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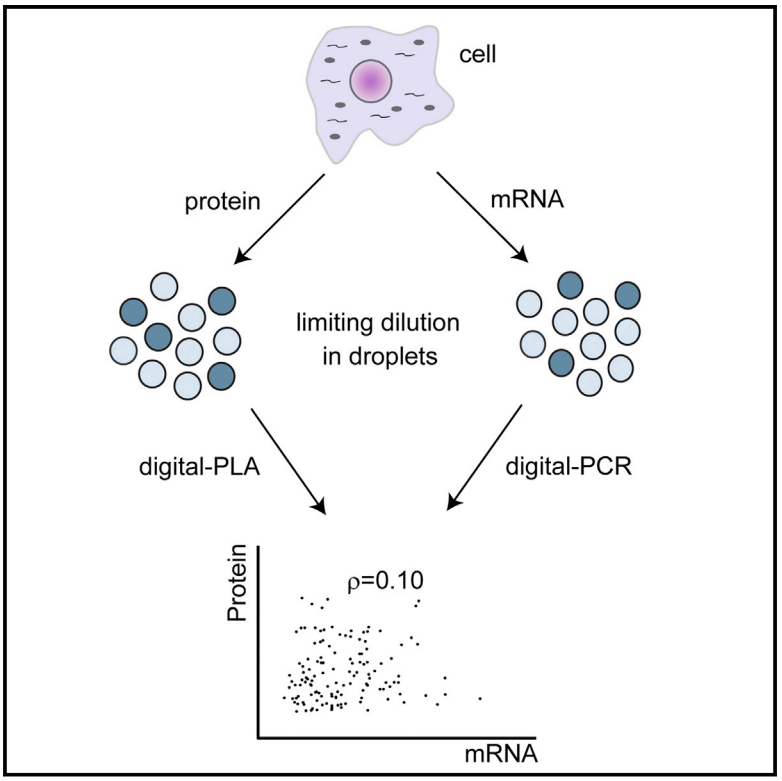
Digital Quantification of Proteins and mRNA in Single Mammalian Cells

Graphical Abstract



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In Brief

A single-protein counting method called digital PLA was developed, allowing ultrasensitive measurement of absolute protein and mRNA copy numbers from single mammalian cells. Joint single-cell mRNA/protein measurements were then used to construct and validate a stochastic two-state model for transcription and translation of the gene CD147.

Highlights

- Digital PLA protocol allows ultrasensitive protein quantification from single cells
- Combination with digital PCR allows joint single-cell protein and mRNA measurements
- Absolute mRNA and protein abundances measured jointly from single mammalian cells
- Joint mRNA-protein data was used to build a two-step model of gene expression

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Digital Quantification of Proteins and mRNA in Single Mammalian Cells

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SUMMARY

Absolute quantification of macromolecules in single cells is critical for understanding and modeling biological systems that feature cellular heterogeneity. Here we show extremely sensitive and absolute quantification of both proteins and mRNA in single mammalian cells by a very practical workflow that combines proximity ligation assay (PLA) and digital PCR. This digital PLA method has femtomolar sensitivity, which enables the quantification of very small protein concentration changes over its entire 3-log dynamic range, a quality necessary for accounting for single-cell heterogeneity. We counted both endogenous (CD147) and exogenously expressed (GFP-p65) proteins from hundreds of single cells and determined the correlation between CD147 mRNA and the protein it encodes. Using our data, a stochastic two-state model of the central dogma was constructed and verified using joint mRNA/protein distributions, allowing us to estimate transcription burst sizes and extrinsic noise strength and calculate the transcription and translation rate constants in single mammalian cells.

INTRODUCTION

Single-cell heterogeneity features in diverse biological phenomena such as the emergence of antibiotic resistance (Allison et al., 2011), differential response to vaccines (Flatz et al., 2011) and signaling inputs (Kellogg and Tay, 2015), presence of cancer stem cells (Reya et al., 2001), variability in dynamics of immune signaling pathways (Tay et al., 2010), and virus infection (Snijder et al., 2009). Since proteins conduct the various actions that give rise to the observed phenotypes, their accurate quantification from single cells is necessary to understand the phenomena that arise from single-cell heterogeneity (Gordon et al., 2007; Sigal et al., 2006) and to build accurate mathematical models of complex biological systems (Karr et al., 2012). mRNA abundance is often a poor surrogate for protein quantity, since the two values are not necessarily correlated, as shown in prokaryotic cells (Taniguchi et al., 2010). In addition to determining presence and degree of correlation, joint mRNA and protein quantification from single cells would also enable researchers to build and accurately calibrate mathematical models of transcription and translation. If the mRNA and protein content of each cell can be measured, an mRNA-protein correlation term could be derived exactly for the heterogeneous population and used as an additional input to the model. A practical and sensitive method for absolute joint mRNA and protein quantification would thus be greatly desirable for quantitative systems biology, especially for mammalian cells where the correlations between the two species has remained largely unexplored at the single cell level due to technical difficulties resulting from counting individual molecules at high abundances.

Design

Methods developed for protein quantification had limited application to single cells due to significant shortcomings in sensitivity and practicality. PLA (Gullberg et al., 2004; Schallmeiner et al., 2007) and its variant, the proximity extension assay (Lundberg et al., 2011), can detect proteins at low concentrations in dilute protein solutions. These techniques, however, rely on qPCR readout that scales with exponential amplification and thus becomes inaccurate for quantifying differences smaller than fold changes (Whale et al., 2012). Microfluidic PLA (Blazek et al., 2013) and light-mediated cellular barcoding (Agasti et al., 2012) provide only relative protein quantification from single cells. Single-cell mass cytometry (CyTOF) enables multiplexed readout of protein and mRNA content but provides relative quantification as well (Bendall et al., 2011; Frei et al., 2016). Yet other methods such as the single-cell barcode chip and western blot chip either provide relative quantification or require extensive genetic manipulation, sophisticated device manufacture, and advanced microscopy (Huang et al., 2007; Hughes et al., 2014; Lu et al., 2015; Ma et al., 2011; Shi et al., 2012; Taniguchi et al., 2010). Digital quantification based on limiting dilution provides high sensitivity and the ability to quantify differences much smaller than fold changes (Fan et al., 2012). For example, digital ELISA (Kim et al., 2012; Rissin et al., 2010) achieved sub-femtomolar limit of detection (LOD) for proteins like prostate-specific antigen in human sera. Furthermore, PLA using rolling circle amplification reduced the LOD of the method compared to

