A quantitative pipeline for whole-mount deep imaging and multiscale analysis of gastruloids

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Whole-mount 3D imaging at the cellular scale is a powerful tool for exploring the complex processes of organoid morphogenesis, as it allows examining tissue architecture, cell types, and morphology simultaneously in 3D models. To address the challenges of whole-mount imaging in dense and diffusive tissues, we focused on gastruloids—3D embryonic organoids derived from mouse embryonic stem cells that replicate key aspects of *in vivo* organogenesis and present significant imaging challenges. We developed an integrated two-photon microscopy pipeline to image immunostained and cleared gastruloids *in toto*, achieving detailed visualization at both cellular and whole-mount scale. Our pipeline, implemented in Python with a Napari interface, includes image preprocessing to correct optical artifacts and segment individual cell nuclei. This enables comprehensive quantitative analysis of gene expression patterns, cellular events, and morphologies across multiple spatial scales using an interactive post-processing pipeline. This approach not only advances our understanding of gastruloids development but also lays the groundwork for applying these methods to other organoid and tumoroid systems, enhancing our ability to study a wide range of 3D biological models.

INTRODUCTION

Understanding organoids and tumoroids development and variability at multiple scales. The biology of organoids and tumoroids represents a frontier in fundamental biology and biomedical research, driven by the need for accurate 3D models complementary to 2D cell cultures and animal studies [1, 2] in the context of the "3Rs" (Replacement, Reduction, and Refinement) aimed at minimizing the use of animals in research and enhancing ethical experimental practices [3]. Developing these models in 3D is crucial for mimicking the complex architecture and functionality of tissues, enabling deeper insights into developmental or disease mechanisms and treatment responses [4, 5]. Organoids models exhibit less stereotypic development compared to embryos, where cell identification is typically straightforward based on position within the embryo at specific developmental stages [6, 7]. In contrast, organoids present more complex developmental trajectories [8–11], characterized by variability in morphology, cell type composition, and differentiation levels. This variability may stem from differences in the initial cell differentiation state or number [12], as well as from a less controlled biochemical and mechanical environment than that of embryos [13], which grow confined within maternal tissues for mammals or in a rigid shell for insects [14]. This inherent variability underscores the need for detailed characterization of a sufficient number of organoids in parallel to properly characterize the diversity of their developmental processes. To this end, coarse-grained methods have been developed to classify phenotypes of intestinal organoids [15] and gastruloids [16, 17] by analyzing maximum projections from 3D immunofluorescence staining using high-throughput confocal imaging. These approaches are effective for systematically screening the impact of chemical compounds or signaling pathway perturbations on organoid morphology, as well as on the localization and proportion of various cell types and tissues within the organoid.

However, understanding how organoids or tumoroids develop and self-organize also requires capturing how stem cells or cancerous cells differentiate and modulate their behavior and morphology in response to their local microenvironment [18, 19]. Simultaneously, it is essential to quantify tissue characteristics at a more coarse-grained scale (where each measurement integrates data from groups of several neighboring cells) to capture the mechanical and biochemical interactions among different tissues and cell populations within the overall geometry of the organoid [20]. To achieve this, a challenge is to image these 3D tissues *in toto* at a resolution sufficient to identify each cell and its neighbors both in live and fixed samples [21]. On fixed samples, multiple specific fluorescent markers can be used to capture cell fate by measuring the expression levels of particular genes or proteins

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by immunostaining or in situ hybridization. Complementary, live imaging is essential for understanding how local cellular events (division, migration, rearrangements) underlie the morphogenesis of these systems, as it has been done previously for embryonic development [22, 23].

Imaging organoids *in toto* at cell resolution. Recently, light-sheet and confocal imaging systems have been optimized for parallel imaging or long-term live imaging of organoids [24–27]. Using deep-learning-based segmentation, tracking, and classification tools, these protocols generate digital atlases of developing organoids at single-cell resolution. For example, [25] employed a dual illumination inverted light-sheet microscope to live-image gut organoids over several days, enabling cell lineage reconstruction from nuclei tracking. In [26], a single-objective light-sheet microscope was used to image tens of 3D tissues, such as gut, hepatocyte, and neuroectoderm organoids, in parallel for phenotypic classification.

However, light-sheet and confocal imaging approaches remain limited to relatively small organoids (typically under 100 micrometers in diameter) [24, 28, 29] or hollow organoids with cavities, lumens, and epithelial structures [25], making them less optically opaque than larger organoids like gastruloids [30, 31], neuromuscular organoids [32], or cancer spheroids [33], which can reach diameters of 300 microns and more.

For such tissues, multiphoton microscopy provides a powerful alternative due to its ability to penetrate deep into thick tissues with minimal photodamage [34]. This technique utilizes longer wavelengths of light to excite fluorescent molecules within the specimen, allowing the visualization of cellular structures and interactions in high resolution [35]. Furthermore, it avoids drawbacks of confocal or light-sheet microscopy on large, densely packed samples, such as strong intensity gradients, image blurring, and reduced axial information due to light scattering, aberrations, degradation or divergence of the light-sheet [36].

Gastruloids: a toy model for an integrated pipeline to analyze organoids development *in toto* at cell resolution. We have recently developed two-photon live imaging protocols to image developing gastruloids over multiple hours [31, 37]. Gastruloids are mouse embryonic stem cells that self-organize into 3D embryonic organoids, sharing similarities with their *in vivo* counterparts [30]. Recent studies have shown that, within a few days, gastruloids undergo significant morphological changes, developing structures that closely resemble organs both genetically and morphologically, such as neural tube-, [38] gut-, and cardiac-like structures [39]. Live two-photon imaging of gastruloids around their mid-plane has enabled us to propose biophysical models for their early symmetry breaking and elongation, using coarse-grained 2D analysis of collective tissue flows and gene patterning [37]. However, investigating in a full 3D context the relation between cellular fate and local tissue architecture during gastruloids morphogenesis [40] is still a key challenge. Indeed, it necessitates imaging *in toto* these dense 3D cell aggregates, which have a typical diameter above 200 microns and are highly light-diffusive objects.

In this work, we present an integrated pipeline to: (1) image multiple immunostained and cleared gastruloids in whole-mount configuration using two-photon microscopy, capturing both *in toto* and cellular scale details; (2) process and filter the resulting 3D images to correct optical artifacts from deep imaging and segment individual cell nuclei; and (3) analyze gene expression patterns, cellular events, and morphologies in 3D across multiple spatial scales (Fig.1).

I. RESULTS

An experimental and computational pipeline for *in toto* organoid imaging. We have developed a versatile pipeline to image, process and analyse tens of immunostained gastruloids (with diameters ranging from 100 to 500 μm). The experimental pipeline consists of sequential opposite-view multi-channel imaging of cleared samples, imaged with a commercial two-photon microscope (Fig.1). Afterwards, multiple processing steps are performed to extract meaningful information from the aquired images: i) spectral unmixing to remove signal cross-talk, ii) dual-view registration and fusion to reconstruct *in toto* images, iii) sample and single cell segmentation, and iv) signal normalization across depth and channels. Finally, reconstructed *in toto* images are analyzed at different scales, from cell-level correlations of different genes to coarse-grained maps of gene expression patterns, cell shapes, densities, and division events. All processing and analysis tools are open-source and Python-based. They are openly accessible as notebooks and interactive Napari plugins.

***In toto* multi-color two-photon imaging.** To facilitate dual-view imaging, we mounted immunostained gastruloids between two glass coverslips using spacers of defined thickness (typically $250 - 500\,\mu m$, adapted to match the size of the gastruloids without compressing them), allowing us to image the sample iteratively from two opposing sides (Fig.2a, see Methods III A 3). To optimize imaging performance, we compared several refractive index matching clearing agents, glycerol [41], ProLong Gold Antifade mounting medium (ThermoFisher), and optiprep [42], on gastruloids labeled with Hoechst nuclei stain (see Methods III A 1). We identified 80% glycerol as the mounting medium with best clearing performance (Fig.2b, Fig.S1c), leading to a 3-fold/ 8-fold reduction in intensity decay at $100\,\mu m$/ $200\,\mu m$ depth compared to mounting in phosphate-

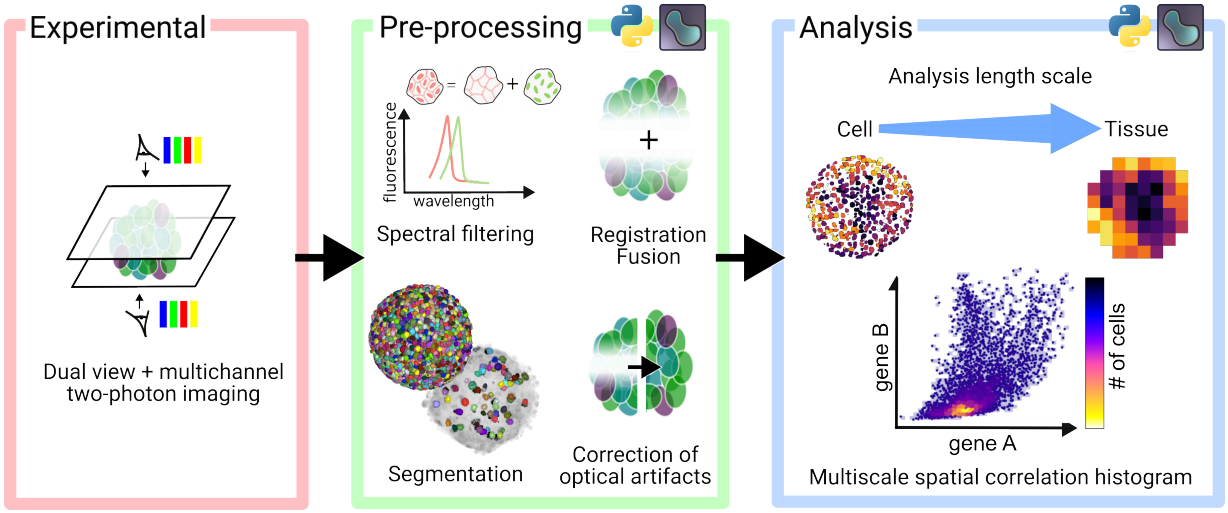

Fig. 1. **Overview of the experimental and computational pipeline for *in toto* imaging of organoids at cellular resolution and multiscale analyses.**

buffered saline (PBS) and superior performance to gold antifade and live-cell compatible optiprep medium (Fig.S1c). At these depths, information content was significantly improved by 1.5- and 3-fold, quantified using Fourier ring correlation quality estimate (FRC-QE) [43] (Fig.2c). Segmenting cell nuclei in images acquired on glycerol-cleared samples reliably detected cells at depth up to 200 μm, whereas a continuous decline in cell density was observed for PBS mounting, with four times fewer cells detected at 200 μm depth (Fig.2c, see details on the segmentation in the next section). These degradation effects were much more pronounced in confocal imaging even in glycerol clearing, which showed 2× lower intensity and 8× lower FRC-QE than two-photon imaging at 100 μm depth (Fig.S1a,b). Nevertheless, two-photon microscopy in glycerol beyond 200 μm depth suffered from decreased signal-to-noise-ratio (SNR) (Fig.2b,c). To properly image larger gastruloids *in toto*, a second detection side was required. We, therefore, flipped the sample slide and re-imaged the same set of gastruloids from the opposing side. Whereas the flipping was done manually, all mounted gastruloids were imaged automatically after defining their positions in the imaging software. A typical acquisition took about 5-10 min per gastruloid per side for 1 μm z-spacing and full field-of-view (318 μm with 0.62 μm pixel size at 40× magnification). To reconstruct *in toto* image stacks, we automatically identified opposite views of the same gastruloid by applying a pattern matching algorithm to gastruloids positions in the two acquisitions (Fig.2d, see Methods III F). Next, we registered each pair of image stacks acquired on the same aggregate using a rigid 3D transformation determined by a content-based block-matching registration algorithm [44] previously applied for multi-view and time registration of light-sheet imaging data [6, 7]. Finally, the registered image stacks were fused using a sigmoid decay function to weigh contributions of the two sides (Fig.2e,f and S4). The registration was performed on the ubiquitous nuclei channel, i.e. Hoechst staining. In some instances, flipping of the slide resulted in additional minor rotations (on average $(-13 \pm 11)^\circ$, $(3 \pm 18)^\circ$ and $(5 \pm 10)^\circ$ around the X-, Y-, and Z-axis for n=37 aggregates), which occasionally prohibited convergence of the registration algorithm (Fig.2g). For these cases, we implemented a Napari plugin to pre-register the images manually and visualize the result in 3D (Fig.6). Fused gastruloid images exhibit about 4-fold lower intensity in the mid-plane compared to the outer ends, but approximately constant FRC-QE across depth (Fig.2f).

A common limitation in fluorescence imaging is the low number of targets that can be excited simultaneously and spectrally discriminated. To image multiple targets in parallel, we excited four fluorophore species (Hoechst, AF488-, AF568-, AF647-tagged secondary antibodies on immunostained gastruloids) simultaneously. Thanks to the broad two-photon excitation spectra, the four dye species could be excited with just two laser lines, 920 nm and 1040 nm. However, detecting their emission simultaneously on four non-descanned detectors resulted in significant signal cross-talk, due to spectral overlap (Fig.2h-j). We circumvented this problem by applying spectral decomposition [45]. We calibrated spectral patterns, i.e. apparent emission spectra for each separate fluorophore species, in gastruloids stained with a single fluorophore species, and used these as reference patterns to decompose multi-color data (Fig.2h). Because of chromatic effects due to dispersion, spectral patterns were not constant at different depth in the sample. For example, shorter wavelength emission decays stronger with imaging depth than longer wavelength fluorescence (Fig.S1d). To account for this, we performed the unmixing with depth-dependent spectral patterns (see Methods III E).

