT/3T3 cells at a concentration of 2.0×10^5 cells/mL each separately in a 100 mm dish and cultured them for 1 day. After trypsinisation, we aliquoted cells equally into eight sub-pools per cell type in 16 tubes and individually stained with the 16 different combinations of four types of CellTrace (5 μM Violet, 5 μM CFSE, 5 μM Yellow, and 1 μM Far Red, Invitrogen™) at the concentration of 1.0×10^6 cells/mL. We then individually suspended the stained cells in Gene Pulser® Electroporation Buffer (Bio-Rad) with 100 nM of DNA tag (Table S2) corresponding with the respective fluorescence colour. Immediately after the electroporation by Gene Pulser Mxcell™ Electroporation System (Bio-Rad, voltage: 250 V, capacitance: 2000 μF, resistance: ∞ Ohm, duration: 20 ms for HeLa cell, and 400 V, capacitance: 950 μF, resistance: ∞ Ohm, duration: 20 ms for NIT/3T3 cell), we added five-fold volume of culture medium and incubated them for 1 h at 37°C in 5% CO_2. We washed the cells three times with 1× phosphate-buffered saline (PBS, 14249-24, Nacalai tesque), and combined the 16 sub-pools in the loading buffer (1% polyvinylpyrrolidone in 1× PBS).

For the experiments of paclitaxel treatments, we seeded the HeLa cells at the concentration of 5.0×10^4 cells/mL in eight wells of a 24-well plate and cultured them for one day. We transfected cells individually with different types of DNA tags using Lipofectamine® 3000 reagents (Invitrogen™) according to the manufacturer’s protocol (incubation for 4 h at 20 nM DNA

tag concentration). After the lipofection, we washed the cells three times with a culture medium. We stained the cells individually in each well with eight combinations of three CellTrace (5 μM CFSE, 5 μM Yellow, and 1 μM Far Red). We cultured cells in a culture medium containing paclitaxel (163-28163, FUJIFILM) at different concentrations for one day. We washed the cells three times with 1 × PBS. After trypsinisation, we pooled the eight sub-pools of the cells at the equal cell concentrations. Subsequently, the cells were stained with 10 μg/mL Hoechst 33342 and resuspended in the loading buffer. For the experiment of tag retention assay, we seeded the HeLa cells at a concentration of 5.0×10^4 cells/mL for one day, followed by lipofection with 20 nM DNA tags and cultured for four h. In addition, we performed electroporation on 1.0×10^6 cells/mL HeLa cells in Gene Pulser® Electroporation Buffer with 100 nM DNA tag under the same conditions described above. We then cultured the cells in a 24-well plate for varying durations up to 48 h and stained them with six different combinations of three CellTrace (5 μM CFSE, 5 μM Yellow, and 1 μM Far Red). After three PBS washes, we pooled all of the cells at the same concentration and resuspended them in the loading buffer.

Chip fabrication

The workflow is based on the protocol reported in previous work[1,2]. We fabricated microwell arrays from polydimethylsiloxane (PDMS, SILPOT 184, Dow Corning) by soft lithography using a SU-8 mould. To hydrophilise the microwell array and to perform efficient sealing in cell lysis and hybridisation step, we functionalized the array with the same protocol as the previously reported[2].

On-chip experimental workflow

We placed a PDMS slab with the microwell array superstructure onto a glass-based dish (3961-035, IWAKI), dispensed PBS over the microwells, and kept it under vacuum for 15 min to remove bubbles in the microwells. We then dropped pooled cells suspended in the loading buffer onto the microarray and incubated them for 5 min at room temperature to allow the cells to settle. After washing the microwell array with PBS, we added 2 mL of DMEM without phenol red (08490-05, Nacalai tesque) and acquired the scanned images of the microwell array containing the cells. In every experiment, we adjusted the exposure times to effectively use the full dynamic range of the camera and used the same setting for the entire chip. We dropped 20 μL of the colour-coded bead suspension at the concentration of 1.0×10^6 beads/mL onto the microwell array and incubated them for 10 min to capture the beads in microwells, followed by tapping and resting for 1 min at 37°C, which was repeated five times. To seal the microwells with a track-etched membrane with nanopores of 10 nm in diameter (Sterlitech), which was pre-treated with atmospheric plasma (BD-20, Electro-Technic Products) for 60 s and then hydrated in the PBS, we pressed the membrane and the PDMS slab by placing a glass slide (8 mm square per side, S7214, MATSUNAMI) and a 100-g weight at 37°C for 30 min. We removed the glass side by adding 3 mL of PBS. We lysed the cells by dispensing 3 mL of a cell lysis buffer (5 M Guanidine Thiocyanate, 1 mM EDTA, 0.50% Sarkosyl, 1.0% 2-Mercaptoethanol) and agitating them in a microplate shaker at 5~60 rpm for 20 min. Next, we washed the microwell array with 3 mL of hybridisation buffer (2 M NaCl, 0.64% PEG8000, 0.52× PBS) to hybridise the released mRNA and DNA tag with the primers on the hydrogel beads by agitation at 5~60 rpm for 40 min. After removing the membrane over the microwell array, we acquired the images of the microwell array containing the hydrogel beads with the adjusted exposure times. To collect beads, we placed the microwell array directly into a 200 μL tube and flushed with 200 μL of wash solution 1 (2 M NaCl, 3 mM $MgCl_2$, 20 mM Tris-HCl (pH 8.0), 0.64% PEG8000, 0.1% tween20). We exchanged wash solution 1 for wash solution 2 (50 mM Tris-HCl (pH 8.3), 75 mM KCl, 6 mM $MgCl_2$, 0.4 U/μL Recombinant RNase inhibitor (2313A, Takara), 0.1% Tween 20) by repeating centrifugation (3000 g, 4℃, 3 min) and the buffer exchange twice.

Library preparation

To construct cDNA and DNA-tag libraries, we performed the reverse transcription (RT) and polymerase chain reaction (PCR) according to the protocol of the CITE-seq[6] with modifications. We added 10 μL of RT mix (1xFirst-Strand Buffer, 4.8 μM biotinylated template switching oligonucleotide (TSO, Qiagen), 2 mM dNTP mix, 4 mM DTT, 2 U/μL Recombinant RNase inhibitor (2313A, Takara), 20 U/μL SMARTScribe Reverse Transcriptase (Takara) to 10 μL of suspended beads and incubated them in a thermal cycler at 42˚C for 90 min to obtain first-strand cDNA by reverse transcription and then heated at 70˚C for 10 min to stop the reaction. To remove excess RT primers, we added 2 μL of 2.5 U/μL Exonuclease I (2650A, Takara) and incubated them at 37˚C for 50 min, followed by inactivation, heating at 80˚C for 20 min.

