

Glucokinase activity controls peripherally-located subpopulations of β -cells that lead islet Ca^{2+} oscillations

Reviewed Preprint

v2 • January 9, 2025

Revised by authors

Reviewed Preprint

v1 • November 7, 2024

Erli Jin, Jennifer K Briggs, Richard KP Benninger , Matthew J Merrins 

Department of Medicine, Division of Endocrinology, Diabetes & Metabolism, University of Wisconsin- Madison, Madison, United States • Department of Bioengineering, University of Colorado Anschutz Medical Campus, United States; Barbara Davis Center for Childhood Diabetes, University of Colorado Anschutz Medical Campus, Aurora, United States

 https://en.wikipedia.org/wiki/Open_access
 Copyright information

eLife Assessment

This study provides **compelling** evidence for functional subpopulations of β -cells responsible for Ca^{2+} signal initiation and maintenance using novel three-dimensional light sheet microscopy imaging and analysis of pancreatic islets. The findings are **important** as they help decode mechanistic underpinnings of islet calcium oscillations and the resulting pulsatile insulin secretion. The work will be of general interest to cell biologists and particular interest to islet biologists.

<https://doi.org/10.7554/eLife.103068.2.sa4>

Abstract

Oscillations in insulin secretion, driven by islet Ca^{2+} waves, are crucial for glycemic control. Prior studies, performed with single-plane imaging, suggest that subpopulations of electrically coupled β -cells have privileged roles in leading and coordinating the propagation of Ca^{2+} waves. Here, we used 3D light-sheet imaging to analyze the location and Ca^{2+} activity of single β -cells within the entire islet at >2 Hz. In contrast with single-plane studies, 3D network analysis indicates that the most highly synchronized β -cells are located at the islet center, and remain regionally but not cellularly stable between oscillations. This subpopulation, which includes ‘hub cells’, is insensitive to changes in fuel metabolism induced by glucokinase and pyruvate kinase activation. β -cells that initiate the Ca^{2+} wave (‘leaders’) are located at the islet periphery, and strikingly, change their identity over time via rotations in the wave axis. Glucokinase activation, which increased oscillation period, reinforced leader cells and stabilized the wave axis. Pyruvate kinase activation, despite increasing oscillation frequency, had no effect on leader cells, indicating the wave origin is patterned by fuel input. These findings emphasize the stochastic nature of the β -cell subpopulations that control Ca^{2+} oscillations and identify a role for glucokinase in spatially patterning ‘leader’ β -cells.

Highlights

- Studies of islet Ca^{2+} oscillations by 3D light-sheet imaging provide a more complete picture of β -cell subpopulations than prior 2D studies.
- Highly synchronized β -cells (including ‘hub cells’) are a regionally-stable subpopulation located at the islet center that is insensitive to metabolic perturbation.
- Glucokinase activation patterns the Ca^{2+} wave axis, which originates from stochastic β -cell subpopulations on the islet periphery that change between oscillations.
- The stochasticity of ‘leader’ β -cells, and the stability of ‘hubs’, is geographically consistent with the peripheral location of α/δ -cells in mouse islets.

Introduction

Pulsatile insulin secretion from pancreatic islet β -cells is key to maintaining glycemic control. Insulin secretory oscillations increase the efficiency of hepatic insulin signaling and are disrupted in individuals with obesity and diabetes¹. The primary stimulus for insulin release is glucose, which is intracellularly metabolized to generate a rise in ATP/ADP ratio, which closes ATP-sensitive K^+ channels (K_{ATP} channels) to initiate Ca^{2+} influx and insulin secretion². At elevated glucose, β -cells oscillate between electrically silent and electrically active phases with a period of minutes, both in vivo and in isolated islets. The depolarizing current can be transmitted between β -cells across the whole islet through gap junction channels. However, the activity of individual electrically coupled β -cells is functionally heterogeneous^{3–9}. This heterogeneity results in the emergence of β -cell subpopulations that may be crucial for maintaining the coordination of the whole islet and regulating pulsatile insulin release^{10–13}. Understanding the underpinnings of β -cell functional heterogeneity and islet cell communication is important for understanding islet dysfunction and the pathogenesis of diabetes.