Thereby, we could significantly remove cross-talk, for example, false positive cells in the far-red detection channel that resulted from cross-talk of bright cells visible in the red channel (Fig.2i,j). Notably, spectral decomposition with four-channel detection was even possible for spectrally strongly overlapping fluorophores, which we verified on gastruloids with transgenic H2B-GFP expression in the nuclei, stained with E-cadherin (Ecad)-AF488 at cell membranes (Fig.S1e,f). We thus applied spectral unmixing to all data presented throughout this work. This way, we could generate cross-talk free four-color images of several biologically relevant markers imaged simultaneously in multiple gastruloids in the same experiment (Fig.2k, Suppl.Movies 1-3).

Single cell segmentation. Quantifying cell-scale gene expression and nuclei morphological properties requires accurate instance segmentation of individual nuclei. In early-stage gastruloid datasets acquired with two-photon microscopy, accurate segmentation of nuclei is hindered by high nuclei packing (Fig.2b), shape heterogeneity, and spatially varying SNR due to optical aberrations and scattering, especially deeper in the sample. We thus trained a custom Stardist3D [46] model to segment nuclei, as it excels with separating star-convex objects in close contact.
A mid-plane section of the StarDist prediction is shown Fig.3a, exhibiting a qualitatively good result on outer layers as well as inner part of the sample. To increase robustness, the network was trained on three datasets acquired with two-photon microscopy in different experimental conditions, namely on (1) live-imaging of Histone 2B (H2B)-GFP gastruloids, (2) live-imaging of sparsely labeled mosaic gastruloids (composed of a mix of 75% of non-fluorescently labeled cells and 25% of cells expressing H2B-GFP under the Brachyury gene promoter [31]), and (3) 96 h fixed samples stained with Hoechst. This combined dataset presented variations in labeled nuclei density, nuclei texture, and in voxel dimensions (Fig.3b, see table I). In total, we annotated 4414 nuclei in 3D and used data augmentation (see Methods III G) to enrich the training datasets (Fig.3b). Both during training and inference, we normalized the intensity of the datasets by equalizing intensity histograms computed in local windows. This step was crucial to homogenize the intensity distribution across and inside datasets during training, and improved segmentation quality by reducing the number of false detections at depths at which the SNR is reduced. To assess the performance of the training, we manually annotated few 2D planes at different depths throughout a sample, and compared the result of StarDist3D to the ground truth (Fig.3c), in terms of nuclei detection and volume reconstruction. To evaluate the performance, we computed the recall and the precision (resp. quantifying how many relevant items are retrieved and how many retrieved items are relevant), and the F1 score as the average between the two. We show in Fig.3d that our trained model recovers a constant precision and recall across the full depth, and the F1 score is superior to 0.8 up to intersection over union (IoU) threshold 0.5. Comparing the recall and precision to the ones obtained with global normalization, i.e., image normalization based on the percentiles of the whole image, our local normalization mitigates both false positives and false negatives in deeper z planes (Fig.S2). Furthermore, by computing the IoU of 3D objects based on a 2D image, we obtain a lower bound of the estimated score: for some nuclei, the network prediction was accurately detecting the item on the planes right above or below, but the volumes of the nuclei were not completely recovered and in particular not in the annotated plane, where the score is computed. These instances are classified as false negative whereas the nuclei are actually segmented in 3D, and the same is true for false positives. Finally, we observed that the model preserves a constant cell density across depth in spherical gastruloids of up to 475 μm in diameter (Fig.3e).
Overall, our custom model achieved an F1 score of 85±3% at 50% IoU, this F1 score being a lower estimate of the performance in 3D. Using a variety of annotated datasets and a local normalization algorithm, we trained a powerful StarDist3D model that shows good segmentation performance regardless of depth and is robust to sample size and experimental conditions.

Maps of proliferation and cell density. Differential division and growth rates in tissues are key drivers of morphogenetic changes [47]. Therefore, quantifying tissue-scale gradients in cell proliferation is crucial for understanding the morphogenesis of gastruloids. To detect division events, we stained gastruloids with phosphohistone H3 (ph3) and trained a separate custom Stardist3D model using 3D annotations of nuclei expressing ph3. This allowed us to detect all mitotic nuclei in whole-mount samples for any stage and size (Fig.3f and Suppl.Movie 4). To probe quantities related to the tissue structure at multiple scales, we smooth their signal with a Gaussian kernel of width σ, with σ defined as the spatial scale of interest. From the segmented nuclei instances, we compute 3D fields of cell density (number of cells per unit volume), nuclear volume fraction (ratio of nuclear volume to local neighborhood volume), and nuclear volume at multiple scales. We plot each field on Fig.4a at three spatial scales ranging from the nuclei scale, i.e σ set to the average nuclear radius, to the tissue scale, i.e σ set to six times the average nuclei radius. Taking this smoothing approach, we computed fields of division density (number of division events per unit volume), that represent the local density of cells in mitosis, from the division labels detected on ph3 as described above. An increased volumetric division density can result from either elevated cell proliferation or higher cellular volumetric density. To distinguish between these effects, we computed a proliferation probability field that represents the local fraction of cells undergoing mitosis within the 3D sample (by dividing the division density field by the

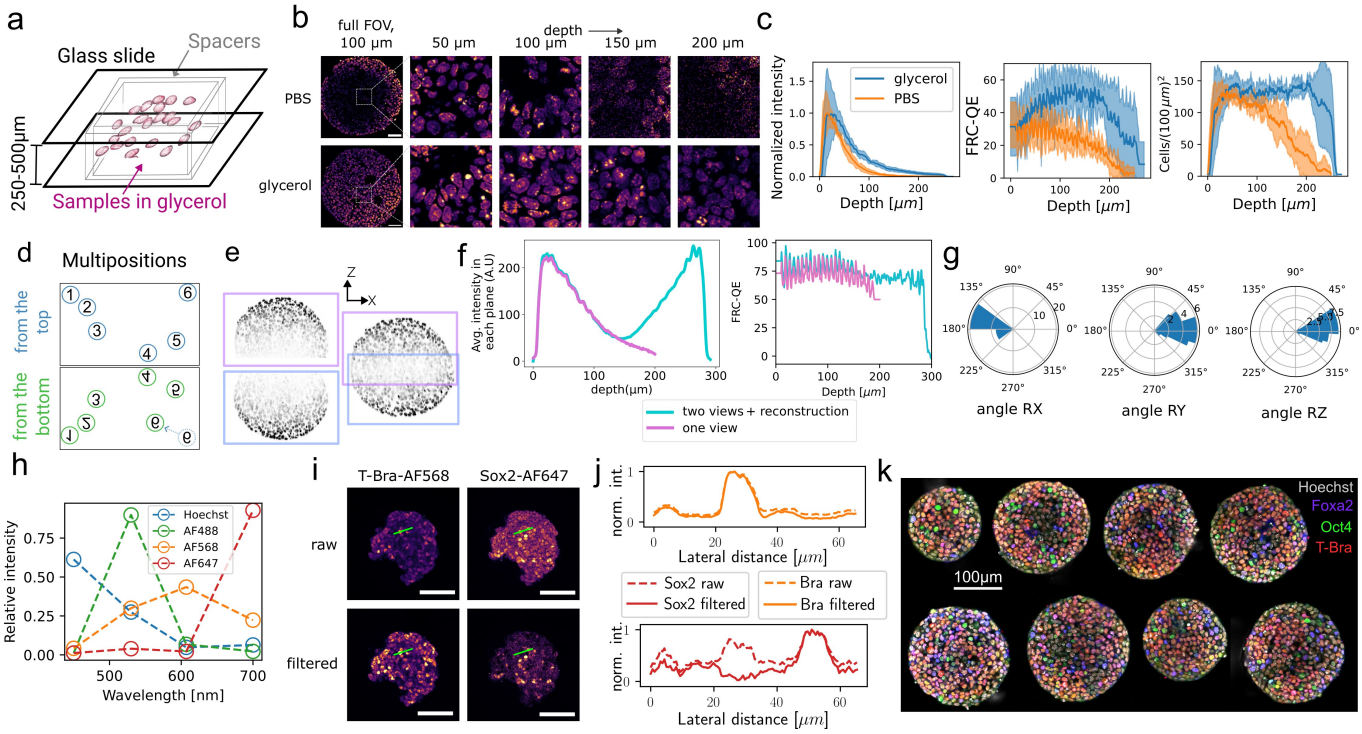

Fig. 2. **Dual-view multi-color two-photon imaging.** **(a)** Multiple gastruloids are mounted in glycerol clearing medium in between two glass slides using spacers. **(b)** Mounting gastruloids in 80% glycerol significantly improves imaging at depth compared to PBS mounting. Insets show images at different depth in a central square region of $60 \times 60\,\mu m^2$. **(c)** Quantification of intensity, FRC-QE image quality metric and density of segmented nuclei as a function of depth in the central region depicted in (b) for both glycerol- and PBS-mounted samples. Shaded areas show standard deviation for six (PBS) and nine (glycerol) gastruloids. **(d-f)** Top and bottom positions are assigned using a pattern matching algorithm that is robust to residual movements of individual gastruloids, as illustrated for position 6 (d). Respective image stacks are registered using rigid 3D transformations and fused applying sigmoid fusion weights (e). This leads to *in toto* coverage of whole gastruloids, in which individual cells are still visible in the mid-plane (e), as shown for a gastruloid of typical size of $250\,\mu m$ diameter. The average intensity per plane and FRC-QE are shown in (f) for one- and dual-view images. **(g)** Polar histogram plots of rotation angles around X-,Y-, and Z-axis from the 3D registration of dual-view top and bottom acquisitions, pooled for 37 aggregates. The sample slide was flipped around the X-axis. **(h-j)** Multi-color detection using two-photon excitation can lead to significant spectral cross-talk, as shown in the apparent emission spectra detected on gastruloids stained with a single fluorophore species (h). Using spectral unmixing, false-positive signal due to spectral cross-talk is effectively removed, as shown in the raw and filtered images (here at $50\,\mu m$ depth) of gastruloids stained with T-Bra-AF568 and Sox2-AF647 (i) and the quantification of the intensity along a line (10 pixels width) across few nuclei for raw and spectrally filtered images (j). **(k)** Four-color images of the mid-plane of 77 h gastruloids stained with Hoechst, FoxA2-AF488, Oct4-AF568 and T-Bra-AF647, obtained with dual-view four-channel two-photon imaging and spectral unmixing. The gastruloids were acquired in the same experiment. Scale bars are $50\,\mu m$ in (b,i) and $100\,\mu m$ in (k).

cell density field). A cross-section of each of these 3D maps is represented in Fig.4b, showing a typical heterogeneous pattern of division density and cell density. These maps can be visualized in parallel for several samples, which allows systematic comparison of patterns for high-throughput acquisitions. Analyzing proliferation fields in 3D gives us insight on growth patterns during development and is key to understand and quantify gastruloid morphogenesis. Importantly, this quantification can be applied across various developmental stages, providing quantitative insights into growth phases under different stages or media conditions. A proliferation pattern for a strongly elongated 120 h gastruloid grown in a modified culture protocol is shown in Fig.S5b.

Morphometric analysis. Tissue-scale patterns of cell/nuclei deformations in developing embryos or organoids are good indicators of the existence of mechanical stresses which can contribute to tissue morphogenesis [48] and affect in return cell differentiation [49]. To explore changes in tissue structure and organization during gastruloid development, we studied spatial heterogeneities in cell densities and cell deformations emerging during the first morphogenetic phase of gastruloids development, which consists in a global tissue elongation between 72 and 96 h after their initial aggregation. We have shown in previous work [31, 37] that such elongation is associated with the polarization of the gastruloid, exhibiting a posterior pole rich in E-cadherin and con-