The first-strand cDNA was amplified by PCR in a 50 μL reaction containing 0.24 μM primer2, 9 nM additive primer, 1xSeqAmp PCR Buffer and 0.025 U/μL SeqAmp DNA Polymerase (Takara) (Table S2) using the following program: 95°C for 1 min; 16-18 cycles of 98˚C for 10 s and 65˚C for 30 s; 68˚C for 4 min; and 72˚C for 10 min. We purified the mRNA-derived cDNAs (long cDNA) and the DNA tag-derived cDNAs (<200 bp short cDNA) by size fractionation using SPRIselect beads (B23318, Beckman Coulter). We mixed the cDNA product with 0.6× SPRIselect beads and placed them on the DynaMag™- Spin Magnet (Invitrogen™) to capture the beads. We then transferred the first supernatant containing the DNA-tagged product to a new tube and further purified it with 1.4× SPRI beads. The magnetic beads were respectively washed three times (long) and twice (short) respectively on a magnetic stand with 0.2 ml of fresh 80% (vol./vol.) ethanol and air-dried for 2.5 min at room temperature. The cDNAs derived from mRNA and DNA tag were eluted with 13 and 11 μL of elution buffer (10 mM Tris-HCl, pH 8.5), respectively.

For the mRNA-derived cDNA, we examined the yield, quality, and size distribution respectively using a Qubit 4 Fluorometer

(Thermo Fisher Scientific) and a quantitative real-time PCR (qPCR) targeting *GAPDH* (glyceraldehyde-3-phosphate dehydrogenase, Hs02758991_g1, Thermo Fisher Scientific) and with an Agilent High Sensitivity DNA Kit using Bioanalyzer 2100 (Agilent). We then performed the tagmentation of 600 pg of cDNA using a Nextera XT DNA Library Prep Kit (Illumina) and PCR with custom indexing primers. We then cleaned up the PCR products with 0.6× SPRIselect beads and eluted them with 6.5 µL of Resuspension Buffer (RSB, Illumina).

To construct the DNA tag library, the short cDNA was amplified in 20 µL of 1xKAPA Hifi Hotstart Ready Mix (Roche) containing 1.6 µL of 10-fold diluted templates and 0.25 or 0.5 µM of indexing primers (Table S2) using the following program: 98˚C for 2 min; 2 cycles of 98˚C for 20 s and 74˚C for 30 s; 12-18 cycles of 98˚C for 20 s and 72˚C for 30 s; 72˚C for 5 min. The library was then purified with 1.5× SPRI beads and eluted with 8 µL of elution buffer. We assessed the yield and length of the library respectively using a Qubit™ dsDNA HS Assay Kit and the Agilent High Sensitivity DNA Kit (Agilent), respectively.

The typical size of the mRNA-derived cDNA library was approximately 500 bp, while the size of DNA tag libraries was 224 bp. Finally, we quantified the library using the KAPA Library Quantification Kits (Roche) according to the manufacturer's protocol. The library was sequenced on a HiSeq X (Illumina) instrument with 2 x 150 bp paired-end reads.

Cell and bead image processing

We scanned the entire PDMS chip with the Micro-Magellan[29] to image the cells and beads, respectively. We performed flat-field correction on all fluorescence images using a built-in MATLAB function before stitching them together. We visually detected the cells and beads captured in the wells and registered their respective colour codes. To identify cell and bead pairs co-captured in the same wells, we applied an affine transformation to cell images to align the positions of the microwells of cell images to the microwells of bead images. When the centres of the cells were within the radii of the bead-captured wells, we assigned them as co-captured pairs. To compensate for the different focus of the nuclei of paclitaxel-treated cells in the microwells, z-stack images were taken with a 10x lens (10x, UPlanFL N) at 3 µm intervals from the bottom to the top of the wells. We then ran an extended depth of field algorithm[30] provided by Fiji software. We count the spindle poles using CellProfiler[31] by enhancing the speckles with '*EnhabceOrSuppressFeature*' module and segmenting them into individual poles with '*IdenfifyPrimaryObjects*' module.

Single-cell RNA data processing

We demultiplexed the sequence reads derived from cDNA and DNA tags using UMI-tools[32] into each cell barcode and each UMI. We demultiplexed DNA-tag UMI counts into each tag type by CITE-seq-Count program. We mapped cDNA reads to reference genomes and transcriptomes of GRCh38 (human, .p12 for the experiment of species-mixing and p13 for the experiments of paclitaxel treatments) and GRCm38.p6 (mouse) by the STAR (version 2.7.10b) mapping program[33]. We filtered out the cells with less than 800 UMI counts. To link the sequencing data and the image data, we assessed the cosine similarities between the centred log ratio (CLR) of the UMI counts of DNA tag from the sequencing data and dummy variables of the joint colour code from the image data. Here we assumed that cosine similarity is a function of the signal-noise ratio of tag counts expressed by the following equation.

$$(Cosine\ similarity) = \frac{\boldsymbol{c}\cdot\boldsymbol{e}}{|\boldsymbol{c}||\boldsymbol{e}|} = \frac{s}{1\cdot\sqrt{s^2+(k-1)\bar{n}^2}} = \frac{1}{\sqrt{1+(k-1)\frac{\bar{n}^2}{s^2}}}$$

where $\boldsymbol{c}$ is a vector of the one-hot encoded joint colour code, $\boldsymbol{e}$ is a vector of the tag count, which consists of an element of signal s and others of noise n ($\bar{n}$ is the mean value), and k is a pooling number of tags. We optimized the combinations that maximized the sum of the cosine similarities within each chip and further filtered out the linked data whose signal-noise ratios were less than $\sqrt{5}$. To remove batch effects, we integrate data from different batches with the functions of '*SelectIntegrationFeatures*', '*FindIntegrationAnchors*', and '*IntegrationData*' from Seurat (version 4.3.0.1)[34] package.

Weighted nearest neighbouring analysis for paclitaxel-treated cells

For paclitaxel-treated cells, we filtered out the cells with less than 2000 UMI count, excluded data linked to doublet cells in a well, and genes with low detection rates below 0.2, and mitigated the batch effect as described above. Subsequently, we isolated cells whose unique joint colour code was unique on the chip. We then transformed gene expression into the principal components using '*runPCA*' function from Seurat package. Furthermore, we combined paclitaxel concentrations (log10-transformed with a 0.1 offset) and the number of spindle poles to create principal components using the '*prcomp*' function from the stats package. To incorporate both sets of principal components in subsequent analyses, we performed a weighted nearest neighbouring (WNN) analysis[34] utilizing the '*FindMultiModalNeighbors*' function (with a k-nearest neighbors' parameter of 25) from the Seurat package.