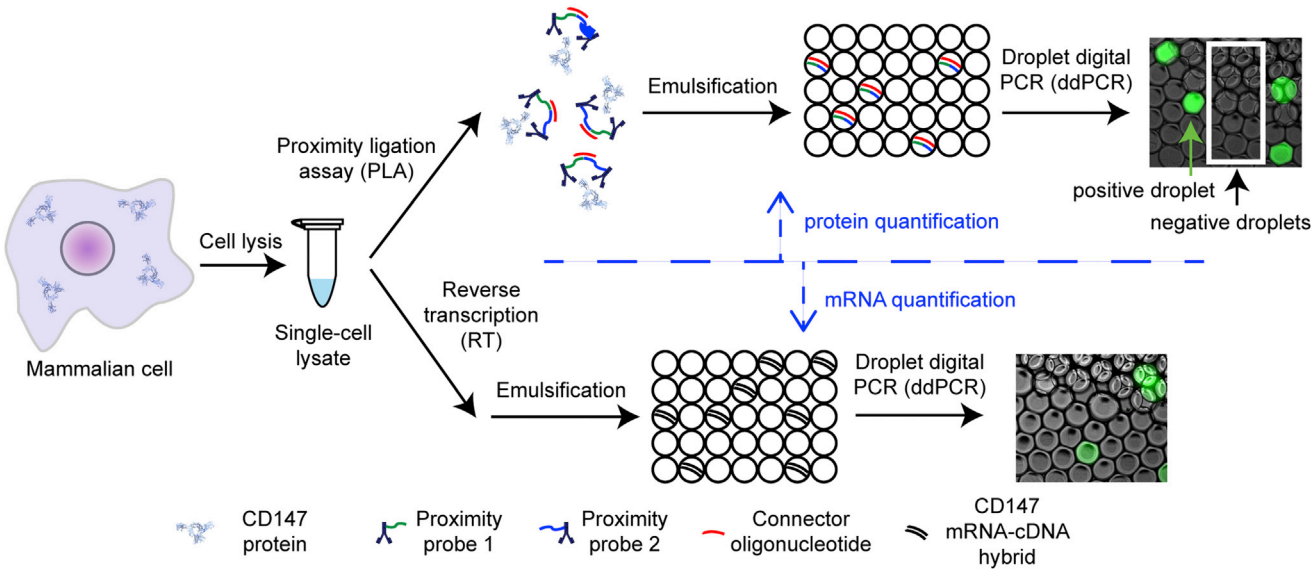

Figure 1. Digital PLA Protocol for Absolute Protein and mRNA Quantification from Single Cells

The single-cell lysate is split into two, and the mRNA and protein from individual mammalian cells are quantified using two-step RT-PCR and digital PLA, respectively. In digital PLA, proximity probes bind the target protein; the connector oligonucleotide hybridizes with the probes; a double-stranded DNA is formed following ligation; and the proteins are digested by proteases. The remaining dsDNA (and the cDNA in RT-ddPCR workflow) is distributed among 20,000 droplets at limiting dilution, each of which contains zero or one dsDNA molecule. These molecules are amplified by PCR to be detected. Pictures on the right shows fluorescent droplets that contain or lack DNA after ddPCR. CD147 structure was retrieved from RSCB PDB (PDB: 3B5H) (Yu et al., 2008).

qPCR readout (Ke et al., 2013). Besides CyTOF, two of the reported methods were used for joint protein and nucleic acid quantification from single cells, namely advanced fluorescence microscopy for bacteria and PLA in combination with RT-qPCR for mammalian cells. Single-molecule resolution was attained with the former, but the method required substantial genetic manipulation and is applicable only to dilute proteins in bacteria (Taniguchi et al., 2010), and the latter two only provided relative quantification and had low sensitivity due to qPCR comprising the terminal step in the workflow (Ståhlberg et al., 2012).

Here we describe absolute and simultaneous quantification of both proteins and mRNAs from single mammalian cells by combining PLA with digital PCR in a very practical, sensitive, and robust protocol called digital PLA. We first use droplet digital PCR (ddPCR) to achieve digital PLA and later combine it with two-step RT-ddPCR to generate a single workflow for joint mRNA and protein quantification (Figure 1). The use of ddPCR rather than qPCR enables absolute quantification of proteins independent of amplification efficiency, and with much greater precision (Hindson et al., 2013) (Figures S1A and S1B).

We quantified three proteins using digital PLA; namely the endogenous transmembrane proteins CD147 (also known as extracellular matrix metalloproteinase inducer [EMMPRIN]) and intercellular adhesion molecule-1 (ICAM-1), and exogenously expressed GFP. Femtomolar LODs were achieved for all three proteins, and digital PLA has a linear dynamic range over two to three orders of magnitude. Digital PLA and digital PCR were then used to quantify CD147 mRNA and protein copy numbers in the same single cell. CD147 mRNA and protein data from single cells, and especially their co-variance, were subsequently used to develop and evaluate different models of the central dogma. A two-state model of gene expression is shown to fit well to our experimental data (Peccoud and Ycart, 1995; Blake et al., 2003; Paulsson 2005). Using this model, we calculated the transcription burst sizes, transcription and translation rate constants, and extrinsic noise strength in single mammalian cells.

Our method for absolute mRNA-protein quantification from single cells can be readily adapted by other researchers; since the entire assay reagents and equipment are commercially available, complex microfluidic device fabrication is not needed, and no genetic manipulation of the cells is required. A single researcher can quantify proteins from 100 samples (single cells or clinical samples) in a day. Absolute mRNA and protein measurements from individual mammalian cells will enable scientists to better understand cell-to-cell heterogeneity and evaluate and/or construct more accurate biological models of the central dogma in various systems.

RESULTS

Digital PLA Development

In order to quantify proteins from single cells, they are first isolated, lysed, and combined with oligonucleotide-bound antibodies (proximity probes, Figure 1) and the connector oligonucleotide. The antibodies bind to their epitopes, the oligonucleotides bound to the antibodies come in close proximity, and the connector oligonucleotide hybridizes to them, thereby forming a complex of target protein, proximity probes, and connector DNA. The three-oligonucleotide complex becomes a double-stranded DNA (dsDNA) after ligation, completing the conversion