Similar to studies of neuronal networks, functional network analysis can be used to quantify interactions within the heterogeneous β -cell system. Interactions (termed ‘edges’) are drawn between β -cell pairs with highly correlated Ca^{2+} dynamics. Studies suggest that the β -cell functional network exhibits high clustering or ‘small-world’ properties¹⁴, with a subpopulation of β -cells that are highly synchronized to other cells (‘hub cells’)¹⁰. Silencing the electrical activity of these hub cells with optogenetics was found to abolish the coordination within that plane of the islet^{10,15,16}. Similarly, time series-based lagged cross correlation analysis has identified subpopulations of cells at the wave origin, termed ‘early-phase’ or ‘leader cells’, that lead the second-phase Ca^{2+} wave by depolarizing and repolarizing first^{12,13}. However, questions have been raised whether the highly networked or leader subpopulations have the power to control the entire islet^{15,17–19}. Underlying this controversy lies several unanswered questions: what mechanisms drive the existence of these functional subpopulations? Do these subpopulations arise primarily from mechanisms intrinsic to β -cells, making the subpopulations consistent over time? Alternatively, do they arise from the combination of intrinsic mechanisms and emergence due to surrounding cells, allowing the subpopulations to fluidly change over time? To date, experiments have been restricted to imaging a single two-dimensional (2D) plane of the islet which contains only a small fraction of the β -cells present in the three-dimensional (3D) islet tissue, limiting the ability to address these questions.

With these caveats in mind, prior studies using a mixture of computational and molecular approaches suggested that β -cell subpopulations are patterned by glucokinase, which is often referred to as the ‘glucose sensor’ for the β -cell^{13,20,21}. By phosphorylating glucose in the first step of glycolysis, glucokinase activation lengthens the active phase of Ca^{2+} oscillations by committing more glucose carbons to glycolysis²². Until recently, it was believed that downstream glycolysis was irrelevant to pulsatile insulin secretion. However, in conflict with this model, allosteric activation of pyruvate kinase accelerates Ca^{2+} oscillations and increases insulin secretion^{22,23}. As a potential mechanistic explanation for these observations, plasma membrane-associated glycolytic enzymes, including glucokinase and pyruvate kinase, have been demonstrated to regulate K_{ATP} channels via the ATP/ADP ratio²⁴. However, it remains unknown whether these glycolytic enzymes influence β -cell heterogeneity and network activity.

To study single β -cell activity within intact islets, we engineered a 3D light-sheet microscope to simultaneously record the location and Ca^{2+} activity of single β -cells over the entire islet during glucose-stimulated oscillations. In concert, we developed 3D analyses to investigate the spatial features of subpopulations that underlie the β -cell network and Ca^{2+} wave, and the consistency of these features over time. We further examined the consequences of sampling islet heterogeneity in 2D compared to 3D. Finally, we investigated the role of the glycolytic enzymes glucokinase and pyruvate kinase in controlling β -cell subpopulations during glucose-stimulated oscillations.

Results

Light-sheet microscopy enables high-speed 3D imaging of oscillations in single β -cells within intact islets

To acquire high-speed 3D time course imaging of β -cell Ca^{2+} oscillations within intact islets, we utilized a lateral-interference tilted excitation light-sheet system²⁵ mounted on an inverted fluorescence microscope (**Fig. 1A** and *Methods*). To image Ca^{2+} activity and spatially resolve individual β -cells in intact islets, islets were isolated from *Ins1-Cre:Rosa26^{GCaMP6s}/H2B-mCherry* mice that express cytosolic GCaMP6s Ca^{2+} biosensors and nuclear H2B-mCherry reporters selectively within β -cells. We first compared the images collected by the light-sheet system with a commercial spinning disk confocal using the same 40 $\times$ water immersion objective. Similar to a widefield microscope, the axial resolution of the light-sheet microscope is dictated by the numerical aperture (NA) of the objective lens ($\sim 1.1\ \mu\text{m}$ for a 1.15 NA objective and GCaMP6s emission)²⁵, whereas the spinning disk uses a pinhole array to enhance axial resolution. At a shallow depth of 24 μm from the coverslip, H2B-mCherry-labelled nuclei and GCaMP6s-labelled β -cells were resolved both by the light-sheet and the spinning disk confocal. However, the nuclei were only resolved by the light-sheet system at depths $\geq 60\ \mu\text{m}$ due to the reduced light scatter from side illumination (**Fig. 1B**). Thus, the main advantage of the light-sheet system is the ability to image the entire islet in 3D (**Fig. 1C**).