Extraction of transcriptomic response

We clustered cells and projected them on the UMAP based on the neighbouring information from WNN using the '*FindCluster*' and '*RunUMAP*' functions from Seurat package. Using the clusters and UMAP, we performed trajectory analysis with slingshot[35] and extracted the transcriptomic response, ψ, with '*slingAvgPseudotime*' function. To determine the differentially expressed genes that share the increase in transcriptomic response within trajectories, we fit the gene expression with the following model using the edgeR[36] package

$$log(\mu_{gi}) = \beta_0 + \beta_\psi \psi + log(N_i)$$

where μ_{gi} is an expected expression of gene g in a cell I calculated by edgeR, ψ is the transcriptomic response, N_i is a size factor of cell i. We assessed the significance of β_ψ to derive fold changes and p values. with the quasi-likelihood F-test. To

determine differentially expressed genes between trajectories, we fit the gene expression with the following model,

$$log(\mu_{gi}) = \beta_0 + \beta_{\psi,1} t_1 \psi + \beta_{\psi,2} t_2 \psi + log(N_i)$$

where t_k is a factor denoting the assignment to trajectory k. We assessed the significance of $\beta_{\psi,2} - \beta_{\psi,1}$ to derive fold changes and p values.

Data availability

The sequencing data generated in this study have been deposited in the NCBI BioProject under accession code PRJNA1027139.

Author Contributions

A.T., K.N., and M.K. performed experiments; A.T., T.K., and H.S. analysed the data. R.Y. helped to analyse the data. A.T. T.K. and H.S. designed experiments. H.S. supervised the project. A.T. K.N., T.K., and H.S. wrote the original manuscript. All authors approved the final manuscript.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgements

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Figures

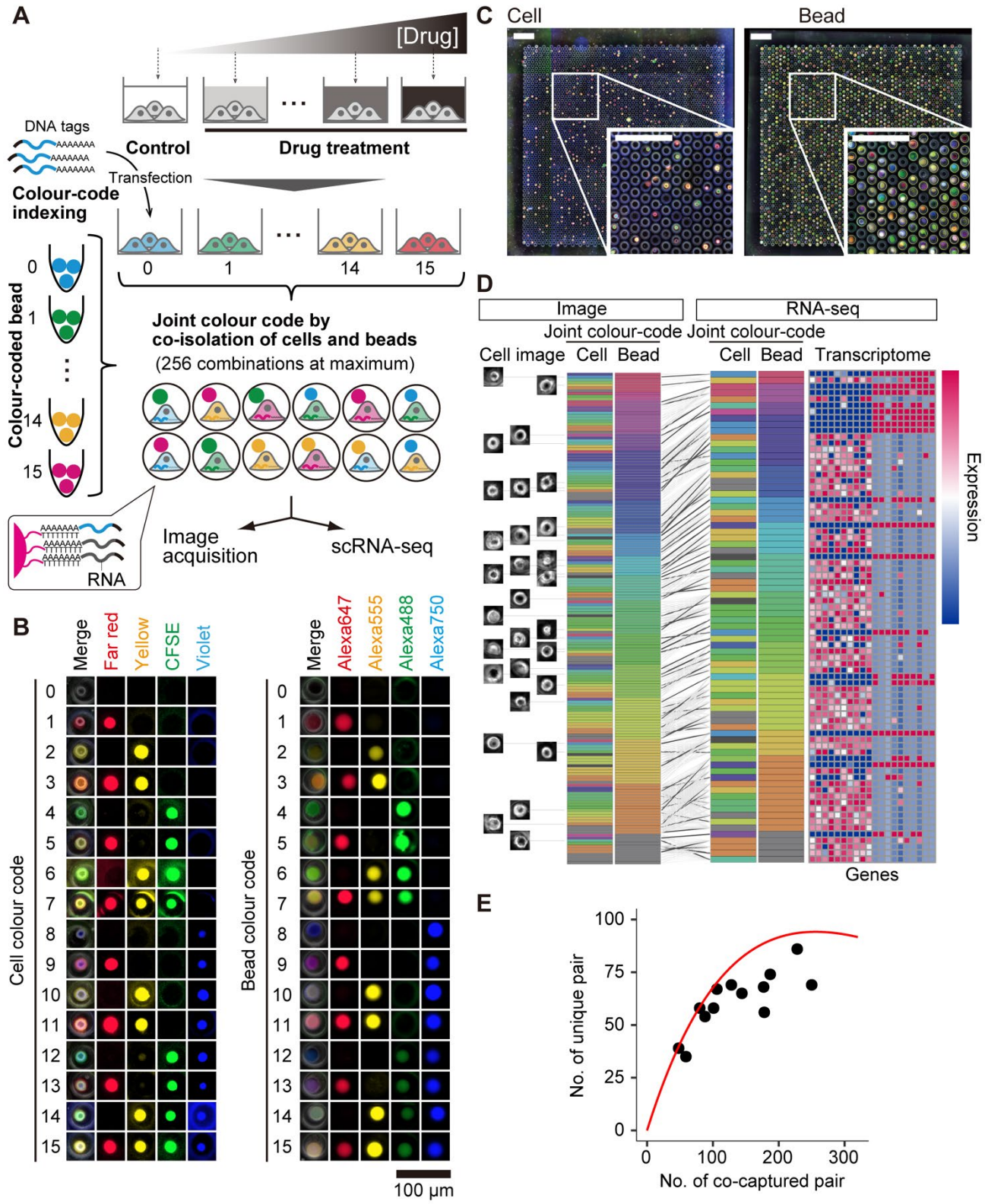

Figure 1. Linking a cellular image to single-cell RNA-seq with the combination of colour code. A. Cells were colour-coded with matching DNA tags and a set of fluorophores as per the 16 different conditions. Hydrogel beads were also colour-coded with matching barcode sequences and fluorophores. Colour-coded cells and hydrogel beads were co-isolated in microwells. We imaged fluorescence combinations of a cell and a hydrogel bead, followed by the generation of the concatenated DNA fragments from the DNA tag of the cell and the barcode sequence of the hydrogel bead, along with reverse transcription of cDNA from mRNA. Cell images and transcriptome data were linked by matching the fluorescence combinations from imaging with the library of the joint colour code generated from the concatenated DNA fragments. B. Representative fluorescence images of colour-coded cells

and beads in microwells. Scale bar = 100 µm. C. The single cells were co-isolated with single hydrogel beads out of a pool of those bearing 16 different colour codes in microwells. Cells are outlined with red borders, while bead-captured wells are outlined with yellow borders. The isolated single cells were processed to yield a scRNA-seq library and a joint colour code library that read out the gene expression and the colour code combination, respectively. Scale bar = 300 µm. D. The single cells with unique joint colour code combinations resulted in linked datasets of cellular morphology and gene expression. E. The expected number of unique joint colour codes per experimental run follows the Poissonian distribution.