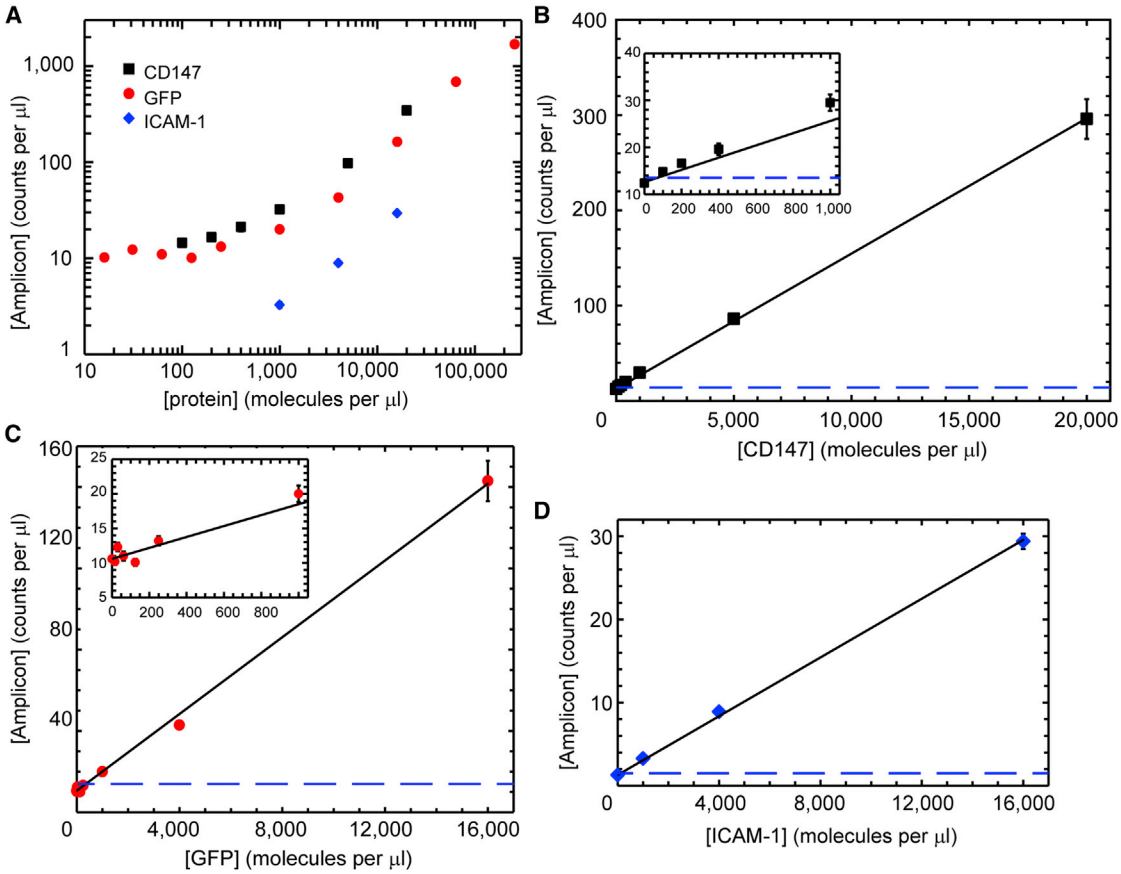

Figure 2. Dynamic Range and Sensitivity of Digital PLA for Protein Quantification

(A–D) Assay calibration curves are plotted either together in logarithmic scale (A) or individually in linear scale ([B]–[D]). Digital PLA readout is given in number of double-stranded DNA amplicons per µl and subsequently converted to absolute protein amounts using these calibration curves. Solid lines indicate linear regression for each of the three proteins: (B) CD147, $y = 0.0142x + 12.4$, $R^2 = 0.9997$; (C) GFP, $y = 0.0094x + 10.6$, $R^2 = 0.9982$; and (D) ICAM-1, $y = 0.00177x + 1.30$, $R^2 = 0.9993$. Insets in (B) and (C) given to clearly show sub-femtomolar assay detection limits (Assay LOD, blue dashed lines); exact LOD values are given in Table 1. Error bars show combined error from both Poisson noise and technical error from replicates (n = 15 or 29 for CD147, 3 or 6 for GFP, and 12 for ICAM-1). Additional details concerning digital PLA development can be found in Figure S1.

of the targeted protein to dsDNA as in standard PLA (Gullberg et al., 2004). After a brief proteolysis step, the dsDNA is quantified by ddPCR (Hindson et al., 2011; Pinheiro et al., 2012). Using a commercially available microfluidic device, the PLA solution (which now only contains the dsDNA) is emulsified to create ~20,000 nanoliter-sized droplets under limiting dilution, each of which contains either zero or one dsDNA molecule. Single dsDNA molecules in the droplets are then amplified by PCR and counted by measuring the resultant fluorescence from hydrolysis probes using the commercially available droplet reader. These absolute DNA counts are then converted to absolute protein numbers using a calibration curve. The method shows good reproducibility as confirmed by making triplicates of eight PLA samples—seven of which did not show any significant variation other than fundamental digital PCR error (Figure S1E).

We evaluated the digital PLA performance on pure protein standards. Dilution series of human CD147, murine ICAM-1, and GFP spanning three to four orders of magnitude were analyzed by digital PLA (note that GFP is used here as the target protein and not as a fluorescent tag for protein detection). The calibration curves show that digital PLA has a linear dynamic range across three orders of magnitude (Figure 2). Femtomolar LOD (defined as signal at 3 SDs above background) was achieved for all three proteins, CD147 giving the lowest LOD at 86 proteins per µl of ddPCR solution (corresponding to 16.2 fM in the sample solution) and the most sensitive calibration curve (i.e., 1/slope = 70 proteins per count) (Table 1). Specificity of the CD147 and GFP probes was confirmed by analyzing antigen-free lysate. No positive signal was generated when the human CD147 probes were used to analyze mouse 3T3 bulk lysate (Figure S3A). Mouse cells transfected with a plasmid expressing human CD147 recovered the PLA signal (Figure S3B). Background signal from one-cell equivalent lysate of GFP-negative cells was comparable to that from buffer (Figure S3C). In terms of absolute protein amounts (~20,000 proteins per cell, Table 1), the LOD of our method is comparable to those of other single-cell methods such as the barcode and western blot chips (Hughes et al., 2014; Shi et al., 2012). A major advantage of

Table 1. Digital PLA Specifications for Analyzed Proteins

Protein	Assay LOD[a] (fM)	Sensitivity[b] (proteins per DNA)	Sample LOD[c] (fM)
CD147	0.14	70	16.2
GFP[d]	0.18	95	20.1
ICAM-1	0.34	565	38.3

[a]Assay limit of detection (LOD), gives the detection limit in the assay conditions (mol protein per unit volume of ddPCR solution). LOD is defined as the protein concentration at which the signal is 3 SDs above background.
[b]Sensitivity, equal to the inverse of the slope of the calibration curve, is an inverted metric: the lower the number of proteins per counted DNA molecule, the higher the assay sensitivity.
[c]Sample LOD, given in moles of protein per unit volume of the original sample. The 113-fold dilution in the digital PLA workflow results in the difference between the sample and assay LODs.
[d]LOD and sensitivity calculated using data from a single day ("Curve 1," Figure S1F).

digital PLA over analog (i.e., qPCR-based) methods is the ability to measure very small protein concentration differences over its entire dynamic range.

Direct and Digital Quantification of Protein Copy Numbers in Single Cells

GFP-p65 (a subunit of the NF-κB protein family) fusion proteins were quantified from single mouse macrophages (RAW264.7) using digital PLA; individual macrophages were sorted by FACS into wells containing 2 μl of standard lysis buffer (Figure S2B). GFP-p65 counts from 45 single cells lie in the linear range of the assay and show significant variation, ranging from 32,400 ± 2,500 to 188,000 ± 11,000 proteins (Figures 3C and S3D). This large heterogeneity can only be observed on the single cell level and is masked in bulk measurements (Figure 3D). Error due to Poisson noise was small (6%–8% CV); we could thus determine single-cell protein content within several thousand molecules. In addition to the exogenously expressed GFP-p65 proteins, we also quantified endogenous CD147 proteins from individual human embryonic kidney (HEK) cells, as described in the following sections.