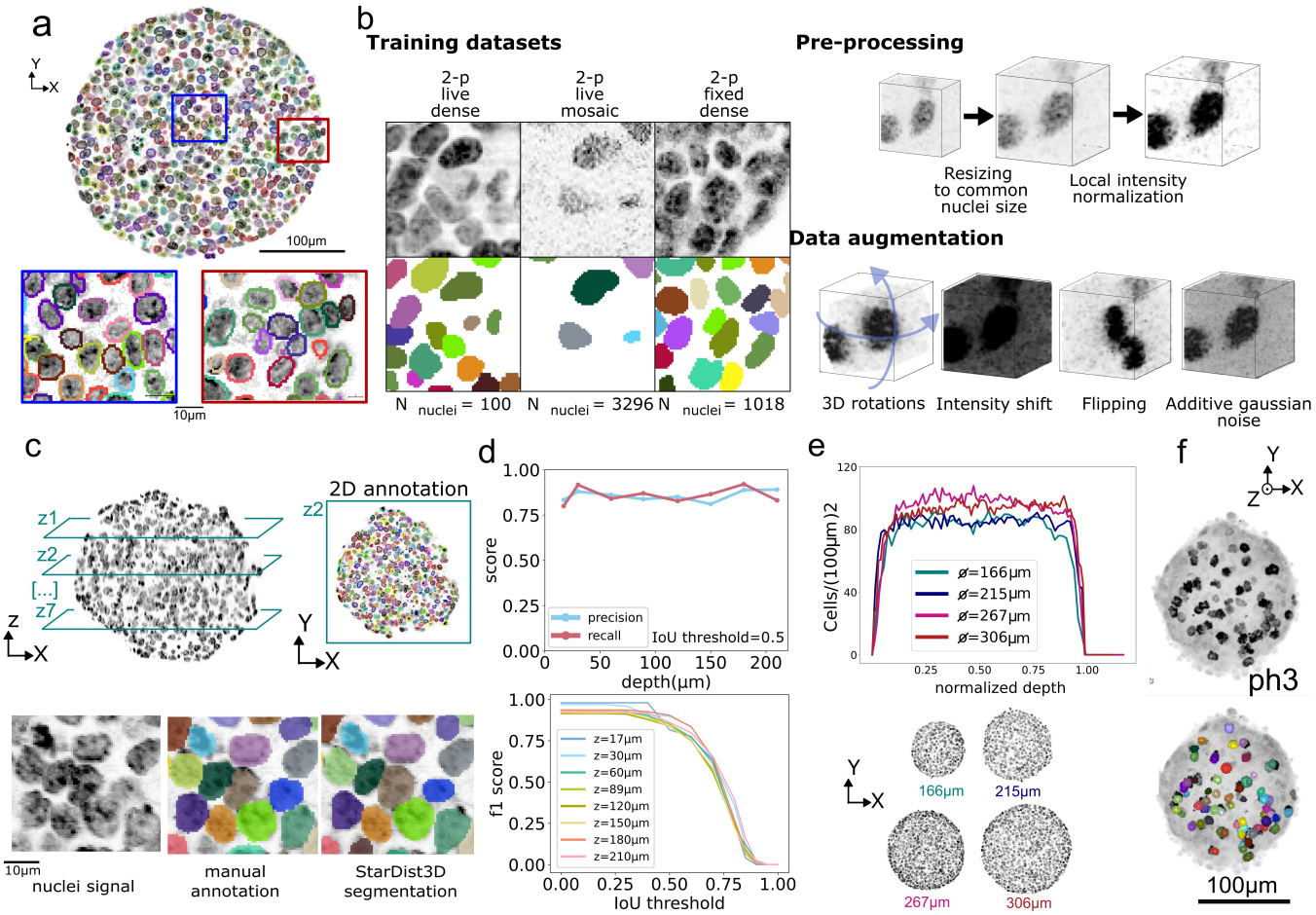

Fig. 3. **3D nuclei segmentation with StarDist3D. (a)** Exemplary segmentation (contours) of Hoechst stained nuclei (grey) using custom trained StarDist3D model. Insets show segmentation results in inner and outer cell layers, at 150 μm depth. **(b)** Three different datasets were annotated and used for training. Images show exemplary annotated patches (top row: intensity images, bottom row: label images). Before training, images were resampled to a common voxel size of $0.62 \times 0.62 \times 0.62\,\mu m^3$. Image intensities were equalized using local histogram stretching. During training, data augmentation was used to maximize training input. **(c)** To evaluate segmentation performance, entire z-planes were annotated at different depths in 2D, on a 250 μm size gastruloid imaged from two views and fused, and the segmentation result was compared with the ground truth. **(d)** Top : Precision and Recall at IoU threshold 0.5 as a function of depth. Bottom: F1 score as a function of IoU thresholds, color represents depth. **(e)** Cell density obtained from 3D segmentation of gastruloids of different diameters. The corresponding images at the mid-plane are shown at the bottom. **(f)** 3D rendering of the detection of mitotic cells using StarDist3D. Top image shows ph3 stained sample, bottom image shows detected cell divisions overlayed with the ph3 signal.

stituted of a mixed population of both endoderm and nascent mesoderm tissues, and an anterior pole poor in E-cadherin constituted of cardiac and vascular mesoderm tissues which are mesenchymal. Here, to prevent any relaxation of cellular deformation caused by tissue fixation, we performed 3D acquisition of live gastruloids with an H2B-GFP marker. We illustrate the full approach on a single sample in Fig.4c-d, and show that the results are reproducible across different samples (see Fig.S5a). The cell density field revealed a high level of heterogeneity at the nuclei scale, but analysis at different scales always showed the presence of two tissue-scale populations of low and high cell densities located respectively in the posterior and anterior part of the sample, separated by a sharp boundary characterized by the length scale of a few nuclei. These two populations and the boundary were also visible, although less clearly, from the nuclear volume and nuclear volume fraction fields, with the high-density population showing a higher nuclear volume fraction but lower nuclear volumes. The nuclear volume fraction indicates regions of high packing located in the high-density population, with a maximum of 61%, close to the theoretical value for random close packing of spheres (64%). As extra-cellular space volume fraction is low in such sample [37], this indicates high nuclei-to-cell volume ratios, which suggests that nuclei shapes are a good proxy for cell shapes, and thus nuclei could be relevant in cell-scale mechanotransduction processes.

To quantify cell deformation, we first computed the inertia tensor from each segmented nuclei instance and obtained the true strain tensor [50] for each cell (see Methods III K), which is a size independent measure of object deformation. This justifies averaging these tensors among nuclei with large size variations by effectively removing the size bias. We plot the major axis (associated with the largest eigenvalue) of the true strain tensor for each nucleus on Fig.4 at the nuclei scale. The major axis is oriented along the direction of the largest deformation of the nuclei. Close to the low-to-high density boundary, we observed that nuclei are elongated in the direction of the boundary, i.e perpendicular to the gradient of cell density. We further quantified this observation by computing the angle θ between the gradient of cell density and the major axis of the true strain tensors. In Fig.4d, we plot the continuous field representing the quantity $\cos^2(\theta)$ averaged at the tissue scale. For random orientations of the major axis with respect to the gradient of cell density, the average value of $\cos^2(\theta)$ is $1/3$, and the value approaches 0 or 1 for respectively perpendicular and parallel orientations. The field reveals a wide region with values below 0.1 around the boundary, confirming that nuclei are elongated along the tissue boundary. Other regions show comparatively smaller values of the local gradient amplitude or no tissue-scale alignment. These descriptions appear reproducibly in several samples, see Fig.S5a, and are consistent with an interpretation of the boundary as a region where mechanical stresses are generated between gastruloids anterior and posterior poles. This analysis also shows how nuclei shapes at small scales are appropriate proxies for deformation inside and around tissue micro-structures like lumen and cavities, which allows for an accurate description of the local epithelial architecture. At the tissue scale, nuclei shapes can serve as a proxy for tissue mechanical stresses in the context of tissues modeled as visco-elastic liquids with residual elasticity in cell deformation [51].

Quantitative analysis of gene expression at global and cell-scale level. A key interest in *in toto* imaging is that it allows quantifying expression gradients of genetic markers and proteins of interest across entire organoids. In the case of gastruloids, gradients of differentiation emerge during Wnt activation, prior or concomitant with symmetry breaking [16, 31, 52, 53]. Due to the previously mentioned limitations of light-sheet microscopy for *in toto* coverage and quantitative intensity analyses for gastruloids beyond $100-200\,\mu m$ diameter, investigations of such gradients have thus far been restricted to analyses of low resolution 2D images [16, 52]. Because of this limitation, it is still unknown when gradients of differentiation are established during gastruloid development. To explore this, we analyzed images of gastruloids fixed at 77 h, labelled with Hoechst and additionally immunostained with T-Bra, a mesendoderm marker expressed upon Wnt mediated cell differentiation. Previous investigations with 2D imaging indicated a gradient of higher T-Bra expression in outer cell layers and lower expression in the interior [31].

Although our dual-view imaging pipeline delivers *in toto* coverage, images of the ubiquitous Hoechst nuclei stain still exhibited intensity gradients along the z direction and between outer and inner cell layers (Fig.5a). We attributed these gradients to optically induced heterogeneities and developed a correction method that re-normalizes the channels of interest based on the local nuclei intensity. To this aim, we applied a convolution with a 3D Gaussian kernel to the Hoechst signal masked with the nuclei segmentation. The result of that convolution is a coarse-grained map of nuclei intensity, that we use to locally rescale every channel of the original image (Fig.5a). Since this normalization was done in 3D, the intensity values in the mid-plane of a gastruloid were enhanced while the intensities in the first and last z-planes remained constant (Fig.S7c). Furthermore, the method effectively and robustly homogenized nuclei intensities across gastruloids from different acquisitions and imaging conditions (Fig.S7d and e). We evaluated different standard deviations for the Gaussian kernel of the convolution and chose an optimal one, with a typical value around the diameter of the nuclei ($10-15\,\mu m$), that lead to the most homogeneous Hoechst signal after re-normalization (see Methods III I and Fig.S7f). This normalization scheme accounts for heterogeneities in gastruloids of arbitrary shape as well as local cell density and thus variations in the optical paths of excitation and fluorescence light rays that cannot be captured by a simple geometrical model.

When we applied the correction method to the T-Bra signal and evaluated re-normalized T-Bra intensity in a lateral section across the mid-plane of a 77 h gastruloid, we still observed a gradient with higher intensity in outer cell layers (Fig.5a), while the nuclei signal recovered a flat profile. Besides reflecting a true T-Bra expression gradient, a possible explanation for this observation could be hindered penetration of primary and secondary antibodies being considerably larger than Hoechst stain. To evaluate this, we compared immunostained T-Bra signal with the intensity of a T-Bra reporter (H2B-GFP expressed under a T-Bra promoter) in gastruloids grown from a transgenic cell line fixed at 72 h. We found a strong correlation between the two channels at all depths, excluding penetration artifacts (Fig.S6).

In addition to optical artifacts, our re-normalization method also corrects for intensity variations effectively induced by residual rotations of aggregates after flipping, which tilt the optical axis with respect to the axis of the first acquisition (Fig.2g). This is illustrated in Fig.5b, providing an example where the nuclei signal exhibits an asymmetrical gradient due to the fusion of two opposite views that were subject to residual rotations. After re-normalization, the nuclei profile is

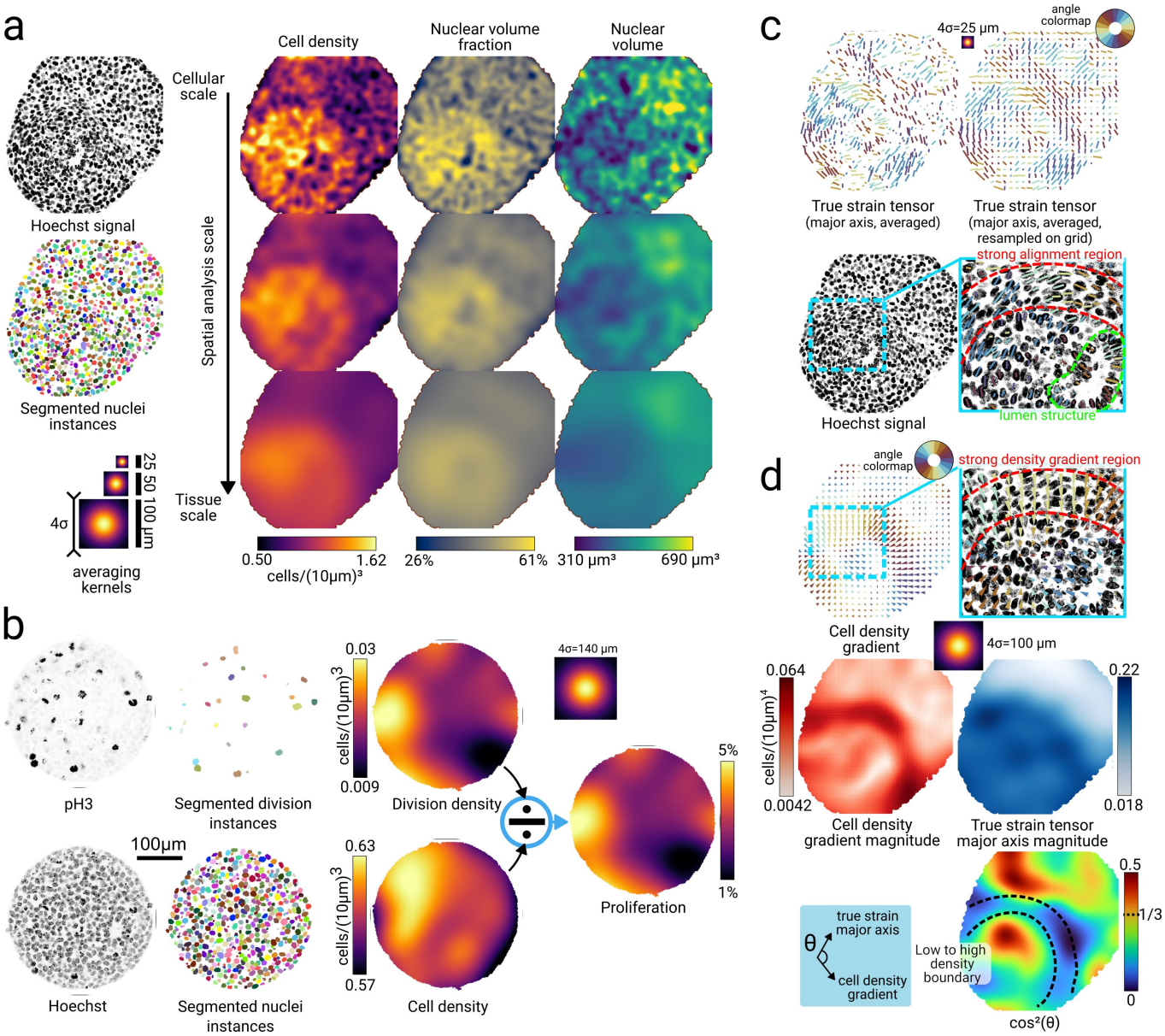

Fig. 4. **Cell-to-tissue scale morphological analysis.** **(a)** Segmenting individual nuclei instances in 3D allows a complete characterization of object packing by quantifying cell density, nuclear volume fraction, and nuclear volume. Each quantity is shown at three resolutions ranging from the cell scale to the tissue scale, which correspond to convolution with Gaussian averaging kernels with $\sigma = 6,\ 12$, and $25\,\mu m$, respectively. **(b)** Divisions stained with ph3 and nuclei stained with Hoechst are segmented using StardDist3D and used to compute respectively maps of division density and cell density. The proliferation is defined as the ratio of the division density with the cell density, showing the local fraction of cells undergoing mitosis. **(c)** Cell-scale fields of deformation, quantified by the major axis of the nuclei true strain tensors. A version sampled on a regular grid is provided for better readability. The deformation field reveals a region of spatially persistent alignment that overlaps with the density boundary and highlights nuclei forming the lining of a lumen. **(d)** We compute the tissue-scale field of squared cosine of the angle between the cell density gradient and the true strain tensor major axis to quantify local regions of anti-alignment. The vector magnitudes of the two fields are shown to add perspective to the analysis in regions where the gradient or the local deformation is small. All quantities shown in this figure are computed in 3D, but we show a single z-slice (vector quantities are projected onto the slice) for convenience.