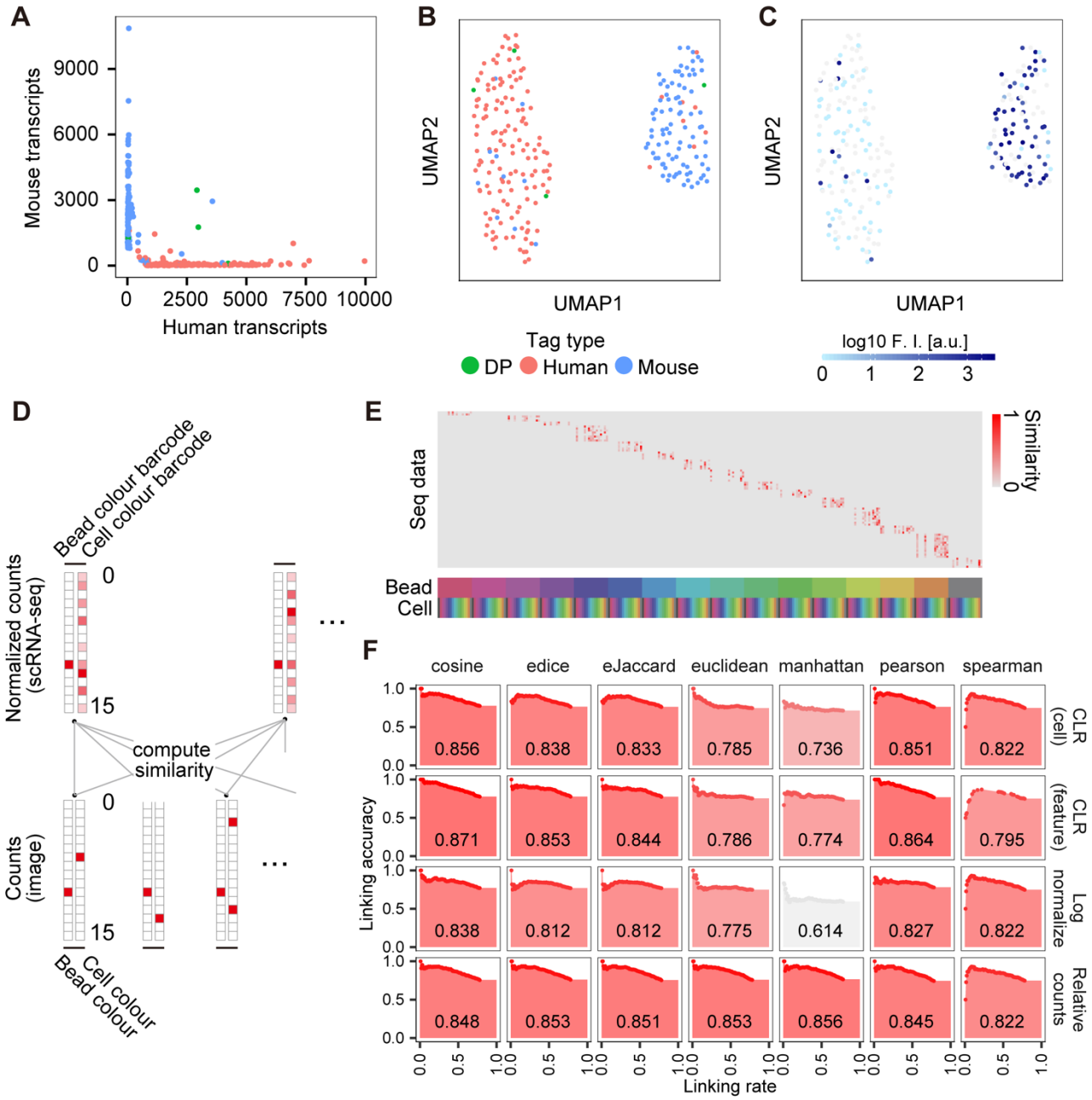

Figure 2. Mixed species experiment (mouse and human) validating the linkage between transcriptomic data and imaging data. A. The number of detected transcripts associated with individual cell barcodes. B-C. Uniform manifold approximation and projection (UMAP) of the cells. The colour represents cell type identified from linked cell image (B, BP is linked to cells co-captured with cells from different species.) and logarithmic fluorescence intensities of cells unique to the mouse cells (C). D. Schematic image of computation for the cosine similarity. E. A look-up table that shows the matching of sequencing data (columns) and colour codes decoded from image data (rows). F. The area under the curve of linking rates (the number of linked joint colour codes over all the number of joint colour codes detected in the image) versus linking accuracies (the number of linked data with consistent species over all the number of linked data) using different similarities and normalizations of DNA tag counts. We identified the species of cells by the abundance of the transcripts when one species exceeds 70% of the total unique molecular identifier (UMI) counts.