Direct and Digital Quantification of mRNA Copy Numbers in Single Cells

We developed a robust protocol for counting mRNAs in single cells so that they can be quantified simultaneously with proteins from the same single cell. Different combinations of RT-PCR protocols, primers, hydrolysis probes, and PCR cycle numbers were tested for mRNA quantification from bulk-extracted total RNA (see Experimental Procedures for detailed description of assay optimization). The combination of a two-step protocol with Probe 2 and 40 amplification cycles yielded the highest number of CD147 mRNAs (101 ± 1) per cell (Figures S4A and S4B) and easily distinguishable positive and negative ddPCR droplets (Figure S4C). Other permutations either failed to produce sufficient cDNA or suffered from high background fluorescence of empty ddPCR droplets (Figure S4D).

After a suitable PCR protocol for mRNA detection had been found, the remaining challenge was to find a cell lysis strategy compatible with both digital PLA and RT-ddPCR. After screening various conditions, particularly regarding the lysis buffer concentration (see Supplemental Experimental Procedures), we found that 0.1X TM lysis buffer did not interfere with droplet formation during ddPCR preparation (Figure S4E), could lyse up to 100 mammalian cells (Figure S4F), did not inhibit RT (Figures S4G and S4H), and was compatible with PLA (Figure S5A). Digital PLA was even more sensitive in the new buffer matrix (Figure S5B). Therefore, we successfully established a direct lysis protocol compatible with RT-ddPCR. We verified the performance of our RT-ddPCR workflow using T7-in-vitro transcribed CD147 mRNA and found that we recovered 88% of the theoretical signal (Figure S5C). The discrepancy is possibly due to RT biases (Ståhlberg et al., 2004). We corrected our entire single cell RT-ddPCR reads by the observed difference and introduced a LOD for mRNA quantification at 52.5 copies per cell (87aM).

Joint Protein and mRNA Measurements from Single Cells

CD147 proteins and mRNA were quantified from the same single cells using a joint two-step RT-ddPCR and digital PLA workflow in the new buffer matrix. Individual HEK293T cells were sorted into wells containing 3 μl of 0.1X TM buffer (Figure S2A). Single-cell lysates were then split in a 1:2 ratio; 1 μl was taken out for mRNA quantification, while CD147 proteins were quantified by digital PLA from the remaining 2 μl (Figures 3 and 4). In this configuration, the LOD for CD147 proteins was 29,300 molecules per cell. Analyzing both fractions of the sample with PLA revealed good agreement between the two half-lysates, which indicates that no further error, besides the fundamental ddPCR error was introduced (Figure S5D) in six out of nine cases. Of the 186 single cells sorted, 138 cells had measurable CD147 protein content above the LOD. Single-cell CD147 counts varied 18-fold, ranging from 35,900 ± 2,900 to 636,000 ± 36,000 proteins (Figures 3A). All single cell measurements lay within the calibrated range of the assay, whereas the 100 cell populations were slightly above (Figure S3E). The mean CD147 protein value (218,000 molecules per cell) from human cells we measured agrees well with estimates from single mouse fibroblasts (258,978 molecules per cell; Schwanhäusser et al., 2011). The range of CD147 amounts per cell narrowed as the number of cells per well increased from 1 to 100. Protein counts from 100 cells show an average of 67,200 ± 1,000 to 229,000 ± 3,000 CD147s per cell (Figure 3B).

Single-cell CD147 mRNA numbers ranged from 57 ± 18 to 2,651 ± 121 molecules per cell, with a population mean of 188.2 and a SD of 90 (Figure 4A). These mean mRNA values are comparable to 189 CD147 mRNAs per cell reported for single mouse fibroblasts (Schwanhäusser et al., 2011). Additionally, 100 cells were sorted and measured, serving as estimates for bulk average. 100-cell averages ranged from 106 ± 2 to 215 ± 3 copies per cell, exhibiting a narrower range on a per cell basis (Figure 4A). As a result, on average, approximately 1,000 proteins were translated from each CD147 mRNA in HEK cells.

Analysis of mRNA and Protein Correlation in Single Mammalian Cells

The unique ability to absolutely and sensitively quantify CD147 mRNA and protein content of the same single cell allowed us

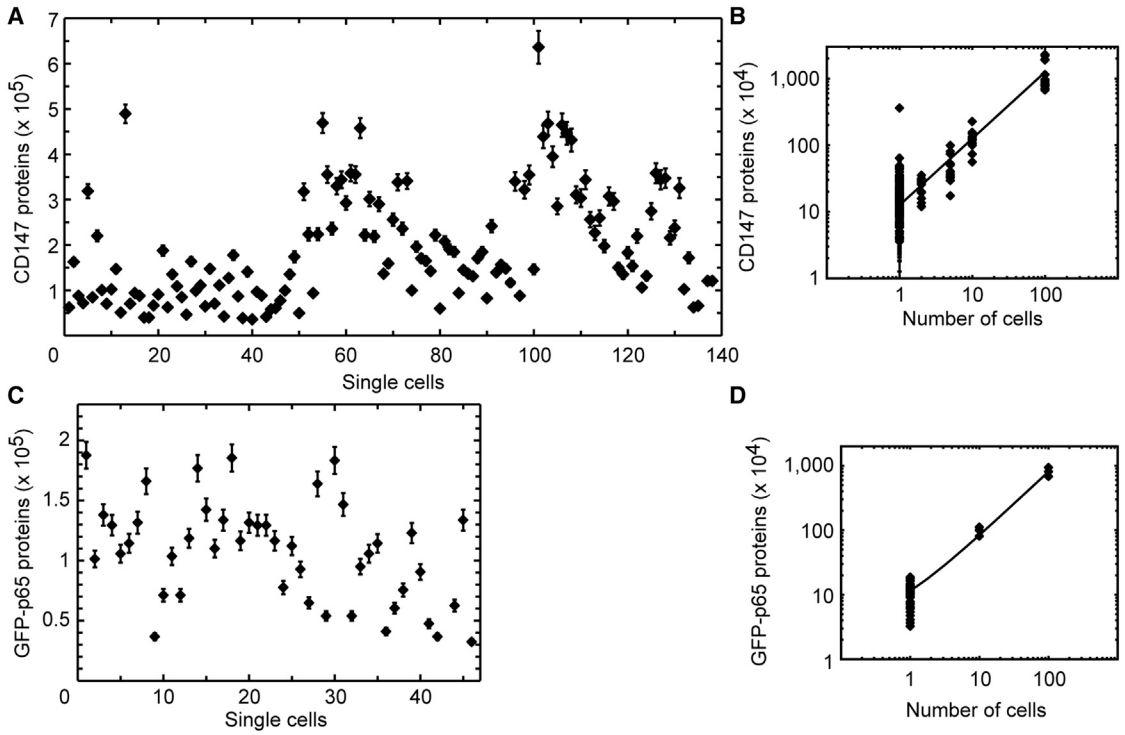

Figure 3. Absolute CD147 and GFP-p65 Protein Quantification from Single Mammalian Cells Using Digital PLA

(A) CD147 values from 138 single human embryonic kidney (HEK293T) cells display great single-cell heterogeneity.