homogeneous, whereas the profile in T-Bra drastically changed, showing a polarization in the opposite direction with respect to the initial gradient that was also visible both in the nuclei stain and T-Bra channel. This emphasizes the importance of our method to properly quantify gene expression gradients in 3D. The observed polarized T-Bra appearance is in agreement with our previous study, in which we have reported that T-Bra

expression already commences to be polarized at 77 h in some gastruloids [31].
We then applied the correction scheme to four-color 3D acquisitions of multiple gastruloids of different size (obtained by varying the initial cell number of the culture) imaged in the same slide, immunostained with T-Bra, the pluripotency marker Oct4, and the early endoderm marker FoxA2 (Fig.5c). We sorted these gastruloids into two groups and observed an approximately constant T-Bra expression for small aggregates ($193 \pm 20\,\mu m$ average diameter, n=8), whereas big aggregates ($291 \pm 15\,\mu m$ average diameter, n=5) showed a clear decay of T-Bra expression towards the interior (Fig.5c). Notably, we quantified T-Bra intensity as a function of distance to the gastruloid border using the *in toto* 3D image stack, thus reflecting expression gradients in 3D. For FoxA2, a similar pattern was observed, but expression appeared in much fewer cells (Fig.5d). Because FoxA2 signal was sparse and noisy, we could not compute simply the map of expression as done previously for T-Bra. To properly analyze the spatial expression of FoxA2, we first thresholded the signal in segmented nuclei, using the interactive visualization tools developed in Napari (see Fig.6 and Methods) to select an appropriate intensity threshold and inspect the signal and distribution of FoxA2 positive cells. From the distribution, we could qualitatively assess that more cells were expressing FoxA2 in outer layers. We then analyzed it quantitatively by generating a coarse-grained map of FoxA2 positive cell density fraction. This was done by computing the number of FoxA2 positive cells rescaled by the local nuclei density, using the same method as applied for proliferation analysis, except that we consider FoxA2 positive cells instead of ph3 positive cells. The coarse-grained map of FoxA2 positive cells was then analyzed radially for gastruloids of various sizes, small gastruloids of $193 \pm 20\,\mu m$ average diameter (n=8) and bigger gastruloids of $278 \pm 16\,\mu m$ average diameter (n=3). We observed higher FoxA2 levels in more outer cell layers, although more restricted in smaller and less restricted in bigger aggregates (Fig.5e) compared to T-Bra.

Our ability to image multiple expression markers in the same acquisition without cross-talk and to reliably segment all cells allows correlating expression of different genes at the single cell level. To demonstrate this, we analyzed correlations between T-Bra, Oct4, and FoxA2 in the data described above, after spectral filtering and intensity re-normalization. Both processing steps were crucial to obtain unbiased results (Fig.S7a,b). To discriminate marker positive from cells only showing background levels, we applied Otsu thresholding on the cells' intensity distribution for each marker and confirmed the distinction by visible inspection.
We expected that FoxA2 and Oct4 are mutually exclusive (since cells are either in the process of endoderm differentiation or still pluripotent). A similar behaviour was expected for T-Bra and Oct4/ T-Bra and FoxA2, although some co-expression could be present since T-Bra marks very early mesendoderm differentiation en route to meso- or endoderm and Oct4 is a relatively long-lived pluripotency marker [54].
We indeed observed that Oct4 and FoxA2 appeared as two mutually exclusive populations (Fig.5f, left). On the contrary, while the brightest Oct4 cells also showed low T-Bra signal and vice versa, a large pool of T-Bra and Oct4 positive cells (at low Oct 4 signal) appeared, not showing a striking correlation pattern for most cells (Fig.5f, center). For FoxA2 and T-Bra, a clear anti-correlation was observed, with cells appearing in all four quadrants (Fig.5f, right). Interestingly, we overall detected fewer FoxA2 positive cells than T-Bra positive cells. While we found many cells that were T-Bra positive and FoxA2 negative, most of the FoxA2 positive cells showed at least some T-Bra signal. This indicates that T-Bra expression might be required to activate FoxA2. However, cells expressing both markers still showed a negative correlation, suggesting that once FoxA2 is activated, T-Bra expression is repressed. Overall, these data suggest a sequence of cellular transitions from Oct4 progressively to T-Bra, from which a fraction of cells, presumably the ones expressing low T-Bra levels, will commit to FoxA2. To further explore such transitions and localize specific cell populations, tools that allow interactive mapping of cell populations selected in the correlation plot to the actual gastruloid are needed. We have, therefore, integrated this functionality into our Napari plugin (see Fig6). We believe that our integrated imaging and analysis pipeline will allow researchers to study cell differentiation and cell state transitions at different stages of gastruloid development for the first time in full spatial context.

Community-driven tools We packaged our preprocessing and analysis pipeline into a *Python* library called *Tapenade* (for "Thorough Analysis PiEliNe for Advanced DEep imaging"). The code is freely available on *Github* at github.com/GuignardLab/tapenade/. The library comes with an extensive documentation and *Jupyter* notebooks accessible to non-specialist users. All datasets used to train our custom *StarDist* models to detect nuclei and mitotic events, along with the optimized weights for nuclei and mitotic events detection are currently available upon reasonable request. A non-specialist user can quickly segment a custom dataset by downloading the weights and loading them into one of the user-friendly implementations of *Stardist* like the *Stardist Fiji* plugin, the *Napari* plugin *stardist-napari*, or the *ZeroCostDL4Mic* notebook [46, 55].
While working with large and dense 3D and 3D+time gastruloid datasets, we found that being able to visualise and interact with the data dynamically greatly helped processing it. During the pre-processing stage, dynamical exploration and interaction led to faster tuning of the parameters by allowing direct visual feedback,

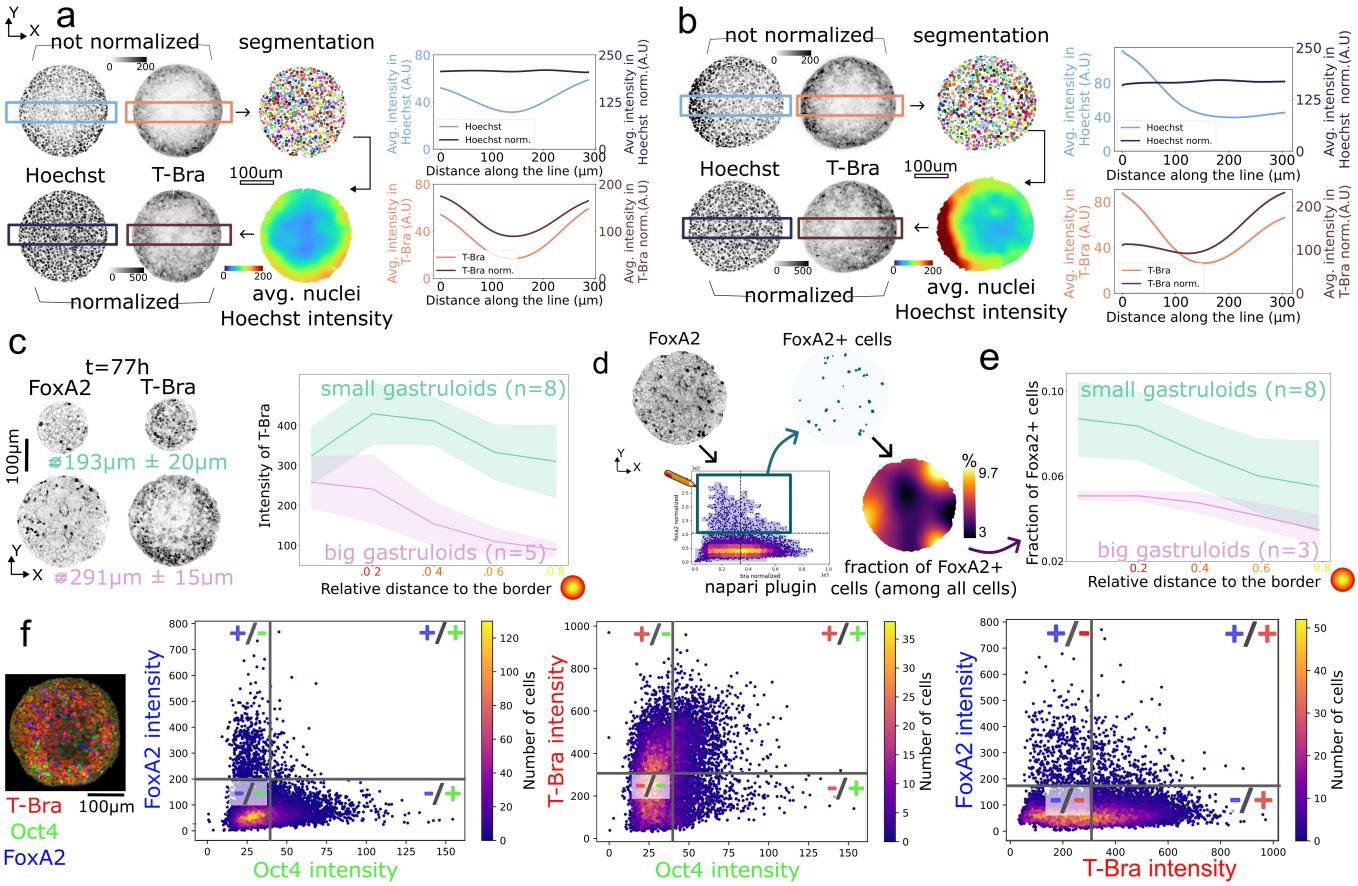

Fig. 5. **Coarse-grained and cell-level gene expression analysis. (a,b)** Images of Hoechst and T-Bra in the mid-plane of 77 h gastruloids. Using the nuclei segmentation, maps of averaged nuclei intensity were generated and used to locally re-normalize the T-Bra signal. The graphs on the right side of each panel show the intensity across rectangular sections of the mid-plane, shown in the images as blue/ brown boxes, before and after intensity normalization. This intensity profile is smoothed using a Gaussian kernel on the images to extract the large-scale intensity variations. (a) example of a radially symmetric gradient of nuclei intensity, from the exterior to the interior. (b) example of an asymmetric gradient, the left side of the sample has a high nuclei intensity that is corrected after normalization, changing the T-Bra profile (bottom right graph). **(c)** Images of 77 h gastruloids (mid-plane) of different size, immunostained for T-Bra and FoxA2 gene expression markers. From the re-normalized 3D images, radial intensity plots were generated for big ($291 \pm 15\,\mu m$ average diameter, n=5) and small ($193 \pm 20\,\mu m$ average diameter, n=8) gastruloids as a function of distance to the border. Shaded regions show standard deviations. **(d)** For one of the previously described samples fixed at 77 h, FoxA2 positive cells are visualized from the re-normalized data using the interactive Napari tools and the image thresholded accordingly. Using the binary image of FoxA2 positive cells, a map of local fraction of FoxA2 positive cells, rescaled by the local cell density, was computed, showing a radial pattern. **(e)** Analysis of the radial distribution, i.e. fraction of FoxA2 positive cells as a function of distance to the border, for big ($278 \pm 16\,\mu m$ average diameter, n=3) and small ($193 \pm 20\,\mu m$ average diameter, n=8) aggregates, computed from the coarse-grained maps as shown in (d). Shaded regions show standard deviations. **(f)** Three-color image of a 77 h gastruloid immunostained for T-Bra, Oct4, and FoxA2. The three plots show a cell-level correlation analysis of the three markers for the entire gastruloid. Each dot in the correlation plot represents an individual cell. Shown are all three marker combinations. Quadrants show regions of background signal (-) and actual expression (+) for each marker in the respective color, defined by Otsu thresholding.

and gave key biophysical insight during the analysis stage. We thus created three user-friendly Napari plug-ins designed around facilitating such interactions (Fig.6):

a. napari-manual-registration When using our automatic registration tool to spatially register two views of the same organoid, we were sometimes faced with the issue that the tool would not converge to the true registration transformation. This happens when the initial position and orientation of the floating view are too far from their target values. We thus designed a Napari plugin to quickly find a transformation that can be used to initialize our registration tool close to the optimal transformation. From two images loaded in Napari representing two views of the same organoid, the plugin allows the user to either (i) annotate matching

salient landmarks (e.g bright dead cells or lumen-like structures) in both the reference and floating views, from which an optimal rigid transformation can be found automatically using principal component analysis (Fig.6a), or (ii) manually define a rigid transformation by continually varying 3D rotations and translations while observing the results until a satisfying fit is found (Fig.6b). The plugin is freely available on the *Napari* hub or at github.com/GuignardLab/napari-manual-registration.

b. napari-tapenade-processing From a given set of raw images, segmented object instances, and object mask, the plugin allows the user to quickly run all pre-processing functions from our main pipeline with custom parameters while being able to see and interact with the result of each step (Fig.6c). For large datasets that are cumbersome to manipulate or cannot be loaded in Napari, the plugin provides a macro recording feature: the users can experiment and design their own pipeline on a smaller subset of the dataset, then run it on the full dataset without having to load it in Napari. The plugin is freely available on the *Napari* hub or at github.com/GuignardLab/napari-tapenade-processing.

c. napari-spatial-correlation-plotter This plugins allows the user to analyse the spatial correlations of two 3D fields loaded in Napari (e.g. two fluorescent markers). The user can dynamically vary the analysis length scale, which corresponds to the standard deviation of the Gaussian kernel used for smoothing the 3D fields. If a layer of segmented nuclei instances is additionally specified, the histogram is constructed by binning values at the nuclei level (each point corresponds to an individual nucleus). Otherwise, individual voxel values are used. The user can dynamically interact with the correlation heatmap by manually selecting a region in the plot. The corresponding cells (or voxels) that contributed to the region's statistics will be displayed in 3D on an independant Napari layer for the user to interact with and gain biological insight (Fig.6d). The plugin is freely available on the *Napari* hub or at github.com/GuignardLab/napari-spatial-correlation-plotter.