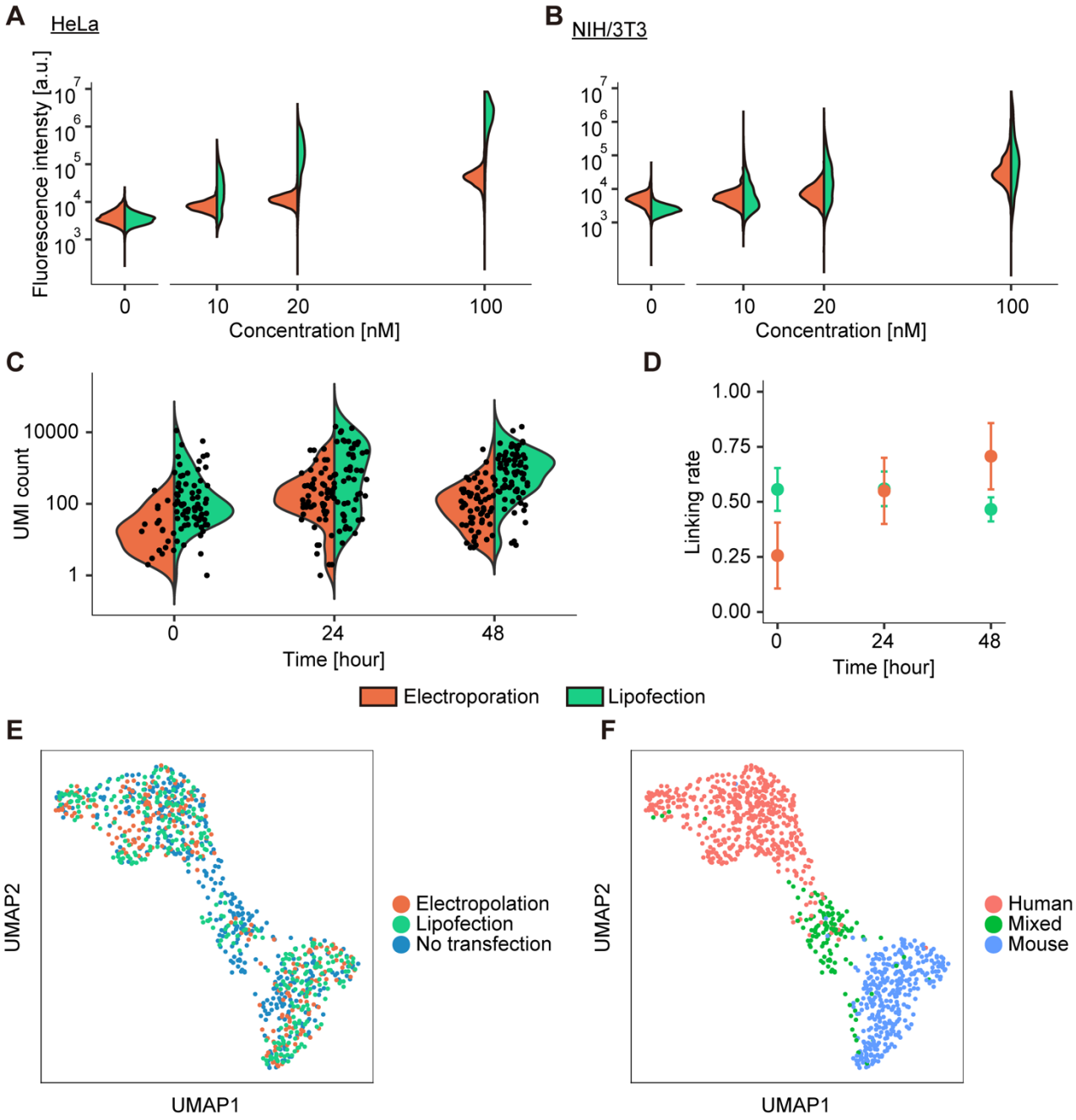

Figure 3. Comparison of electroporation and lipofection for DNA-tag labelling. A-B. Quantities of FAM-labelled DNA tags at various DNA-tag concentrations for (A) HeLa cells and (B) NIH/3T3 cells. C. Unique molecular identifier (UMI) counts of DNA tag against the different durations of incubation at 20 nM for lipofection, and 100 nM for electroporation. D. Liking rates against the different durations of incubation. E-F. Uniform manifold approximation and projection (UMAP) of single cells labelled by electroporation and lipofection (E) and species determined by the ratio of UMI counts (F).

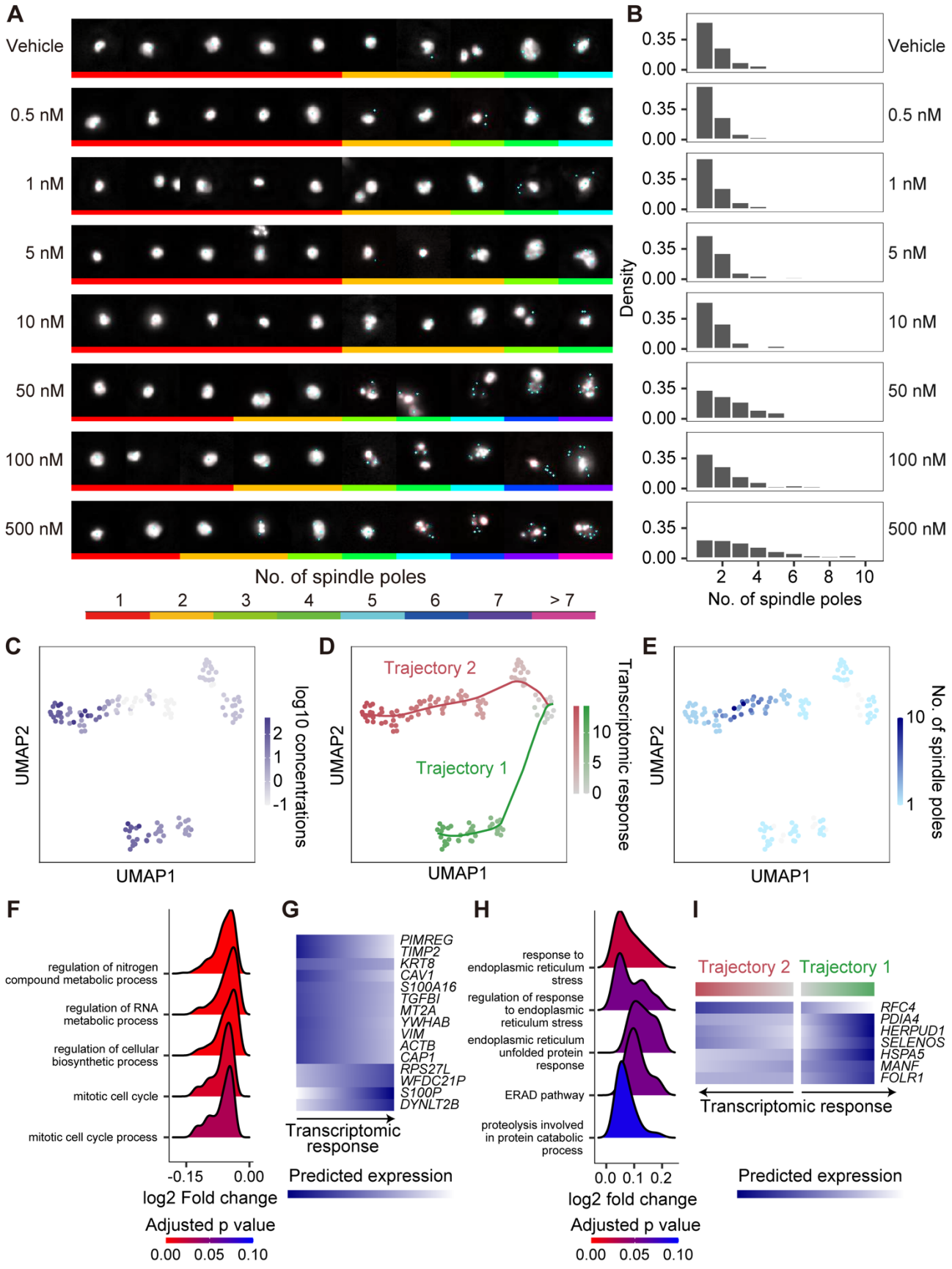

Figure 4. Integrated analysis on paclitaxel-induced transcriptomic and phenotypic response A. On-chip images of nuclei in HeLa treated with different concentrations of paclitaxel. Cian points are the positions of spindle poles. The colour labels on the bottom of the images indicate the number of spindle poles. The images are stratified according to the number

of spindle poles. B. Distributions of the number of spindle poles in HeLa cells. C-E Uniform manifold approximation and projection (UMAP) of the integrated dataset by weighted nearest neighbour analysis. The colour intensity represents the concentrations of paclitaxel, (C) the magnitudes of transcriptomic responses in the two distinct trajectories (D), and the numbers of spindle poles (E) F-G. Gene set enrichment analysis (GSEA) of differentially expressed genes associated with the increase of transcriptomic response shared among the two trajectories (F) and its predicted expression of individual genes. (G) H-I. GSEA comparing the two distinct trajectories with and without multipolar spindle formation (H) and predicted expression of individual genes (I).