(B) CD147 measurements from 1, 2, 5, 10, and 100 HEK293T cells. Solid line indicates linear regression (y = 125,000x, R^2 = 0.785).

(C) GFP-p65 measurements from 45 single mouse macrophages.

(D) GFP-p65 measurements from 1, 10, and 100 macrophages. Solid line indicates linear regression (y = 80,900x, R^2 = 0.980). Single-cell data included in (B) and (D) are the same as those plotted in (A) and (C), respectively. Error bars show Poisson error from 11,679 to 16,882 droplets. Additional information regarding the performed FACS sorts and used controls and calibration curves can be found in Figures S2 and S3.

to analyze the correlation of these molecules. Surprisingly, our high-sensitivity measurements showed that CD147 mRNA and protein are poorly correlated (Spearman R = 0.10, Figure. 4B), which contrasts with previous bulk observations that found a significantly higher degree of correlation (Pearson R = 0.41, 0.59, Schwanhäusser et al., 2011; Tian et al., 2004), similar to single-cell measurements from bacteria (Pearson R = 0.01, Taniguchi et al., 2010). We note that the mRNA/protein correlation would (incorrectly) appear to be higher if a method with insufficient sensitivity (i.e., qPCR/PLA) was used here, as most of the single-cell protein and mRNA variability lie within a 2-fold difference around the mean. These findings highlight the importance of high-resolution single-cell measurements compared to low-sensitivity or population-averaged (bulk) analysis in understanding protein transcription and translation.

Single-Cell mRNA/Protein Distributions Indicate a Two-State Stochastic Process for Protein Expression

Single-cell CD147 mRNA and protein copy numbers have very broad distributions and cannot be fit with a Poisson probability density function (pdf, Figure 5), suggesting that the intrinsic noise caused by random production and degradation of these macromolecules (i.e., a one-step birth-death process) is not enough to explain their variance (Raj and van Oudenaarden, 2008). A gamma pdf could be fit to the single-cell CD147 mRNA distributions ($p > 0.05$, Figure 5), indicating a two-state stochastic process for gene expression (Paulsson, 2005; Peccoud and Ycart, 1995) (Figure 6A). In this model, transcription occurs in random bursts of varying size and results in larger mRNA copy number variances. The mRNA distribution can take the form of a gamma distribution if the gene is mostly inactive and the RNA degradation during a burst is small (Raj et al., 2006). In this case, the rate and shape of the resulting gamma pdf is interpreted as the transcription burst rate and the average burst size of the gene. For our cell population, we calculated an average burst size of 40 ± 4 CD147 mRNAs, a gene activation rate of 3.78 ± 0.38 per day, and a mean copy number of 188 ± 28 CD147 mRNAs per cell; the latter of which agrees well with the mean of 188.2 CD147 mRNAs obtained from our single-cell measurements.

A Stochastic Model of Gene Expression Parameterized by Single Cell mRNA and Protein Measurements

Measurement of single-cell mRNA and protein abundances allowed us to construct and verify a stochastic model of CD17 gene expression in single-cells (Figure 6). We considered a two-state model, with random promoter switching, transcription, and translation, as well as extrinsic variability (Figure 6A; see Supplemental Experimental Procedures). Unlike fitting a pdf of

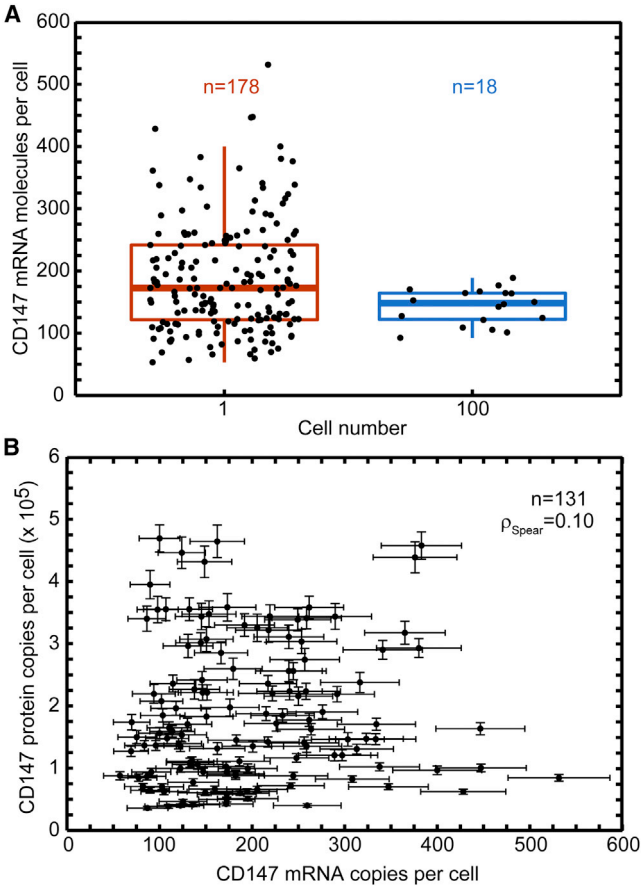

Figure 4. Absolute Quantification of CD147 mRNA and Protein Copy Numbers in Human Embryonic Kidney Cells

(A) CD147 quantification from single and 100 cells measured by digital PLA. Plotted copy numbers were normalized by the number of sorted cells. The number of replicates is indicated above each boxplot. Mean single-cell and population-averaged copy numbers show good agreement.

(B) CD147 mRNA and protein copy numbers from 131 single HEK293T cells. Error bars show Poisson error from >10,000 droplets. Supplemental information concerning RT-ddPCR development and technical controls can be found in Figures S4 and S5.