Prior studies of β -cell Ca^{2+} oscillations utilized 1 Hz imaging to resolve phase shifts for single β -cell traces within a single 2D plane^{26–29}. To image the entire islet at similar acquisition speeds, the hardware was operated under triggering mode to minimize communication delays (Suppl. Fig. 1). In this mode, the lasers and the piezo z-stage were triggered directly by the camera, which received a single set of instructions from the computer via the NiDAQ card. To image 132 μm into the islet at 2 Hz, 15 ms was allowed for photon collection and stage movement for each of the 4- μm z-steps. Initially, an hour-long delay was required to save 120,000 imaging files after running a continuous 30-minute experiment. Because this delay is only observed after the first 3 minutes of imaging, it was possible to eliminate the delay by separating the acquisition into a series of 3-minute loops (Suppl. Fig. 2).

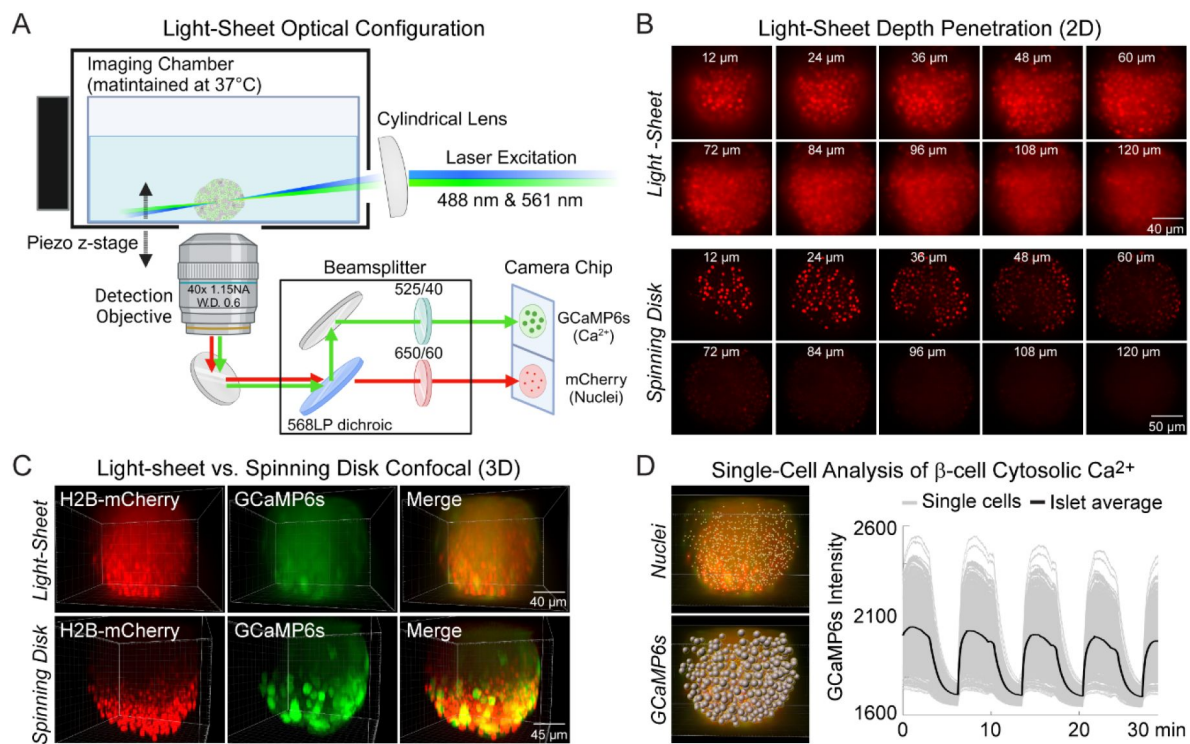


Fig. 1.