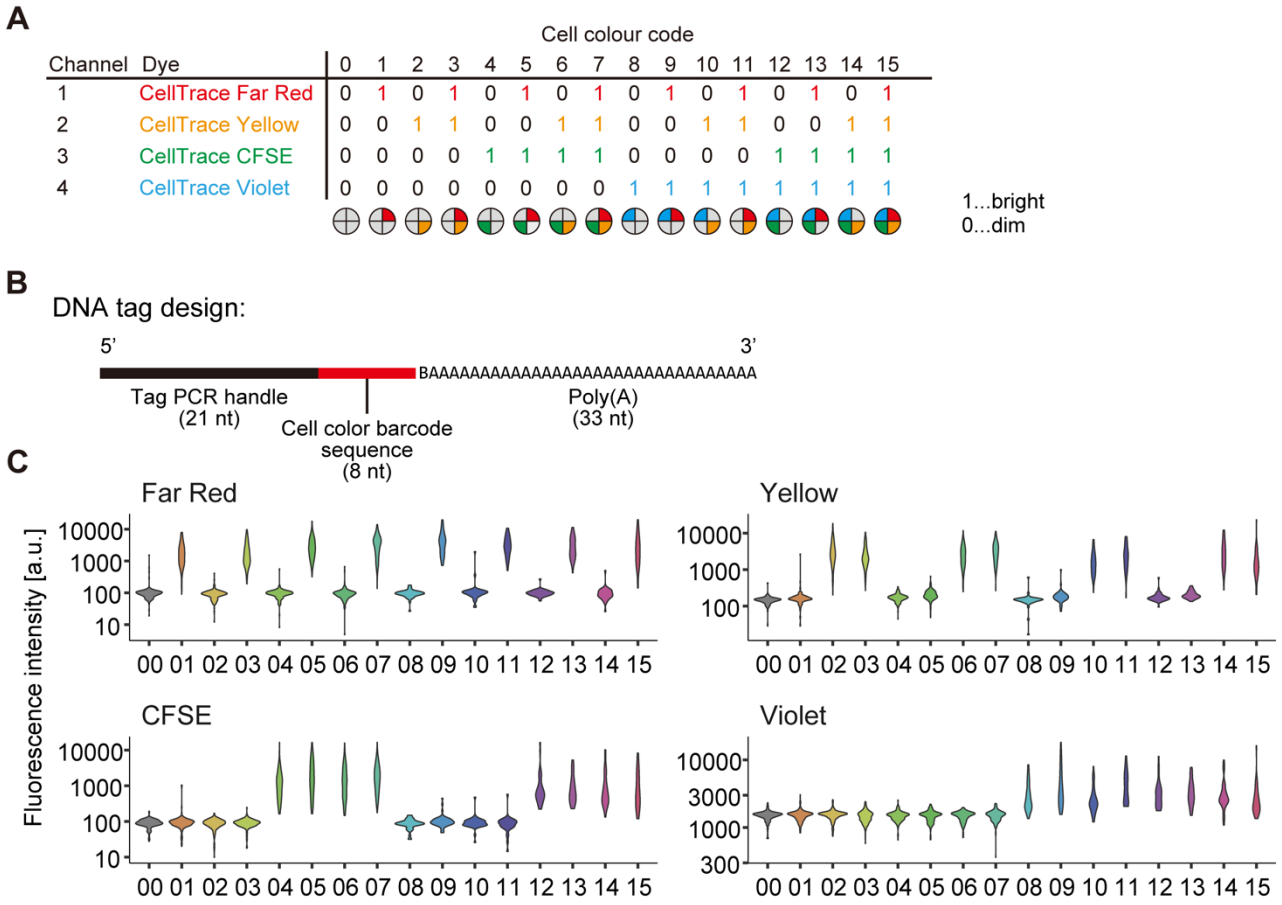

Figure S1. Design of 16 cell colour codes. A. Combination of four fluorophores for 16 colour codes. 1 and 0 respectively indicate bright and dim. B. Design of DNA tag transfected to the cells. C. Mean fluorescence intensities of colour-coded cells.