a presumed type, the stochastic two-state model is not based on any a priori assumptions about the regime in which gene activation and RNA degradation take place. However, exact inference of such models based on mRNA and protein distributions is computationally intractable. We therefore employed a moment-based analysis in which the single-cell abundances and their variability are summarized by only a few statistics such as means and variances (Zechner et al., 2012). We derived equations for first- and second-order moments of mRNA and protein (i.e., E[M(t)], E[P(t)], E[M(t)^2] and E[P(t)^2]), which were used as a basis for subsequent analyses. The combined mRNA and protein readout allowed us to use the correlation between mRNA and protein, E[M(t)P(t)], to verify the model. Since CD147 is expressed constitutively, we assumed stationarity of the system and fitted the analytically derived steady-state moments to the ones obtained experimentally. The model comprises seven parameters in total, which cannot be uniquely determined solely from steady-state measurements of mRNA and protein. We thus introduced a suitable reparameterization of the model in terms of an effective rate of transcription (Zenklusen et al., 2008), subsuming promoter switching and transcription into a single parameter. Furthermore, we incorporated prior knowledge based on the reported mRNA and protein half-lives (20.97 hr, 33.48 hr; Schwanhäusser et al., 2011). Although the used half-lives had been measured in a mouse cell line, we do not expect them to change dramatically in human cells. This assumption is strengthened by the fact that the mean CD147 protein and mRNA copy numbers we determined closely matched the values reported by Schwanhäusser and colleagues. A Markov-chain Monte Carlo scheme was then performed to infer the extrinsic variability and kinetic parameters from E[M(t)], E[P(t)], E[M(t)^2], and E[P(t)^2] (Figure 6B; Table S1). We used those parameters to computationally predict the mRNA-protein correlation E[M(t)P(t)] and checked its consistency with its experimentally measured counterpart (which was not used to fit the model parameters) to cross-validate our model. The data collected on different days were analyzed separately. We found that for four out of five experiments, the model predictions of mRNA-protein correlation agree very well with the experimental data (Figure 6C), indicating that for the considered CD147 expression system the proposed two-state model provides a suitable mathematical description.

DISCUSSION

We achieved digital protein quantification by combining PLA with digital-PCR. Furthermore, we were able to integrate RT-ddPCR into the same practical workflow, thus allowing us to measure absolute and ultrasensitive protein and mRNA copy numbers from single cells. The application of a modified digital PCR protocol to protein measurements resulted in high sensitivity, since digital PCR is better suited to detect small concentration differences than conventional qPCR. As a result, digital PLA enables the quantification of small changes in protein concentration (as few as 70 proteins/μl in the ddPCR solution and 8,000 proteins in single-cells) over the entire dynamic range of the assay (Figure 2). This high sensitivity is necessary for an accurate analysis and understanding of single-cell variability. The femtomolar detection limit and high sensitivity of digital PLA allowed us to spare a fraction of the single-cell lysate for mRNA quantification, where the mRNA molecules are counted using a two-step reverse transcription and droplet digital PCR protocol.

In addition to high sensitivity, digital PLA is very practical, as it does not require any genetic manipulation in the host cell or sophisticated microfluidic device manufacture, and all of the required hardware and consumables are commercially available. The method can thus be rapidly adapted by other laboratories and can be used to quantify macromolecules from primary cells. It can be generalized to any protein, provided that specific antibodies are available, and it can be used to quantify protein complexes. Indirect protein measurements like mass spectrometry can be accurately calibrated with digital PLA measurements. In addition to single-cell applications, digital PLA provides a sensitive method in detecting small changes in the concentrations of

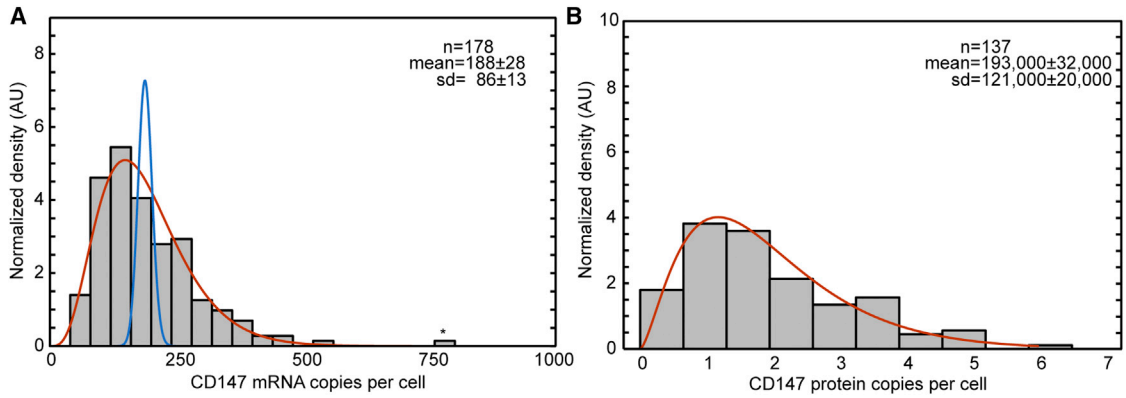

Figure 5. Fitting of Probability Density Functions to Single Cell Copy Number Distributions

(A and B) Histograms of single-cell CD147 mRNA (A) and protein (B) copy numbers.

(A) Poisson (blue) and gamma (red) probability density functions (pdf) were fit to single-cell CD147 mRNA data. The mRNA is binned in groups of 40 copies per cell. p value of the gamma fits generated using a χ^2 test is 0.65. Outliers indicated by an asterisk (*) were not included in the fits. The mRNA distributions fit the gamma pdf well.

(B) Gamma pdf (red) fit to the CD147 protein data (binned in groups of 65,000 copies per cell). Measurements below the LOD were omitted, p = 0.24.

clinically relevant proteins, which is critical for early diagnosis of disease.

Digital PLA complements existing methods such as in situ PLA (Blazek et al., 2013; Söderberg et al., 2006). These methods, while having single molecule sensitivity, require small copy numbers and even spatial distribution of the fluorescent macromolecules so that each diffraction-limited spot can be attributed to a single molecule (Golding et al., 2005; Taniguchi et al., 2010). In contrast, our method has a dynamic range across several orders of magnitude, is suitable for any native mRNA and protein (provided that the abundance of mRNA is >52 per cell and $\geq\sim10^4$ copies per cell for proteins), and does not require appending a bulky fluorescent protein to the target protein (which may alter the regulation and abundance of the latter).

While mRNA and protein levels in bacteria are not well correlated (Taniguchi et al., 2010), population-averaged (bulk) analyses estimated a higher degree of correlation in mammalian cells (Schwanhäusser et al., 2011; Tian et al., 2004). Our single-cell measurements, however, show that CD147 mRNA and protein copy numbers are actually poorly correlated and that mRNA abundance serves as a poor surrogate for protein abundance (Figure 4B). A possible explanation for this discrepancy from theoretical studies is that noisy post-transcriptional mechanisms regulating the translation and maturation of similar membrane-expressed proteins could destroy the correlation between mRNA and protein abundance in single cells (Caldwell et al., 2014). Another possible reason is that fluctuations are diminished when averaging mRNA and protein over multiple cells, resulting in higher correlation among the two (Vogel and Marcotte, 2012). Whether the observed lack of correlation is a general feature of mammalian gene expression, or if there are other genes where mRNA and protein levels better correlate, needs to be further investigated.

Our single-cell measurements revealed practical ''rule of thumb'' values for transcription and translation and allowed us to construct an accurate stochastic model for central dogma in mammalian cells. We found that approximately 1,000 proteins are created from a single mRNA molecule in a single mammalian cell. Cell-to-cell variability in protein abundance ranges from 5- to 18-fold (for GFP-p65 and CD147, respectively), with a mean of approximately 100,000 proteins per mammalian cell.