Engineering of a light-sheet microscope to image intact islets in 3D.

(A) Schematic of the light-sheet microscope showing the optical configuration. (B) Representative light-sheet (upper panel) and spinning disk confocal images (lower panel) of a mouse pancreatic islet expressing β-cell specific H2B-mCherry fluorophore at different 2D focal planes, emphasizing the superior depth penetration of the light-sheet microscope. (C) 3D imaging of β-cells expressing GCaMP6s Ca²⁺ biosensors and nuclei mCherry biosensors. (D) Using *Ins1-Cre:Rosa26^{GCaMP6s/H2B-mCherry}* islets, the software-identified center of β-cell nuclei (yellow dots) was used to generate GCaMP6s regions of interest (gray spheres). A representative Ca²⁺ timecourse is displayed in the right panel for an islet stimulated with glucose and amino acids.

Individual β -cell nuclei were located using the Spots function of Bitplane Imaris software (**Fig. 1D**). For each nucleus, a cellular region of interest (ROI) was defined by a sphere of radius 4.65 microns around the ROI center based on results from a computational automated radius detection³⁰. The mean GCaMP6s intensity of each cell ROI for each time point were calculated and exported as single cell traces. We did not observe any significant photobleaching using continuous GCaMP6s and H2B- mCherry excitation over the course of the experiment. The combination of this light-sheet system, islet cell labeling, and analysis pipeline allows for imaging of Ca^{2+} from nearly all β -cells in the islet at speeds fast enough for spatio-temporal analyses to identify functionally heterogeneous β -cell subpopulations.

3D analyses of islet Ca^{2+} oscillations reveal that the β -cell network is distributed in a radial pattern while Ca^{2+} waves begin and end on the islet periphery

To investigate the synchronization between β -cells across the islet in 3D space, we imaged and extracted Ca^{2+} time-courses for *Ins1-Cre:ROSA26^{GCaMP6s/H2B-mCherry}* islets that exhibit slow oscillations. Following the network analysis methods set forth in^{14,31}, we calculated the correlation coefficient between every cell pair and defined an “edge” between any cell pairs whose correlation coefficient was above threshold (**Fig. 2A**). This threshold was set such that the average number of edges per cell, also called the ‘cell degree’, was equal to 7. A fixed average degree rather than fixed threshold was used to mitigate inter-islet heterogeneity³¹. An example 3D network for a single β -cell within an islet is shown (**Fig. 2B**) along with the frequency distribution of all β -cells within the islet (**Fig. 2C**). The high degree cells (top 10% of the total population, *blue*) and low degree cells (bottom 10% of the total population, *red*) were then mapped onto a 3D projection of the islet and onto the Ca^{2+} time course (**Fig. 2D**).

Compared to average degree cells, the high degree cells were consistently located at the center of the islet while the low degree cells were located on the periphery, indicating that the islet network is distributed in a radial pattern (**Fig. 2D,E**).

To analyze the propagation and spatial orientation of Ca^{2+} wave in 3D space, we calculated the lagged correlation coefficient between every β -cell and the islet average, and identified the phase lag with maximum correlation (**Fig. 2F**). The spatial distribution of phases of an example islet is shown (**Fig. 2G**), along with the frequency distribution of all β -cells within the islet (**Fig. 2H**). The early phase cells (top 10% of the total population that depolarize first and repolarize first, *blue*) and late phase cells (bottom 10% of the total population that depolarize last and repolarize last, *red*) were then mapped onto a 3D projection of the islet and onto the Ca^{2+} time course (**Fig. 2I**). Unlike the islet network, for which the high degree cells emanate from the islet center (**Fig. 2D,E**), the early phase and late phase cells were each located at the islet periphery, and show a clear temporal separation between depolarization and repolarization (**Fig. 2I,J**).