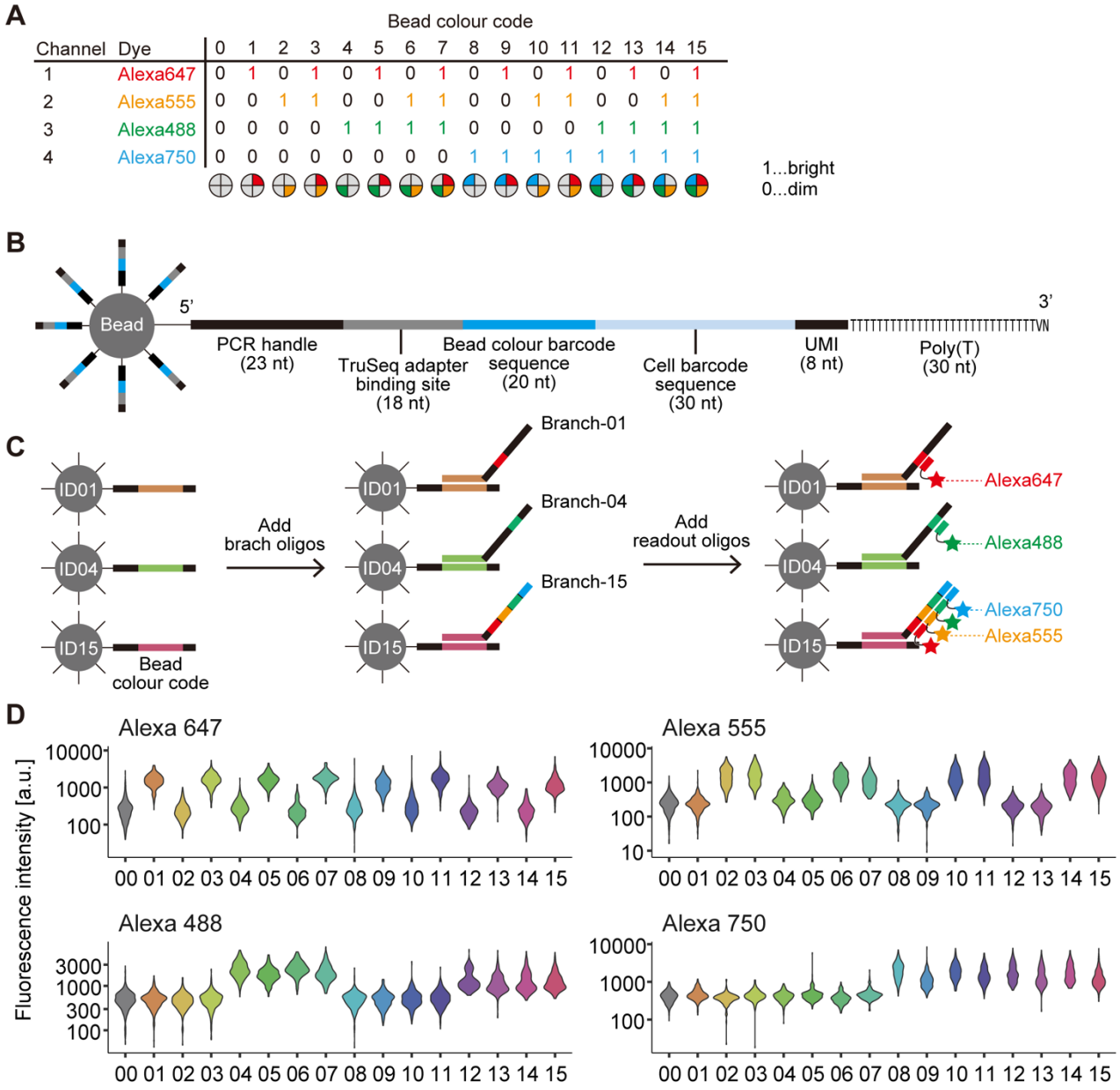

Figure S2. DNA-barcoded hydrogel beads with 16 colour codes. A. Combination of four fluorophores for 16 colour codes. 1 and 0 respectively indicate bright and dim. B. Schematic images of barcoded primers attached to hydrogel beads. C. Example schematic images of colour code staining. The designated fluorophores are attached to beads via branch DNAs hybridising to the sequence of bead colour code. D. Mean fluorescence intensities of colour-coded beads.

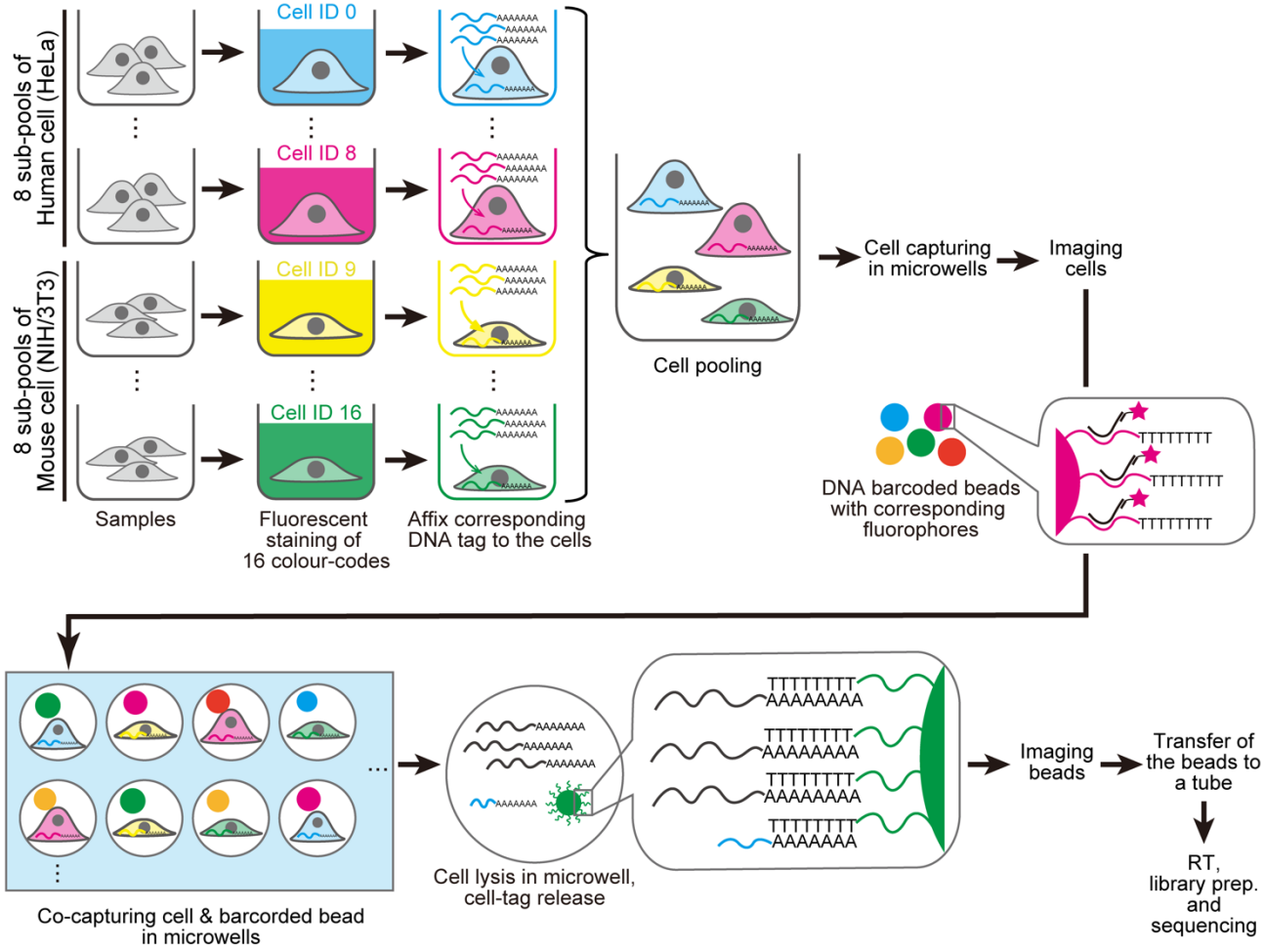

Figure S3. Procedures of species-mixing experiment. We divided human cells (HeLa) and mouse cells (NIH/3T3) into the eight sub-pools respectively for a total of 16 sub-pools. We individually stained with different combinations of fluorescence dyes and transfected with corresponding DNA tags via electroporation. We combined all sub-pools of colour-coded cells into a single tube and captured the cells in a microwell array. After cell imaging, we introduced the colour-coded hydrogel beads into the microwells, creating pairs of a colour-coded cell and bead in each microwell. Upon cell lysis, released mRNAs and DNA tags hybridise with barcoded dT primers on hydrogel beads. We imaged the hydrogel beads and proceeded to reverse transcription, PCR, and next-generation sequencing.