Finally, we used our single-molecule mRNA and protein dataset to parameterize a stochastic two-state model of CD147 transcription and translation. Our unique dataset enabled us to empirically determine the mRNA-protein correlation term E[M(*t*) P(*t*)] for individual mammalian cells and validate its computationally derived counterpart. The agreement between the two terms (Figure 6C) showed that the two-state model described well the stochastic transcription and translation of CD147. The paired mRNA-protein data (i.e., the correlation term) may also be used as an additional input (i.e., in addition to the means and variances of the single-cell mRNA and protein values) for modeling the transcription and translation of a given protein, or investigating fluctuations in dynamic systems in response to a stimulus. Joint absolute mRNA-protein quantification can thus be used to accurately model the central dogma for any gene on a single-cell level.

Limits

The LOD of the described assay currently prevents single cell quantification of very rare protein species. Digital PLA sensitivity is limited by the affinity of the proximity probes and the fact that proximity ligation is conducted in bulk. Furthermore, the target protein is initially diluted by two orders of magnitude, with an additional greater dilution occurring during cell sorting and lysis. The intracellular contents of a single mammalian cell (V ≈ 1–10 pl) are diluted 10^5-fold when the cell is lysed in a 3 μl solution. We hypothesize that digital PLA sensitivity can be further increased by using antibodies with higher affinity and by conducting assay in smaller volumes. Currently, a single researcher can analyze up to 100 samples with digital PLA in a day using standard pipette-and-dish techniques, and this number can be doubled if only

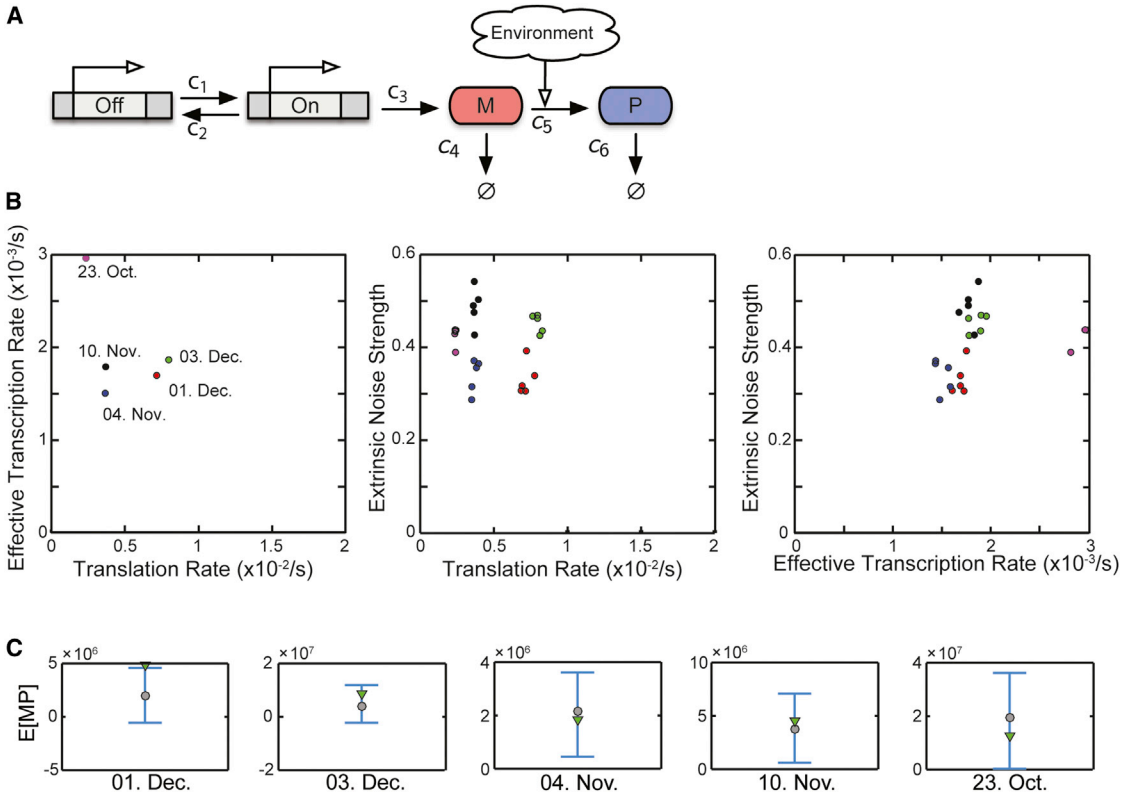

Figure 6. A Stochastic Model of CD147 Expression in Single Cells

(A) Schematic of the model. The gene stochastically switches between its inactive and active state, and mRNA can be transcribed only from the latter. The model comprises six kinetic parameters and an additional parameter describing the amount of extrinsic noise due to environment.

(B) Model parameters inferred from CD147 single-cell measurements shown in previous figures. The plot shows the inferred mean values for five independent repeats of the inference algorithm, indicating little variability across individual runs.

(C) Model validation. The inferred model was used to predict the correlation between mRNA and protein, i.e., E[M(t)P(t)]. The obtained results were compared against the experimentally measured correlation as revealed by our measurements. Markers indicate predicted (triangles) and empirical (circles) correlations, and the whiskers indicate 5% and 95% quantiles of the latter. In four out of five cases, the predictions agree well with the experimental data. Posterior estimates of the fitted model parameters can be found in Table S1.

protein or mRNA are quantified. While the use of such practical techniques provide familiarity and wider use by the community, integration of advanced microfluidic devices or pipetting robots would significantly increase the throughput. Another limitation of the PLA assay is its specific requirements on the used antibodies. Since two antibodies need to bind the antigen at the same time, and the exact position of an antibodies epitope is often unknown, it can be necessary to screen several antibody pairs until a working PLA probe set is found.

EXPERIMENTAL PROCEDURES

Construction of Calibration Curves for Digital PLA

For GFP and ICAM-1, a dilution series of each protein in 1X PBS (pH 7.4) was prepared; pure 1X PBS was also included in the workflow to account for background signal in the absence of protein. For CD147, the pure protein standard was diluted either in lysate dilution buffer (LDB) or 0.1X TM buffer instead of PBS; the diluent buffer was also included to account for background signal. 2 μl of each protein dilution was combined with 2 μl assay probe solution containing both proximity probes (at 400 pM each, thereby giving a final probe concentration of 200 pM) in 8-well PCR strips, and the mixture was incubated at 37°C for 1 hr. After proximity probe adsorption, the protein solutions were diluted 25-fold by adding 96 μl of ligation solution; the resultant solution was incubated at 37°C for 10 min. 2 μl of a diluted protease solution was added, and the mixture was incubated at 37°C for 10 min to terminate the ligation reaction; this step was followed by 15 min incubation at 95°C for inactivation of the protease. The proximity probes, ligation, and diluted protease solutions were prepared as per manufacturer's instructions.