II. DISCUSSION

Multiscale imaging and analysis pipeline. We have developed an integrated pipeline for *in toto* imaging of whole-mount gastruloids and automated image processing. A key innovation of our approach is its specific optimization for dense 3D tissues, such as gastruloids, which present similar imaging challenges and artefacts as tumors and spheroids, unlike many organoids that are shallow and less light-diffusive. Unlocking deep whole-mount imaging is crucial for researchers working with such dense tissues, as cryosectioning strategies cannot fully substitute for comprehensive three-dimensional (3D) *in toto* analysis [18, 21]. Reconstructing 3D tissue microstructure from cryosectioned data is complex and challenging, involving slicing tissue into thin sections and imaging them individually. To achieve a 3D reconstruction, these 2D images must be meticulously aligned and stitched together, a process complicated by frequent issues such as tissue deformation and section loss. In contrast, whole-mount imaging preserves spatial relationships and tissue integrity, making it the method of choice for studying cellular interactions and tissue architecture in their native context. Additionally, whole-mount imaging reduces sampling bias and enhances the detection of rare cell populations or phenotypic variations that might be missed in thin tissue sections. This limitation also apply to state-of-the art spatial transcriptomic techniques, due to the fact that only few RNAs are typically captured per cell for each individual gene and many cells do not show any counts for a gene of interest expressed at low level [56].

A Python integrated pipeline for non-specialists, with Napari-enabled 3D exploration. We built our pipeline in *Python* to leverage its rich ecosystem of scientific computing libraries while keeping the code as accessible and user-friendly as possible. We provide detailed installation instructions and *Jupyter* notebooks with step-by-step instructions designed to be used by non-specialists, with a focus on ease of use and reproducibility. To tackle the challenges that arise from manipulating deep and dense 3D data, we provide *Napari* plugins for manual registration, pre-processing, and analysis. *Napari* provides a user-friendly graphical interface which enables real-time visualization and exploration of 3D data during each step of the pre-processing and analysis. This was essential for the development of the pipeline, as the direct visual feedback allowed us to quickly iterate and optimize the processing steps, while gaining insights into the 3D organization of gastruloids. We believe our pipeline offers a distinctive and effective integration of 3D data exploration and processing, providing a valuable tool for the organoid and tumoroids research community.

The pipeline currently requires users to pre-format their raw data to match specific formats (e.g., the pipeline accepts appropriately-shaped *tif* files, but in the case of batch processing temporal datasets can also be provided as folders of *tif* files that will be processed in parallel to avoid loading the entire dataset into memory). This requirement can be challenging for non-specialists unfamiliar with data formatting, which is why we plan in the future to address this limitation by expanding the pipeline to support a broader range of input data formats, making it more user-friendly and accessible. Secondly, in this work we have not used refined masks of the gastruloids that would account for and exclude hollow structures like lumen. In Fig.4(a) and (c), we noted that this lead to noticeable patterns in the packing-related coarse-grained fields and in the local alignment of the

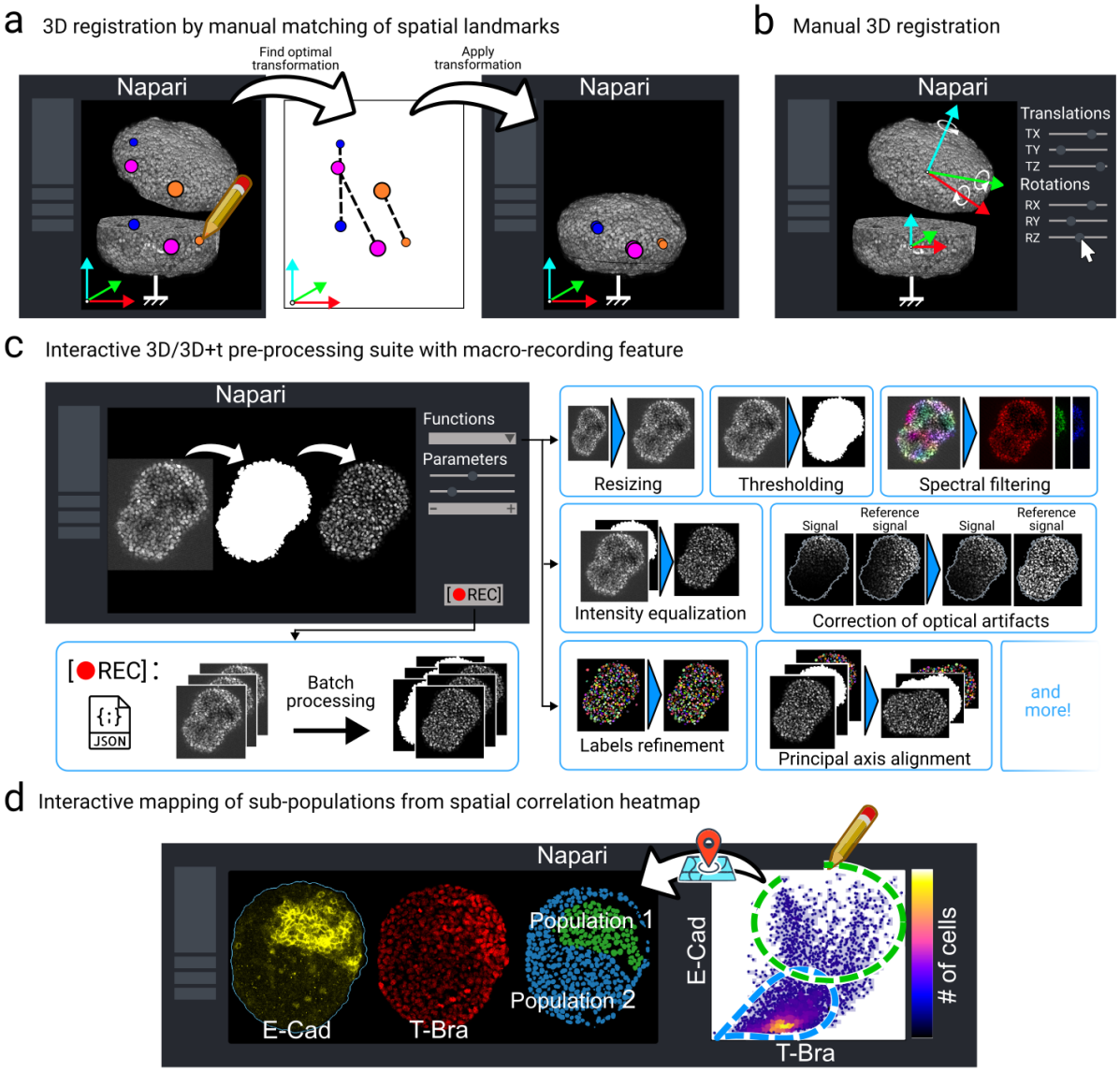

Fig. 6. **Interactive Napari plugins for manual registration, pre-processing, data exploration and analysis. (a,b)** To fuse data acquired with our dual-view setup, we provide a Napari plugin to assist users in manually defining a 3D rigid transformation either when it is trivial (e.g a single axial translation) or to initialize an automatic registration tool close to the optimum. The first mode (left) allows the user to select salient landmarks and match them between the two views. An optimal rigid transformation is found automatically. The plugin's second mode (right) lets the user define each element of the transformation (translations and rotations) until a satisfactory match is observed in 3D or on 2D planes. **(c)** A complete pre-processing suite is provided as a Napari plugin to transform raw 3D and 3D+time datasets into datasets ready for analysis. The Napari implementation allows for quick and visual exploration of parameters best suited to a given dataset. A recording feature can be toggled to save a complete user-defined pipeline into a *JSON* file, that can be used to process large datasets in batch or for sharing. **(d)** Interactive analysis of multiscale correlation heatmaps in Napari is provided by allowing users to (i) change the analysis length scale and to (ii) draw regions of interest directly on the correlation plot to see which cells contributed to the region's statistics on a 3D view of the data.

true strain tensor major axis. Furthermore, obtaining precise masks is essential to extend our analysis to inherently hollow datasets, like intestinal gastruloids. To improve our current implementation, our masking approach could be augmented by a second method used to specifically detect these structures. Pixel classification based on Random-Forests could be used to get accurate segmentation using only a few manually annotated lines. These approaches are now widely accessible to non-specialist users in softwares like *Fiji* (with *Labkit* [57]), *Ilastik* [58], or *Napari* (with *napari-APOC* [59]).

Imaging limitations and extensions. Our sample mounting approach and image registration methodology (originally developed for light-sheet data processing) enables imaging specimen from two opposite views using any inverted or upright two-photon or confocal microscope. This approach is straightforward and efficient, requiring only a single flip of the sample coverslip after imaging all specimens from one side. This effectively doubles the maximum imaging depth achievable for the sample. However, flipping is not always necessary, nor is it possible with live samples, to extract quantitative features from deep tissues. Here, we present quantifications obtained from both fixed samples, which were imaged from both sides and fused (Fig.4b, Fig.5) and live samples, which were imaged from only one side (Fig.4c-d). In the live samples case, gastruloids were imaged in neural differentiation medium without any tissue clearing. In this aqueous medium, signal intensity and information degrade significantly stronger than in cleared samples (Fig.2c). However, the local normalization strategy applied to the nuclei signal is sufficient to enable efficient nuclei segmentation even in deep tissue layers without flipped views fusion up to 150 μm in depth (Fig.4c-d). This approach can be directly employed for two-photon live imaging, but also for single- or multi-view light-sheet data [26, 27] or in label-free imaging methods such as stimulated Raman histology [60].

In this work, we did not explore continuously adjusting laser power based on excitation depth to enhance signals in deeper tissue layers, which could further extend the depth limits of our imaging method. In principle, incorporating such adaptation should not affect our pipeline, as long as the laser used for exciting the nuclei channel (which normalizes all other signals) is the same or maintains the same power-to-depth relationship as the lasers exciting the other fluorophores to be normalized. Here, we did not account for wavelength dependency in the normalization process, but Fig.S6 shows that normalizing both AF488 and AF568 signals to the Hoechst signal does not introduce significant bias between these fluorophores. However, implementing wavelength-dependent normalization may be necessary to avoid bias between the blue and far-red signals. In this study, we did not develop an explicit model for local intensity correction based on cell depth, lateral position, or excitation and emission wavelengths. Future work could focus on creating a model that accounts for photon paths and wavelength variations for each image voxel. Such a model would enable the prediction of a nuclear z-stack of any fluorophore from a Hoechst z-stack.

In this work, we assume that the nuclear signal is the most reliable for normalizing other signals due to its extensive coverage of the tissue (over 60% in gastruloids). Instead of normalizing signals at the level of individual nuclei, we developed a correction scheme that identifies the optimal scale of characteristic gradients in nuclear intensities to generate a continuous field for renormalization. This approach has the added advantage of being applicable to markers with different subcellular localizations (e.g., nuclei, cell membrane, intracellular organelles).

A necessary component of our quantitative imaging pipeline was the use of spectral unmixing to address spectral cross-talk, an inherent challenge in multi-color acquisitions, particularly with two-photon excitation. This allowed us to image four different fluorescent targets simultaneously and was required to capture and correlate multiple genetic markers on the single-cell level. This can be further expanded in the future by using state-of-the-art hyperspectral detection, which allows capturing up to 32 channels simultaneously and thus decompose even more spectrally overlapping fluorescent targets [61]. Two-photon excitation is advantageous in this context, allowing for the excitation of multiple targets with a single laser line. In our work, three of the four fluorophore species (Hoechst, AF488, and AF568) were excited using a 920 nm laser line. Additionally, iterative rounds of immunostaining and washing can be applied to maximize the information content [24, 62]. In this context, the interactive registration tools that we have implemented here will be key ingredients to correct for sample movements between subsequent staining steps.

Exploring gastruloid development in 3D. In the context of gastruloid development, which serves as the central biological theme of this paper, it is crucial to understand how spatial heterogeneities in gene expression arise at both the cell microenvironment scale and the larger gastruloid scale. During early gastruloid symmetry breaking and elongation, radial and later anteroposterior gradients of the gene T-Bra, a nascent mesoderm marker, emerge. These radial gradients can be captured with our coarse-grained analysis (see Fig.5c). However, while both the endoderm marker FoxA2 and T-Bra exhibit radial gradients at the coarse-grained scale, their anti-correlated expression is only evident at the single-cell level (see Fig.5c-f). This example highlights the importance of a multiscale analysis pipeline that allows simultaneous visualization of tissue-scale properties and local cellular events. Our methodology utilizes segmentation of the Hoechst-stained nuclei channel to (1) identify individual cells for cell-scale analysis and (2) normalize other channels using the nuclei signal. By developing a diverse training set for nuclei segmentation, we achieved precise determination of nuclei shapes. This precision enables systematic studies of the relationship between nuclear morphology and gene expression patterns, and can be extended to cell morphology using membrane stains such as ZO-1 and cell shape segmentation methods like CellPose [63]. Nuclei deformation patterns show large-scale alignment at the gastruloid level (see Fig.4c-d) and localized alignment near lumens and cavities, providing potential insights into the structuring of epithelial and mesenchymal tissues during gastruloid development. In

older gastruloids with cavity-containing structures, such as somitic structures [38], automated cavity detection will be crucial for accurately quantifying coarse-grained fields of cell or division densities.