The location of the β -cell network is stable over time while the wave progression varies

We next assessed the stability of high degree cells and early phase cells over time, by assessing their presence across consecutive oscillations (**Fig. 3A,B**; Suppl. Fig. 3). The high degree cells and early phase cells have a similar ~60% retention rate between oscillations (**Fig. 3C**). Strikingly, when we examined the center of gravity for each β -cell subpopulation, we found that the center of gravity of the early phase cells moved significantly more than that of the high degree cells (**Fig. 3D**). This indicates that the early phase cells tend to change their identity more with each oscillation. To further investigate the change in location of early phase cells, we used principal component analysis to identify the principal axis between early phase cells and late phase cells (wave axis) and calculated the rotation of the axis between each oscillation. Of the 25 islets

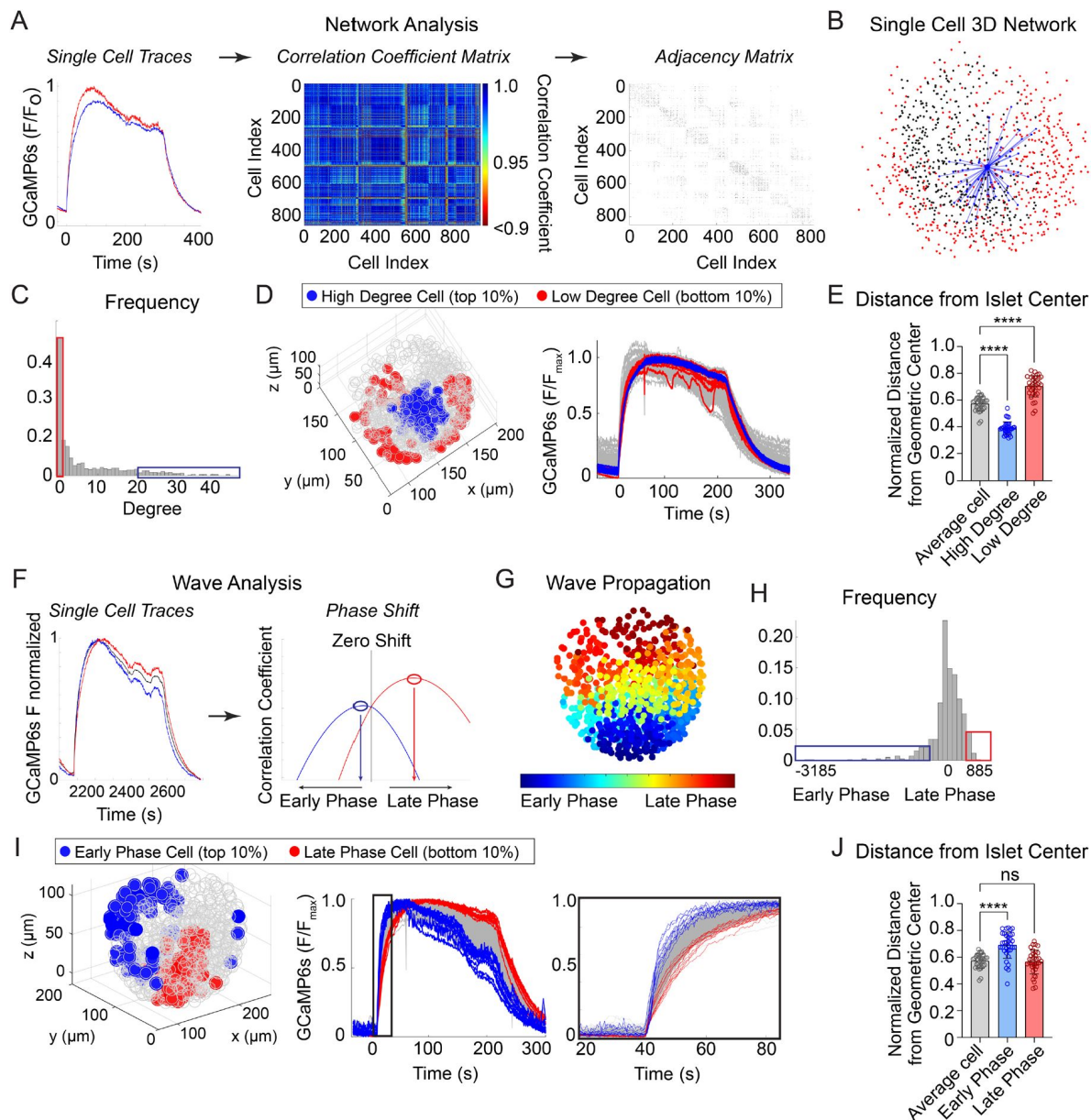


Fig. 2.