For the (ddPCR) step, 9 μl of the resultant PLA solutions (or 1 μl in the case of ICAM-1) was combined with 10 μl of 2X ddPCR Supermix for Probes (Bio-Rad) and 1 μl of 20X Universal PCR Assay (Life Technologies) solution. For ICAM-1 quantification, 8 μl of deionized sterile water was added to bring the total volume to 20 μl. All of the solutions were mixed by pipetting up and down multiple times. The resultant 20 μl ddPCR solutions were transferred to DG8 cartridges, emulsified by the QX100 Droplet Generator (Bio-Rad), and the emulsions were placed in a Veriti thermal cycler (Life Technologies) for PCR. The temperature schedule for PCR was: 1X, 95°C for 10 min; 40X, 94°C for 30 s followed by 60°C for 1 min; 1X, 98°C for 10 min; and the ramp speed was 2.5°C/s. After, the emulsions were analyzed using the QX100 Droplet Reader and QuantaSoft software (Bio-Rad, v.1.3.2.0). Fluorescence from the emulsion droplets was quantified in the Absolute Quantification setting, and the signal threshold was manually set by applying to all wells the threshold value determined by automatic analysis of one of the most concentrated samples (Figures S1A and S1B). Once the threshold is set, QuantaSoft uses the following equation

to convert the numbers of positive and negative droplets (i.e., droplets with and without DNA) into concentration (Pinheiro et al., 2012):

$$C = \frac{-1,000}{V_d} \ln\left(1 - \frac{P}{R}\right),$$

where C denotes the DNA concentration in number of molecules per μl of ddPCR solution, V_d denotes the mean droplet volume in nl, P denotes the number of droplets with DNA (i.e., positive droplets), and R denotes the number of total (i.e., positive and negative) droplets. In the "merged" analysis setting, QuantaSoft gives both concentration and 95% confidence limits for a series of technical replicates. The SD of the DNA concentration can be calculated using this equation:

$$SD = \frac{CI_{max} - CI_{min}}{2 * 1.96},$$

where SD denotes standard deviation of the DNA calculation and CI_{max} and CI_{min} denote the upper and lower limits of the 95% confidence interval (given as "TotalConfMax" and "TotalConfMin" in QuantaSoft), respectively.

It has recently been reported that the used version of QuantaSoft software is using a wrong droplet volume (0.91 nl instead of 0.85 nl) to calculate concentrations (Corbisier et al., 2015), introducing a 10% error in the DNA concentration. By making calibration curves, however, we already correct our measurements for such errors. Therefore, the reported protein concentrations are not affected by the error in droplet volume. The same is true for the mRNA measurements, where the measured recovery rate accounts for this error as well.

The assay LOD of 107 GFPs per μl ddPCR solution corresponds to 24,200 GFP-p65s per cell due to the 113-fold dilution in the digital PLA workflow. Individual RAW macrophages were sorted into and lysed in a 2 μl solution, which was then diluted 51-fold prior to ddPCR. 9 μl of the PLA solution was added to the ddPCR mixture, whose final volume was 20 μl. The successive dilutions can be summarized as:

$$\frac{\text{Total Protein}}{2\ \mu l} \times \frac{1}{51} \times \frac{9}{20} = [\text{Amplicon}].$$

In the case of joint mRNA/protein detection where only 2 μl of the initial 3 μl are used for PLA, an additional 1.5-fold dilution needs to be taken in account.

Different proximity probe concentrations were used in optimization experiments shown in Figures S1C and S1D. In addition, after the probe adsorption step, the protein solutions were diluted either 2- or 25-fold by adding 4 or 96 μl of ligation solution, respectively. Component concentrations in the ligation solutions were adjusted accordingly to obtain the standard ligase and buffer concentrations in the final mixture.

Protein Quantification from Mammalian Cells

2 μl cell lysate (instead of the diluted protein solution) was taken through the PLA workflow as explained above. For CD147 protein quantification from HEK cells, 2 μl of cell lysate (3 μl total) was processed in digital PLA, while the remaining 1 μl was used in CD147 mRNA quantification. Error in absolute single-cell protein abundances was calculated by multiplying the single-cell protein amount with the coefficient of variance (CV) of the measured DNA concentration after digital PLA. A separate calibration curve was constructed on the same day as single-cell CD147 abundances were quantified to account for (albeit small) day-to-day variation in assay sensitivity and background (Figure S1G). A representative example of a daily CD147 calibration curve, together with the measured single cell data can be found in Figure S3E. The GFP-p65 values from individual cells were calculated using a GFP calibration curve from a single day. GFP calibration curves were highly variable on different days (Figure S1F), due to different aggregation levels in protein standards (Krasowska et al., 2010) (M. Shannon and D. Ruff, personal communication). CD147 was thus chosen as the model protein for further method development.

CD147 mRNA Quantification from Human Cells

1 to 100 Tlr4-GFP HEK293T cells were sorted by FACS into 3 μl of 0.1X TM lysis buffer for CD147 mRNA and protein quantification. 1 μl lysate was taken through the two-step RT-PCR workflow, while the remaining 2 μl of cell lysate were used for protein quantification as explained above. Probe 2 end primers and hydrolysis probe (i.e., CD147 TaqMan Gene Expression Assay, Cat. No. Hs00174305_m1) were used, and 40 cycles of amplification were conducted during the ddPCR step (Figures S4A–S4C). Fluorescence from the emulsion droplets was quantified using the QuantaSoft software; the obtained DNA concentrations and SDs were converted to single-cell CD147 mRNA values, accounting for the mRNA recovery rate determined using a synthetic CD147 mRNA standard (87.6%, see Supplemental Experimental Procedures). When multiple cells were sorted into a single well, the mRNA counts and the error were divided by the number of cells sorted to report the values on a per cell basis.

Error Bars

Unless stated otherwise, data are presented as mean ± SD.

Supplemental Experimental Procedures

Detailed information about "Reagents," "Cell Culture," "Fluorescence-activated sorting of mammalian cells," "Bulk protein lysate preparation," "Transfection of 3T3 cells," "Bulk RNA extraction," "Optimization of CD147 mRNA quantification," "Generation of artificial RNA standard," "Fitting of probability density functions (pdf)," "Derivation of gene burst rate and burst size from the parameters of a gamma distribution," "Moment-based modeling of CD147 expression," and "Inference of model parameters" can be found in the Supplemental Experimental Procedures section.

SUPPLEMENTAL INFORMATION

Supplemental Information includes five figures, one table, and Supplemental Experimental Procedures and can be found with this article online at http://dx.doi.org/10.1016/j.molcel.2016.02.030.

AUTHOR CONTRIBUTIONS

C.A., C.A.J., C.A.B., and S.T. designed the research. C.A., C.A.J., and J.L. performed the experiments and analyzed the data. C.Z. and M.K. built the two-state stochastic model and conducted the computational analysis. C.A., C.A.J., C.Z., M.K., and S.T. wrote the manuscript.

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