While this work focuses on gastruloid datasets, we believe that the pipeline effectively extends to organoid, tumoroid, and other datasets that encounter challenges related to whole-mount deep imaging. We designed the library in the prospect of long-term maintenance, and it will receive continuous improvements in the future.

III. MATERIALS AND METHODS

A. Sample preparation

1. Gastruloid culture

Gastruloids were generated using the protocol described previously in [31], from four different cell lines. Briefly, cells were seeded and aggregated for 48 h in low-adherence 96-well plates (Costar ref: 7007) and subsequently pulsed with the Wnt agonist Chiron, which was washed out after 24 h, i.e. at 72 h of aggregate culture. Time points indicated throughout the paper refer to the time after seeding. The two cell lines T-Bra-GFP/NE-mKate2 and E-cad-GFP/Oct4-mCherry were used for gene expression analyses. The E14Tg2a.4 line (ATCC) was used for spectral calibration and benchmarking as it is devoid of any fluorescent construct. The H2B-GFP (a generous gift from Kat Hadjantonakis) was used for live imaging experiments and morphometric analyses. In brief, between 50 and 400 cells were seeded in low adhesive 96 wells plates in a neural differentiation medium. In order to promote endoderm formation and to reduce symmetry breaking variability compared to the standard gastruloids protocol [53], we enrichted the medium with Fibroblast Growth Factor and Activin as in [31]. All cell lines were tested to be free from mycoplasma contamination using qPCR.

2. Immunostaining

Samples were immunostained using the same protocol as in [31] apart from the fact that samples were incubated in a 1 mM glycin solution, and that primary antibodies (see table below) were incubated during 3 consecutive days. Secondary antibodies AF488, A568, AF647 (ThermoFisher) and Hoechst 33342 (ThermoFisher) were chosen to be compatible with four-color two-photon imaging. They were diluted 500 times for incubation, except of Hoechst which was diluted 10000 times in order to minimize the crosstalk of the Hoechst signal into other channels.

Antibodies				
Antibody	Species	Reference	Provider	Dilution
Brachyury	Goat	AF2085	RD system	1:40
E-cadherin	Rat	M108	Takara	1:200
FoxA2	Goat	sc-6554	Santa-Cruz	1:50
Snail	Goat	AF3639	RD system	1:50
OB-cadherin	Rabbit	71-7600	Invitrogen	1:500
pH3	Rat	ab10543	abcam	1:250
Oct4	Mouse	Merck Millipore	MAB4419	1:100
Sox2	Mouse	SantaCruz Biotechnology	sc-365823	1:100
anti-GFP	Chicken	Aves	GFP-1020	1:100

3. Mounting

Samples were mounted between two glass coverslips of standard thickness (0.13 to 0.17 mm) using 250 μm or 500 μm spacers (SUNJin Lab, Taiwan, R.O.C.) in 20 μl or 40 μl mounting medium. For the clearing benchmark, gastruloids were incubated overnight and then mounted in either PBS, 80% glycerol solution in PBS (v/v) [41], 20% optiprep solution in PBS (v/v) [42], or antifade mounting medium (ProLong Gold Antifade Mountant, Thermo Fisher Scientific). For all other experiments with fixed samples, gastruloids were mounted in 80% glycerol solution in PBS (v/v). For live imaging, gastruloids were transferred from 96-well plates to either MatTek dishes (MatTek corporation, ref: P35G-1.5-14 C) or to microwell plates (500 μm wells, SUNBIOSCIENCE ref: Gri3D) in culture medium and imaged in a chamber maintained at 37 °C, 5% CO_2 with a humidifier.

B. Two-photon imaging

Four-colors two-photon imaging of immunostained samples was performed on an upright Nikon A1 R MP microscope using an Apo LWD 40×/1.1 WI λS DIC N2 objective. Fluorescence was simultaneously excited at 920 nm (to excite simultaneously Hoechst, AF488 and AF568) with a tunable femtosecond laser (Chameleon Discovery NX from Coherent) and at 1040 nm (to excite simultaneously AF568 and AF647) with the same laser secondary output at fixed wavelength. Fluorescence was detected on four non-descanned GaAsP detectors with the following emission filters: 450/70 (Ch1), 530/55 (Ch2), 607/70 (Ch3), 700/50 (Ch4). To spectrally seperate the channels, three dichroic mirrors (488 LP, 562 LP, 650 LP) were used. Multiposition imaging was used to automatically acquire image stacks on multiple gastruloids mounted in the same sample slide.
Live imaging of gastruloids was performed on a Zeiss 510 NLO (Inverse - LSM) with a femtosecond laser (Laser Mai Tai DeepSee HP) with a 40×/1.2 C Apochromat objective. The Histone-GFP signal was excited at 920 nm and detected with a non-descanned GaAsP detector with a 560 LP. The images were acquired with the full field-of-view (318 μm, pixel size 0.62 μm), and a z-spacing of 1 μm. Depth in z varies from 150 to 350 μm, depending on the acquisitions and the sample

size, but always past the midplane of the gastruloid.

C. Confocal imaging

Confocal imaging was performed on a Zeiss LSM880 system (Carl Zeiss) using a Plan-Apochromat 40×/1.2 NA water immersion objective. Fluorescence was excited with the 488 nm line of an Argon laser. To split excitation and emission light, a 488 dichroic mirror was used. Fluorescence was detected between 491 and 700 nm on a 32-channel GaAsP array detector, with a pinhole set to one airy unit.

D. Image quality estimation

To quantitatively assess clearing efficiency and compare the information content of images at depth, we used the Fourier ring correlation quality estimate (FRC-QE) [43]. We selected a column of 400×400 pixels for the clearing benchmark and 100×100 pixels for all other analyses in the center of aggregates and computed FRC-QE using the available Fiji plug-in.

E. Preprocessing: Spectral unmixing

To remove spectral cross-talk, four-channel images were spectrally unmixed into n images corresponding to the contribution from each of the n fluorophore species present in the sample.

1. *Spectral calibration*

To this aim, reference spectra p_i^k of the utilized fluorophores were determined from calibration images acquired on aggregates stained with only one fluorophore species at the same excitation and detection settings. To account for wavelength dependent signal decay with imaging depths, spectral patterns were computed as function of imaging depth. It is important to note that spectral patterns depend on the gain settings of each detector. However, once calibrated for a certain set of gain values, reference patterns for different gains can be easily interpolated by simply measuring the count ratios for both sets of gains on a sample providing sufficient signal (i.e. well above background counts) on each detector for all gains.

2. *Spectral decomposition*

Four-channel images $I^k(x, y, z)$ were decomposed using a previously published unmixing algorithm originally developed in the context of fluorescence lifetime correlation spectroscopy [64], image correlation [65] and fluorescence correlation spectroscopy [45, 66]. First, spectral filter functions f_i^k were calculated using the calibrated reference spectra $p_i^k(z)$:

$$f_i^k(z) = \left(\left[\hat{P}^T D \hat{P} \right]^{-1} \hat{P} D \right)_{ik} \tag{1}$$

Here, P is a matrix with elements $P_{ki} = p_i^k(z)$ and D a diagonal matrix computed from the average image intensity in each channel k, $D = diag\left[1/\langle I^k(x, y, z)\rangle_{x,y}\right]$.
The spectral filter functions represent intensity weights per spectral channel. To obtain the filtered images $I_i(x, y, z)$ for each fluorophore species i, the channel images are multiplied with the filter functions and summed over all channels ($m = 4$ here):

$$I_i(x, y, z) = \sum_{k=1}^{m} f_i^k(z) I^k(x, y, z). \tag{2}$$

It should be noted that unmixing successfully works as long as signal levels are well above background counts and all images, acquired for spectral calibration and in actual imaging experiments, are devoid of detector saturation.
This way, even closely overlapping fluorophore species can be discriminated with only few detector channels, at the expense of increased image noise [65]. In this context, pure detector channels, i.e. channels that predominantly detect one of the fluorophore species, are beneficial. This is the case in the example of GFP and AF488 presented in Fig.S1e,f, in which the first channel detects mostly GFP fluorescence. In addition, samples in which signal from different fluorophore species is detected in different pixels (e.g. pixels corresponding to nuclei and membranes) are generally easier to unmix and suffer less from noise increase than samples were different fluorophore species contribute to the signal in the same pixels.

F. Preprocessing: Dual-view registration and fusion

Multiple organoids were acquired from the same slide, first from one side for all of them, then from the other side. Therefore, the first step of the registration and fusion algorithm was to pair the two sides of each organoid together. This pairing was done by extracting the sample positions stored in the metadata of the acquisitions and finding the pairing that minimises the sum of the distances between paired samples using a linear assignment algorithm.
Registration of these dual-view image stacks was achieved using an existing intensity based blockmatching algorithm [44], adapted for 3D microscopy images and previsously used in [6, 7]. From the two distinct images, one is arbitrarily chosen as the reference image and the other, named the floating image, is registered onto the reference one. Starting from an initial transformation, the blockmatching algorithm compares, on multiple hierarchical levels, each block in the floating image with the corresponding neighboring blocks in the reference image, and finds the rigid 3D transformation (specified by rotation around axes X, Y, Z and translation along axes X, Y, Z) from these sets of blocks. Then, we apply the transformation to the floating image, so that the two views are in the same referential, and fuse them into one image stack.
Because of the computational cost of comparing blocks in large 3D images, the size of the neighborhood that the registration algorithm explores is restricted. Therefore, the magnitude of the transformation between the two image stacks has to be relatively small (typically less than 30° rotations and 100 units in translation). As a consequence, the user has to provide an initial transformation to the algorithm, which approximates the actual transformation. In the case of dual-view imaging with opposite views, the initial transformation would

correspond to 180° rotation around the X axis and some additional translation. To explore the initial transformation, we developed the Napari plugin *napari-manual-registration* detailed above and illustrated in Fig.6. This tools allows to interactively rotate and translate the floating with respect to the reference image stack. The tool also allows users to specify manual landmarks in both image stacks, e.g. lumen, dead or dividing cells, from which an initial transformation can be automatically computed.
While the blockmatching algorithm generally allows for any type of transformation (rigid, affine, non-linear, ...), we restrained the search space to rigid transformations. Moreover, since the stacks comprise multiple channels, we used a reference one that was expressed ubiquitously, here the nuclei staining, on which the transformation was computed. The other channels were registered using the same transformation matrix as the reference channel. Because the SNR of each stack decreased roughly with the distance to the objective, we weighted the contribution in the fusion of the two opposing sides of the sample. The weights f_1 and f_2 respectively for the reference view and floating view were computed as a sigmoid:

$$f_1(z) = \frac{1}{1 + e^{p(z-z_0)}}. \tag{3}$$

$$f_2(z) = 1 - f_1(z) \tag{4}$$

with z being the depth in the stack in voxels, z_0 the middle of the sigmoid, where $f_1(z_0) = 0.5$, and p the slope of the sigmoid. The decay length l of the sigmoid and the effective fusion width δ were defined such as:

$$l = \frac{4}{p} \tag{5}$$

$$\delta = 2 * l \tag{6}$$

As illustrated in Fig.2e, the two sides were imaged up to a certain depth depending on the sample size and the image quality, past the mid-plane to ensure some overlap with the other view. Because we acquired the same depth and number of z-planes for both views, the sigmoid is centered in the middle of the overlapping region, which is why we considered $z_0 = 0.5$. The overlapping region to fuse had a typical width value of $w = 70$ to $150\,\mu$m (depending on the image depth) around the midplane. This overlapping region was scaled in the range $[0, 1]$ to define a fusion width that is independant of the gastruloid size, which is illustrated on Fig.S4. The slope of the sigmoid had a typical value of $p = 15\,voxels^{-1}$, which gives $l = 0.27\,voxels$ and $\delta = 0.53\,voxels$ in the $[0, 1]$ range, which means that about half of the overlapping region were used to mix both signals and create the fused part.