Characterization of single β -cells using 3D network and phase analysis.

(A) Flow diagram illustrating the calculation of cell degree from pairwise comparisons between single β -cells. (B) An example 3D network for a single β -cell within a representative islet is shown with synchronized cell pairs in blue, cells that have other synchronized pairs in black, and cells that are asynchronous in red. This analysis is repeated for all cells in the islet. (C) Frequency distribution of cell degree for all β -cells analyzed. Top 10% (blue box) and bottom 10% (red box) are high and low degree cells. (D) Representative 3D illustration and Ca^{2+} traces showing the location of high degree cells (blue) and low degree cells (red). (E) Quantification of the normalized distance from the islet center for average degree cells (gray), high degree cells (blue), and low degree cells (red). (F) Flow diagram illustrating the calculation of cell phase, calculated from the correlation coefficient and phase shift. (G) Wave propagation from early phase cells (blue) to late phase cells (red) in 3D space. (H) Frequency distribution of cell phase for all β -cells analyzed. Top 10% (blue box) and bottom 10% (red box) are early and late phase cells. (I) Representative 3D illustration and Ca^{2+} traces showing the location and traces of high phase cells (blue) and low degree cells (red). (J) Quantification of the normalized distance from the islet center for average phase cells (gray), early phase cells (blue), and late phase cells (red). Data represents $n = 28,855$ cells, 33 islets, 7 mice. Data are displayed as mean $\pm$ SEM. **** $P < 0.0001$ by 1-way ANOVA.

examined, 57% show substantial changes in the wave axis over time (Fig. 3E). Thus, β -cell depolarization is initiated at different locations within the islet over time, while the β -cell network location is relatively stable.

The analyses in Fig. 3 are focused on the top and bottom 10% of the population. To understand the stability of all β -cells within the 3D network or the 3D wave propagation over time, we ranked every β -cell in the islet by their phase/degree ('cellular consistency'), as well as the spatial proximity of every β -cell to the center of gravity of the top 10% of the subpopulation ('regional consistency') (Fig. 4A). We quantified the change in these distributions using a normalized non-parametric, information-theoretic metric termed Kullback-Leibler (KL) divergence (see *Methods*). If the ranking of high degree cell to low degree cell (e.g., $A > B > C$) for the first oscillation remains the same in the second oscillation, the KL divergence will be 0, indicating the cell ranking is completely predictable between oscillations. Alternatively, if the cell ranking changes between oscillations ($A > C > B$), the KL divergence will be 1, indicating the cell ranking is completely random (Fig. 4B). When examining the consistency of the network, the regional stability was much higher than the cellular stability over time (Fig. 4C). In contrast, when examining the wave, the cellular stability was similar to the regional stability (Fig. 4D). This analysis of KL divergence supports the previous conclusions that the β -cell network is regionally stable, but the wave can start at different locations. Additionally, because the wave was consistent cellularly, this analysis may imply that the wave is established by cellular properties, whereas the network is emergent.

The consistency of 2D analyses of the network and wave are much lower than 3D analyses

To investigate whether 2D analysis, as performed in all prior studies^{10,13,14} provides a similar level of robustness as the current 3D analysis, we performed network and wave analyses on a single plane at either $\frac{1}{4}$ -depth or $\frac{1}{2}$ -depth of the z-stack (Fig. 5A). Both the 2D analysis and 3D analysis showed that the wave axis changes over time (Fig. 5B). The analyses also agreed that the high degree cells are located at the center of the islet (Fig. 5C) and that the early phase cells are located at the edge of the islet (Fig. 5D). However, when we looked at the regional and cellular consistency of the β -cell network, the 2D analysis at both $\frac{1}{4}$ -depth and $\frac{1}{2}$ -depth of the z-stack showed no difference for regional and cellular consistency (Fig. 5E). This result contradicts with the 3D analysis which showed the regional consistency of the β -cell network is significantly more stable than cellular consistency. When analyzing the wave, both 3D analysis and 2D analysis at $\frac{1}{4}$ -depth showed that the cellular consistency is more stable than regional consistency, while the results from a plane at $\frac{1}{2}$ -depth showed no difference (Fig. 5F). These findings indicate that 2D imaging at different planes of the islet can sometimes skew the results of the heterogeneity analysis.