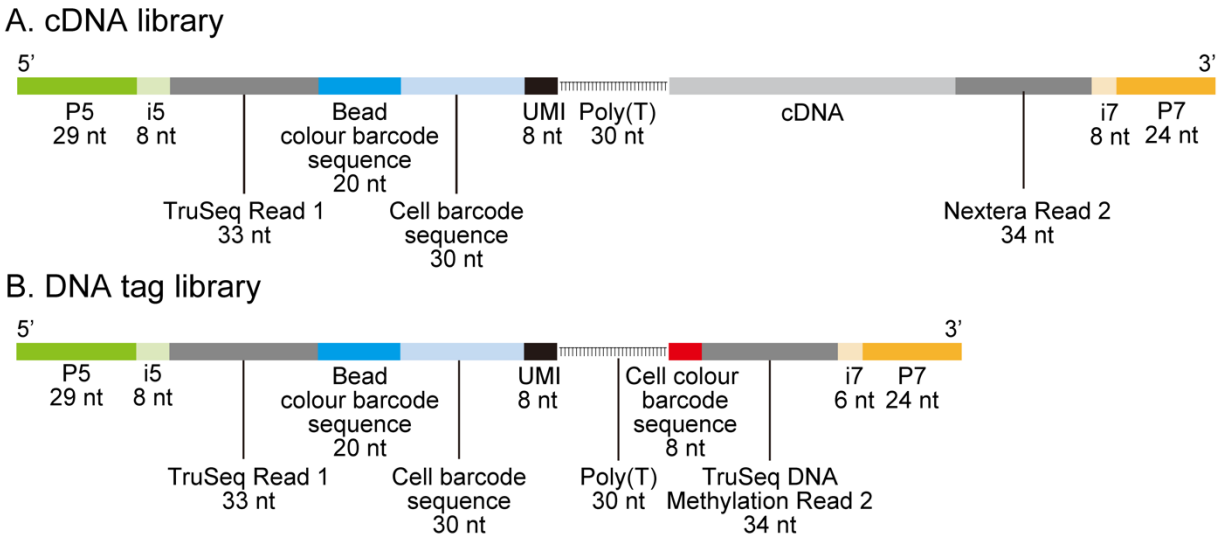

Figure S4. Library designs of cDNA and DNA tag for Illumina sequencing. A cDNA library. B. DNA tag library.

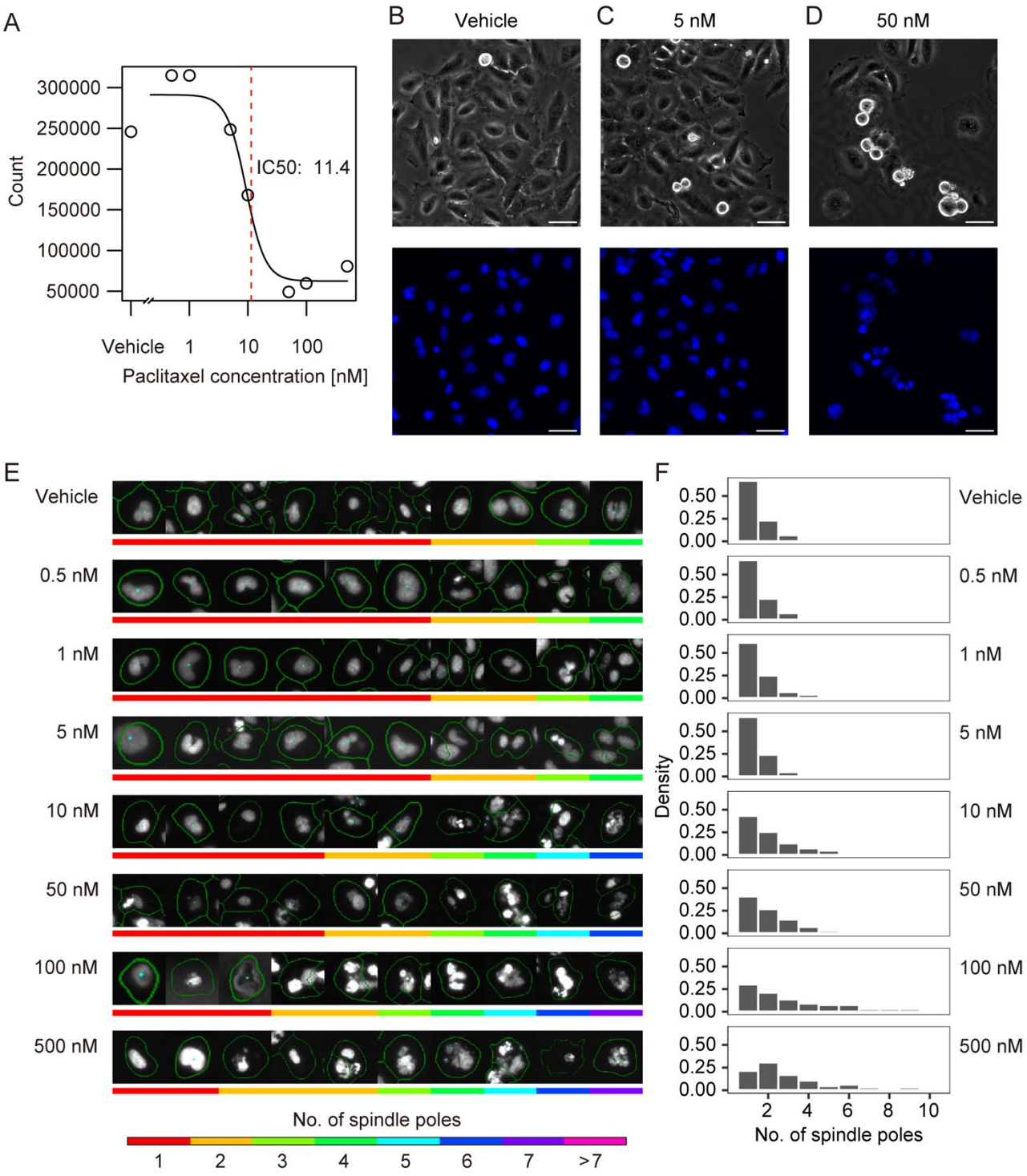

Figure S5. HeLa cell response to paclitaxel on dish A. The drug response curve of HeLa cells treated with paclitaxel for 24 h. The red broken line indicates the half-maximal inhibitory concentration (IC50). B-D. Images of cells in bright fields and nuclei stained with Hoechst 33342 of HeLa cells treated with paclitaxel (B. vehicle, C. 5 nM, and D. 50 nM) for 24 h in standard couture dishes. The scale bars on the bottom right are 50 µm. E. Images of nuclei in individual HeLa cells treated with different concentrations of paclitaxel. Cian points are the detected positions of spindle poles. The colour labels on the bottom of the images indicate the number of spindle poles. The images are stratified according to the number of spindle poles. F. Distributions of the number of spindle poles in HeLa cells.