G. Nuclei segmentation

To segment nuclei, we trained a custom Stardist3D [46] model on three annotated datasets acquired with two-photon microscopy in different acquisition modalities: one fixed dateset, two live datasets (one with mosaic fluorescence labeling), see Table I.
Because the image contrast is not homogeneous within and across samples, it was equalized across the training datasets by applying local percentile-based histogram equalization through histogram stretching and clipping. For a given image voxel at position $\vec{x} = (z, y, x)$, its intensity $I(\vec{x})$ is first transformed as follows:

density	**dimension**	**num. nuclei**	**pixel size** (µm/pix)
dense	3D	1018	Z: 1, Y/X: 0.25
dense	3D+time	100	Z: 1, Y/X: 0.62
sparse	3D+time	3296	Z: 1, Y/X: 0.62

TABLE I. Description of the datasets used for training our custom StarDist3D model to detect nuclei. All datasets were acquired with a two-photon microscope.

$$I'(\vec{x}) = \frac{I(\vec{x}) - P_{min}(\vec{x})}{P_{max}(\vec{x}) - P_{min}(\vec{x})}, \tag{7}$$

where $P_{min}(\vec{x})$ and $P_{max}(\vec{x})$ are low and high percentile intensity values computed within a local window of size w centered at (z, y, x).
In practice, we choose P_{min} and P_{max} to be the 1st and 99th percentile of the intensity values within the window, and w to be close to the average size of the nuclei in the dataset (in our implementation, we set $w = 6\,\mu m$ as a versatile default value). The transformed image I' is finally clipped to the range $[0, 1]$ to obtain the locally equalized image.
The training datasets were rescaled to an isotropic voxel scale of $0.62\,\mu m/pix$ in all directions, from which crops of $64 \times 64 \times 64$ voxels were extracted and augmented during training by 3D rotations, flipping, intensity shifts, and additive Gaussian noise.
Applying scaling transformations to crops during training is often regarded as the best way to achieve robustness in the case of a wide object size distribution. This is typically the case when several raw datasets acquired in different experimental conditions are combined, particularly due to different pixel sizes across datasets. However, we found in our case that the size distribution related to a single dataset is narrow enough that robustness is better achieved by first rescaling all training datasets to a common isotropic nuclei size. [63, 67].
Before inference, a new dataset simply needs to be rescaled to reach that common nuclei size.

Another StarDist model was trained to detect the divisions stained by ph3. To this aim, we iteratively trained StarDist3D models with a very small batch of annotated data, and corrected the prediction using Napari to train again. At the end, 31 images of whole-mount gastruloids and 5300 divisions was used to train a custom Stardist3D model, using the same parameters as for the nuclei detection model in terms of pre-processing, crops size and data augmentation. After prediction, post-processing was used to filter out small volumes, events detected from the background or dead cells, and the result was visualized using Napari to manually check the performance.

H. Masked Gaussian convolution to probe spatial fields at different scales

To probe volumetric signals at different length scales σ ranging from the average nuclei size to the width of the

organoid, we convolve signals with a Gaussian kernel of size σ. We propose two ways to compute convolutions depending on whether the signal is dense (e.g an image representing a signal intensity) or sparse (e.g nuclei volumes defined only locally on nuclei centroids).

a. Dense data We apply convolution with a normalized Gaussian kernel to dense signals. For a given voxel at position $\vec{x} = (z, y, x)$, its value $I(\vec{x})$, whether scalar or vector, is transformed according to:

$$I^{\sigma}(\vec{x}) = \sum_{\vec{x}' \in [-a,a]^3} k_{\sigma}(\vec{x}') I(\vec{x} - \vec{x}'), \tag{8}$$

with $k_{\sigma}(\vec{x}') = (2\pi\sigma^2)^{-3/2} \exp\left(-\|\vec{x} - \vec{x}'\|^2 / 2\sigma^2\right)$, and a the convolution window size. In our implementation, we choose $a = 3\sigma$.

When a binary mask (e.g defining the inside of the organoid) is available, we apply a masked convolution with a correcting normalization factor. Let M be a binary masking function, e.g $M(\vec{x}) = 1$ for voxels at positions $\vec{x}$ inside the organoid, and 0 everywhere else, we compute

$$I^{\sigma,M}(\vec{x}) = \frac{\sum_{\vec{x}' \in [-a,a]^3} k_{\sigma}(\vec{x}') I(\vec{x} - \vec{x}') M(\vec{x} - \vec{x}')}{\sum_{\vec{x}' \in [-a,a]^3} k_{\sigma}(\vec{x}') M(\vec{x} - \vec{x}')}. \tag{9}$$

This additional normalization factor prevents the artifactual decay of the convolved signal close to the mask boundaries by "excluding" voxels outside the mask from the convolution. Note that the masked formulation allows the user to compute values of a quantity outside its domain of expression. For instance, if both a mask M_{inst} of nuclear instances and a mask $M_{in/out}$ that marks the inside and outside of the sample are provided, a quantity like the Hoechst expression can be computed in the full region defined by $M_{in/out}$, even though it only appears in the nuclei.

b. Sparse data For sparse data, i.e quantities defined locally at n specific positions $\mathbf{X} = \{\vec{x}_1, \vec{x}_2, \ldots, \vec{x}_n\}$, we compute the convolution and masked convolution in a similar manner, but with a mask M that is non-zero only at the positions at which the sparse signal is defined (e.g nuclei centroids). This formulation allows the user to choose between studying the sparse signal (i) at its original positions, i.e by computing the above convolution at positions $\vec{x} \in \mathbf{X}$, (ii) at resampled positions, e.g on a uniform grid for convenience, or (iii) as a dense continuous field across the whole domain of the gastruloid.
We provide a second implementation of the masked convolution specifically for sparse, which is more convenient when the smoothed sparse signals should also be smooth (e.g when it should be defined at its initial positions or on a regular grid). This implementation uses the kd-tree data structure implemented in *Scipy* to efficiently find neighbour relationships from the positions at which the sparse signal is defined, which is used to optimize the computation of the convolution (9).

I. Preprocessing: Intensity normalization

Quantifying gene expression in 3D tissue samples from imaging data is hindered by various sources of noise and optical artifacts that induce large scale intensity gradients (e.g. scattering, aberrations). The main sources of artifacts are (local) variations in optical paths and cell density, that usually manifest as decreased intensities towards deep tissue regions. Artifactual gradients can also appear during the registration of two non-colinear views, which further complexifies the expected distribution of artifacts and resulting intensity gradients.

We model the intensity signal $I(\vec{x})$ from a given channel as

$$I(\vec{x}) = M_{inst}(\vec{x}) S(\vec{x}) A(\vec{x}) + \varepsilon(\vec{x}), \tag{10}$$

where $M_{inst}(\vec{x})$ is a binary mask of the signal instances (e.g nuclei or membranes), i.e $M_{inst}(\vec{x}) = 1$ if $\vec{x}$ is inside an instance and 0 otherwise, $S(\vec{x})$ is the gene expression field, which provides a continuous representation of the cell-scale variations of the biological signal, $A(\vec{x})$ is the field representing the large scale artifactual intensity variations, and $\varepsilon(\vec{x})$ is an additive uncorrelated noise term which models both variations in the signal at scales below the cell-scale and acquisition noise.

We hypothesize that the field of optical artifacts A (i) is equivalent in all channels and (ii) has large scale variations, and that (iii) the Hoechst signal $S_h(\vec{x})$ is globally homogeneous throughout the volume, i.e $S_h(\vec{x}) = S_{h,0}$. From these assumptions, we develop a correction scheme based on the Hoechst staining to separate the contribution of artifactual gradients from true gradients in gene expression. We first compute the Gaussian average of the Hoechst signal at a scale σ using equation (9), in which we keep only voxel intensities that belong to the nuclei using a mask M_{nuc}:

$$I_h^{\sigma,M_{nuc}}(\vec{x}) \approx S_h^0 A(\vec{x}). \tag{11}$$

Here, σ is chosen large enough to average out the additive noise ε but small enough that the structure of the field of optical artifacts A is preserved. The practical choice of σ is discussed below.

We then normalize other biologically relevant intensity signals I_b by the Gaussian-averaged Hoechst field $I_h^{\sigma,M_{nuc}}(\vec{x})$ to get

$$\hat{I}_b(\vec{x}) = \frac{I_b(\vec{x})}{I_h^{\sigma,M_{nuc}}(\vec{x})} = M_{inst}(\vec{x}) \frac{S(\vec{x})}{S_{h,0}} + \varepsilon'(\vec{x}), \tag{12}$$

with ε' the normalized version of the additive noise ε. This step effectively removes the field of optical artifacts from the signal. The choice of σ used for the Gaussian averaging of the Hoechst signal depends on the length scale at which the field of artifacts A varies. Since this is not known in practice, we choose in our implementation the value σ that leads to the most homogeneous normalized Hoechst signal across all z-planes. Formally,

$$\begin{cases} \sigma = \operatorname{argmin}_{\sigma} \operatorname{MAD}\left(\mathbf{I}_h^{\sigma}\right) \\ \mathbf{I}_h^{\sigma} = \left\{ \operatorname{median}\left(I_h^{\sigma,M_{nuc}}(z = Z) \right) \right\}_{Z \in [0, Z_{max}]} \end{cases}, \tag{13}$$

with MAD the median absolute deviation and Z_{max} the depth of the last z-slice.

With the aim of comparing normalized signals across different samples acquired with the same imaging setup, we further

rescale the normalized signal by a global multiplicative factor designed to mitigate the sample-dependant impact of the normalizing factor $S_{h,0}$ in equation (12). We multiply each normalized signal by a multiplicative factor such that the median intensity of the normalized Hoechst signal computed in a region of brightest intensity corresponds to the median intensity of the raw Hoechst signal. We multiply each normalized signal by a multiplicative factor such that the median intensity of the raw Hoechst signal computed in a region of brightest intensity is transmitted to the normalized Hoechst signal. The rationale is that the median intensity in the brightest regions reflects the expected intensity in the absence of artifacts, e.g. in outer cell layers close to the cover glass.

J. Density maps

To quantify the local abundance of a target object, e.g. nuclei or specifically mitotic nuclei, we study three spatial fields: the density (number of objects per volume), the volume fraction (percentage of local space filled by the objects), and the map of objects volumes.
All fields are first computed at the voxel scale. The voxel-scale density field and map of objects volumes are computed by replacing each object by a single voxel of value respectively 1 or the object's volume placed at its centroid. The voxel-scale volume fraction corresponds to a binary mask of the target objects, and can be obtained directly with semantic segmentation methods or by binarising segmented object instances as output by Stardist3D. The voxel-scale fields are finally convolved with a Gaussian kernel of the desired analysis scale.
These quantities give a complete description of the local object abundance, as the volume fraction and map of objects volumes inform on the impact of volume on the object density. For instance, a large spatial region can misleadingly display a constant volume fraction but have large variations in object density and local objects volumes if the latter two compensate.

K. Morphometric analysis

To quantify object-scale deformation, we fit an ellipse to each segmented object. This can be done efficiently by computing the inertia tensor I. For a given object composed of N voxels at positions $\{\vec{x}_1, \vec{x}_2, \ldots, \vec{x}_N\}$, we first compute the positions of the voxels relative to the object's centroid $\vec{c}$, $\{\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_N\}$, with $\vec{r}_k = \vec{x}_k - \vec{c} = (r_{k,1}, r_{k,2}, r_{k,3})$. The inertia tensor is then defined as:

$$I_{i,j} = \sum_{k=1}^{N} (r_{k,i} r_{k,j} - \delta_{i,j} r_k^2), \tag{14}$$

with $r_k^2 = r_{k,1}^2 + r_{k,2}^2 + r_{k,3}^2$ and $\delta_{i,j}$ the Kronecker delta. The eigenvectors and eigenvalues of the inertia tensor correspond to the principal axes and moments of inertia of the object. Notably, the principal axes of I are the same as the principal axes of the ellipse that best fits the object. The lengths of the ellipse's semi-axes can be obtained from the moments of inertia: if (I_1, I_2, I_3) are the moments of inertia associated with the principal axes $(\vec{e}_1, \vec{e}_2, \vec{e}_3)$, the lengths of the corresponding semi-axii (L_1, L_2, L_3) are given by:

$$L_i^2 = \frac{5}{2N}(I_1 + I_2 + I_3 - 2I_i), \quad i = 1, 2, 3. \tag{15}$$

Computing the inertia tensor for each object leads to a sparse tensor field that can be studied at arbitrary scales using the sparse Gaussian convolution equation defined previously. For instance, it can be used to study local object alignments by focusing only on the largest semi-axis (the main axis of deformation of the object). In practice, quantifying local object alignment by averaging inertia tensors introduces a bias by over-representing large objects. To avoid this bias, we instead compute the true strain tensor from the inertia tensor. The true strain tensor T is defined as:

$$T = V diag(T_1, T_2, T_3) V^T, \tag{16}$$

with V the matrix of eigenvectors of I and $T_i = \frac{1}{3} \log\left(L_i^3/(L_1 L_2 L_3)\right)$. The eigenvalues (T_1, T_2, T_3) of T represent the relative amount of deviation of each principal length from the radius of a sphere with the same volume as the object. Due to its relative nature, the true strain tensor is suited to compare the deformations of two objects with different sizes, and is thus appropriate for averaging in a local neighbourhood.

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CONTRIBUTIONS

S.T, P-F.L and L.G designed the project. S.T and V.D-E designed the experiments. A.G, V.D-E, S.T and A.R conducted the experiments and collected the data. V.D-E developed the spectral filtering approach, A.G and J.V annotated nuclei data for the training of the StarDist3D network. A.G and L.G adapted the registration algorithm, with input from J.V. and V.D-E. J.V developed and packaged the pipeline and the Napari plugins, with technical input from A.G, and conceptual inputs from A.G, S.T, L.G, V.D-E. A.G, J.V, and V.D-E analyzed the data, with inputs from S.T, L.G, P.R and P-F.L. S.T, V.D-E, A.G and J.V wrote the manuscript with inputs from L.G, P-F.L and P.R. All authors discussed the scientific results and their interpretation. A.G, V.D-E, J.V and L.G created the figures and visualizations, P-F.L, S.T, L.G and P.R acquired funding.

ABBREVIATIONS

SNR: signal-to-noise-ratio

IoU: intersection over union

ph3: phospho-histone H3

PBS: phosphate-buffered saline

FRC-QE: Fourier ring correlation quality estimate

Ecad: E-cadherin

H2B: Histone 2B

[1] H. Clevers and D. A. Tuveson, Annual Review of Cancer Biology **3**, 223 (2019).

[2] J. Kim, B.-K. Koo, and J. A. Knoblich, Nature Reviews Molecular Cell Biology **21**, 571 (2020).