The origin of Ca^{2+} waves in 3D space is determined by the activity of glucokinase, while the β -cell network is patterned independently of metabolic input

Glycolysis exerts strong control over the timing of β -cell Ca^{2+} oscillations^{2,32}. Glucokinase, as the 'glucose sensor' for the β -cell, controls the input of glucose carbons into glycolysis^{2,33}, and the downstream action of pyruvate kinase controls membrane depolarization by closing K_{ATP} channels^{2,22-24,34} (Fig. 6A). We applied glucokinase activator (GKa, 50 nM RO 28-1675) and pyruvate kinase activator (PKa, 10 μM TEPP-46)^{22,23} to determine the effects of these enzymes on β -cell subpopulations during glucose-stimulated oscillations.

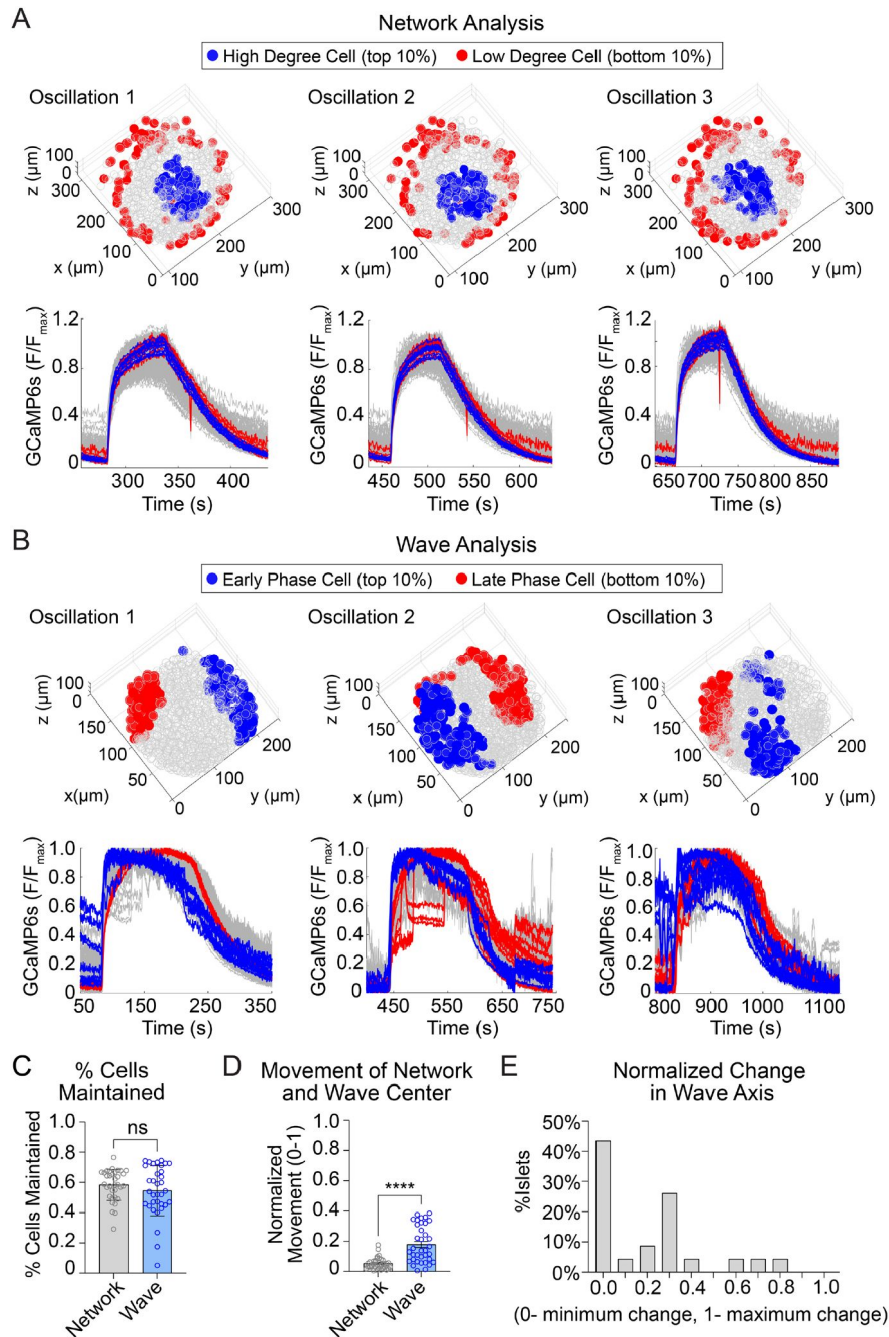


Fig. 3.

The network of highly synchronized β -cells is consistent between oscillations, while the Ca^{2+} wave axis rotates.