[3] W. M. S. Russell, R. L. Burch, C. W. Hume, *et al.*, *The principles of humane experimental technique*, Vol. 238 (Methuen London, 1959).

[4] M. Simian and M. J. Bissell, Journal of Cell Biology **216**, 31 (2017).

[5] M. A. Lancaster and M. Huch, Disease models & mechanisms **12**, dmm039347 (2019).

[6] K. McDole, L. Guignard, F. Amat, A. Berger, G. Malandain, L. A. Royer, S. C. Turaga, K. Branson, and P. J. Keller, Cell **175**, 859 (2018).

[7] L. Guignard, U.-M. Fiúza, B. Leggio, J. Laussu, E. Faure, G. Michelin, K. Biasuz, L. Hufnagel, G. Malandain, C. Godin, and P. Lemaire, Science **369**, eaar5663 (2020), https://www.science.org/doi/pdf/10.1126/science.aar5663.

[8] N. Farag, C. Sacharen, L. Avni, and I. Nachman, Developmental Cell (2024).

[9] S. Suppinger, M. Zinner, N. Aizarani, I. Lukonin, R. Ortiz, C. Azzi, M. B. Stadler, S. Vianello, G. Palla, H. Kohler, *et al.*, Cell Stem Cell **30**, 867 (2023).

[10] A. Villaronga Luque, R. G. Savill, N. López-Anguita, A. Bolondi, S. Garai, S. I. Gassaloglu, A. Poddar, A. Bulut-Karslioglu, and J. V. Veenvliet, bioRxiv , 2023 (2023).

[11] M. Hofer and M. P. Lutolf, Nature Reviews Materials **6**, 402 (2021).

[12] F. Cermola, C. D'Aniello, R. Tatè, D. De Cesare, A. Martinez-Arias, G. Minchiotti, and E. J. Patriarca, Stem Cell Reports **16**, 354 (2021).

[13] N. Gjorevski, M. Nikolaev, T. Brown, O. Mitrofanova, N. Brandenberg, F. DelRio, F. Yavitt, P. Liberali, K. Anseth, and M. Lutolf, Science **375**, eaaw9021 (2022).

[14] P.-F. Lenne, E. Munro, I. Heemskerk, A. Warmflash, L. Bocanegra-Moreno, K. Kishi, A. Kicheva, Y. Long, A. Fruleux, A. Boudaoud, *et al.*, Physical biology **18**, 041501 (2021).

[15] I. Lukonin, D. Serra, L. Challet Meylan, K. Volkmann, J. Baaten, R. Zhao, S. Meeusen, K. Colman, F. Maurer, M. B. Stadler, *et al.*, Nature **586**, 275 (2020).

[16] S. Suppinger, M. Zinner, N. Aizarani, I. Lukonin, R. Ortiz, C. Azzi, M. B. Stadler, S. Vianello, G. Palla, H. Kohler, A. Mayran, M. P. Lutolf, and P. Liberali, Cell Stem Cell **30**, 867 (2023).

[17] N. Gritti, J. L. Lim, K. Anlaş, M. Pandya, G. Aalderink, G. Martínez-Ara, and V. Trivedi, Development **148**, dev199611 (2021).

[18] E. C. Costa, A. F. Moreira, D. de Melo-Diogo, V. M. Gaspar, M. P. Carvalho, and I. J. Correia, Biotechnology advances **34**, 1427 (2016).

[19] R. Hass, J. von der Ohe, and H. Ungefroren, Cancers **12**, 3716 (2020).

[20] Z.-Y. Liu, V. Trivedi, and I. Heemskerk, Nature methods **20**, 1859 (2023).

[21] R. L. van Ineveld, E. J. van Vliet, E. J. Wehrens, M. Alieva, and A. C. Rios, The EMBO Journal **41**, e109675 (2022).

[22] F. Bosveld, I. Bonnet, B. Guirao, S. Tlili, Z. Wang, A. Petitalot, R. Marchand, P.-L. Bardet, P. Marcq, F. Graner, *et al.*, Science **336**, 724 (2012).

[23] B. Guirao, S. U. Rigaud, F. Bosveld, A. Bailles, J. Lopez-Gay, S. Ishihara, K. Sugimura, F. Graner, and Y. Bellaïche, Elife **4**, e08519 (2015).

[24] X. Zheng, M. A. Betjes, P. Ender, Y. J. Goos, G. Huelsz-Prince, H. Clevers, J. S. van Zon, and S. J. Tans, Science advances **9**, eadd6480 (2023).

[25] G. de Medeiros, R. Ortiz, P. Strnad, A. Boni, F. Moos, N. Repina, L. Challet Meylan, F. Maurer, and P. Liberali, Nature Communications **13**, 4864 (2022).

[26] A. Beghin, G. Grenci, G. Sahni, S. Guo, H. Rajendiran, T. Delaire, S. B. Mohamad Raffi, D. Blanc, R. de Mets, H. T. Ong, *et al.*, Nature Methods **19**, 881 (2022).

[27] F. Moos, S. Suppinger, G. de Medeiros, K. C. Oost, A. Boni, C. Rémy, S. L. Weevers, C. Tsiairis, P. Strnad, and P. Liberali, Nature Methods **21**, 798 (2024).

[28] J. F. Dekkers, M. Alieva, L. M. Wellens, H. C. Ariese, P. R. Jamieson, A. M. Vonk, G. D. Amatngalim, H. Hu, K. C. Oost, H. J. Snippert, *et al.*, Nature protocols **14**, 1756 (2019).

[29] H. T. Ong, E. Karatas, G. Grenci, F. Dilasser, S. B. Mohamad Raffi, D. Blanc, T. Poquillon, E. Drimaracci, D. Mikec, C. Thiel, O. Ullrich, V. Racine, and A. Beghin 10.1101/2023.11.08.566158 (2023).

[30] L. Beccari, N. Moris, M. Girgin, D. A. Turner, P. Baillie-Johnson, A.-C. Cossy, M. P. Lutolf, D. Duboule, and A. M. Arias, Nature **562**, 272 (2018).

[31] A. Hashmi, S. Tlili, P. Perrin, M. Lowndes, H. Peradziryi, J. M. Brickman, A. Martínez Arias, and P.-F. Lenne, eLife **11**, 10.7554/ELIFE.59371 (2022).

[32] J.-M. F. Martins, C. Fischer, A. Urzi, R. Vidal, S. Kunz, P.-L. Ruffault, L. Kabuss, I. Hube, E. Gazzerro, C. Birchmeier, *et al.*, Cell stem cell **26**, 172 (2020).

[33] M. Zanoni, F. Piccinini, C. Arienti, A. Zamagni, S. Santi, R. Polico, A. Bevilacqua, and A. Tesei, Scientific reports **6**, 19103 (2016).

[34] I. M. Schießl and H. Castrop, Pflügers Archiv-European Journal of Physiology **468**, 1505 (2016).

[35] F. Helmchen and W. Denk, Nature Methods 2005 2:12 **2**, 932 (2005).

[36] C. M. Hobson, M. Guo, H. D. Vishwasrao, Y. Wu, H. Shroff, and T.-L. Chew, Nature Methods **19**, 1538 (2022).

[37] S. Gsell, S. Tlili, M. Merkel, and P.-F. Lenne 10.1101/2023.09.22.559003 (2023).

[38] J. V. Veenvliet, A. Bolondi, H. Kretzmer, L. Haut, M. Scholze-Wittler, D. Schifferl, F. Koch, L. Guignard, A. S. Kumar, M. Pustet, *et al.*, Science **370**, eaba4937 (2020).

[39] G. Rossi, N. Broguiere, M. Miyamoto, A. Boni, R. Guiet, M. Girgin, R. G. Kelly, C. Kwon, and M. P. Lutolf, Cell stem cell **28**, 230 (2021).

[40] P.-F. Lenne and S. Tlili, Emerging Topics in Life Sciences **7**, 417 (2023).

[41] A. Ahmad, S. Goodarzi, C. Frindel, G. Recher, C. Riviere, and D. Rousseau, bioRxiv 10.1101/2021.01.31.428996 (2021).

[42] T. Boothe, L. Hilbert, M. Heide, L. Berninger, W. B. Huttner, V. Zaburdaev, N. L. Vastenhouw, E. W. Myers, D. N. Drechsel, and J. C. Rink, eLife **6**, 10.7554/ELIFE.27240 (2017).

[43] F. Preusser, N. dos Santos, J. Contzen, H. Stachelscheid, E. T. Costa, P. Mergenthaler, and S. Preibisch, Bioinformatics **37**, 3088 (2021), https://academic.oup.com/bioinformatics/article-pdf/37/18/3088/50579215/btab160.pdf.

[44] S. Ourselin, A. Roche, S. Prima, and N. Ayache, Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) **1935**, 557 (2000).

[45] V. Dunsing, A. Petrich, and S. Chiantia, eLife **10**, e69687 (2021).

[46] M. Weigert, U. Schmidt, R. Haase, K. Sugawara, and G. Myers, in *Proceedings of the IEEE/CVF winter conference on applications of computer vision* (2020) pp. 3666–3673.

[47] S. Fox, P. Southam, F. Pantin, R. Kennaway, S. Robinson, G. Castorina, Y. E. Sánchez-Corrales, R. Sablowski, J. Chan, V. Grieneisen, *et al.*, PLoS biology **16**, e2005952 (2018).

[48] G. A. Stooke-Vaughan and O. Campàs, Current opinion in genetics & development **51**, 111 (2018).

[49] C. J. Chan, C.-P. Heisenberg, and T. Hiiragi, Current Biology **27**, R1024 (2017).

[50] S. Tlili, C. Gay, F. Graner, P. Marcq, F. Molino, and P. Saramito, The European Physical Journal E **38**, 1 (2015).

[51] S. Tlili, M. Durande, C. Gay, B. Ladoux, F. Graner, and H. Delanoë-Ayari, Physical Review Letters **125**, 088102 (2020).

[52] A. V. Luque, R. Savill, N. López-Anguita, A. Bolondi, S. Garai, S. I. Gassaloglu, A. Poddar, A. Bulut-Karslioglu, and J. V. Veenvliet, bioRxiv , 2023.12.04.569921 (2023).

[53] S. C. van den Brink, P. Baillie-Johnson, T. Balayo, A.-K. Hadjantonakis, S. Nowotschin, D. A. Turner, and A. Martinez Arias, Development **141**, 4231 (2014).

[54] E. Abranches, E. Bekman, and D. Henrique, PloS one **8**, e59928 (2013).

[55] L. von Chamier, R. F. Laine, J. Jukkala, C. Spahn, D. Krentzel, E. Nehme, M. Lerche, S. Hernández-Pérez, P. K. Mattila, E. Karinou, S. Holden, A. C. Solak, A. Krull, T. O. Buchholz, M. L. Jones, L. A. Royer, C. Leterrier, Y. Shechtman, F. Jug, M. Heilemann, G. Jacquemet, and R. Henriques, Nature Communications 2021 12:1 **12**, 1 (2021).

[56] M. Schott, D. León-Periñán, E. Splendiani, L. Strenger, J. R. Licha, T. M. Pentimalli, S. Schallenberg, J. Alles, S. Samut Tagliaferro, A. Boltengagen, S. Ehrig, S. Abbiati, S. Dommerich, M. Pagani, E. Ferretti, G. Macino, N. Karaiskos, and N. Rajewsky, Cell **187**, 3953 (2024).

[57] M. Arzt, J. Deschamps, C. Schmied, T. Pietzsch, D. Schmidt, P. Tomancak, R. Haase, and F. Jug, Frontiers in Computer Science **4**, 777728 (2022).

[58] S. Berg, D. Kutra, T. Kroeger, C. N. Straehle, B. X. Kausler, C. Haubold, M. Schiegg, J. Ales, T. Beier, M. Rudy, K. Eren, J. I. Cervantes, B. Xu, F. Beuttenmueller, A. Wolny, C. Zhang, U. Koethe, F. A. Hamprecht, and A. Kreshuk, Nature Methods 2019 16:12 **16**, 1226 (2019).

[59] R. Haase, D. Lee, D. D. Pop, and L. vZigutytė, haesleinhuepf/napari-accelerated-pixel-and-object- classification: 0.14.1 (2023).

[60] B. Sarri, V. Chevrier, F. Poizat, S. Heuke, F. Franchi, L. De Franqueville, E. Traversari, J.-P. Ratone, F. Caillol, Y. Dahel, *et al.*, npj Imaging **2**, 18 (2024).

[61] F. Cutrale, V. Trivedi, L. A. Trinh, C. L. Chiu, J. M. Choi, M. S. Artiga, and S. E. Fraser, Nature Methods **14**, 149 (2017).

[62] M. M. Bolognesi, M. Manzoni, C. R. Scalia, S. Zannella, F. M. Bosisio, M. Faretta, and G. Cattoretti, Journal of Histochemistry & Cytochemistry **65**, 431 (2017).

[63] C. Stringer, T. Wang, M. Michaelos, and M. Pachitariu, Nature methods **18**, 100 (2021).

[64] A. Ghosh, N. Karedla, J. C. Thiele, I. Gregor, and J. Enderlein, Fluorescence lifetime correlation spectroscopy: Basics and applications (2018).

[65] W. Schrimpf, V. Lemmens, N. Smisdom, M. Ameloot, D. C. Lamb, and J. Hendrix, Methods **140-141**, 97 (2018).

[66] A. Benda, P. Kapusta, M. Hof, and K. Gaus, Optics Express **22**, 2973 (2014).

[67] J. Vanaret, V. Dupuis, P.-F. Lenne, F. Richard, S. Tlili, and P. Roudot, IEEE Journal of Selected Topics in Quantum Electronics **29**, 1 (2023).