(A) 3D representation of the islet showing the location of high degree cells (blue) and low degree cells (red) over three consecutive oscillations (top panel) and their corresponding Ca^{2+} traces (bottom panel). (B) 3D representation of the islet showing the location of early phase cells (blue) and late phase cells (red) over three consecutive oscillations (top panel) and their corresponding Ca^{2+} traces (bottom panel). (C) Quantification of the retention rate of high degree and early phase cells. (D) Relative spatial change in the center of gravity of β -cell network vs. the β -cell Ca^{2+} wave. (E) Frequency distribution showing the normalized change in Ca^{2+} wave axis for all islets. Data are displayed as mean $\pm$ SEM. **** $P < 0.0001$ by normality test followed by Paired Student's t-test or Wilcoxon Signed-Rank Test.

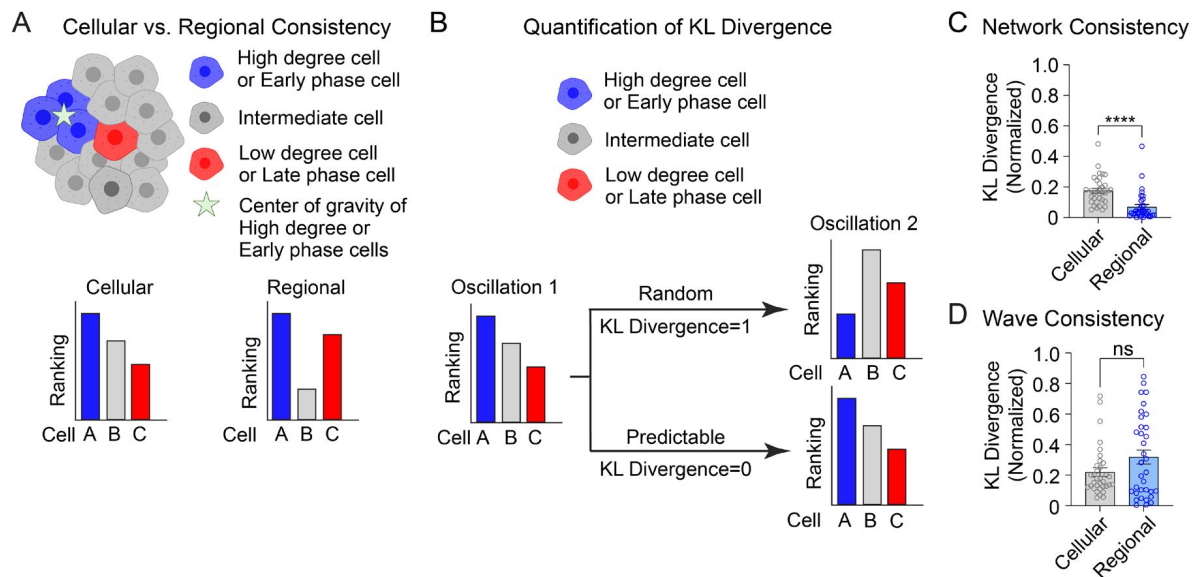


Fig. 4.

Cellular and regional consistency of the β -cell network and Ca^{2+} wave quantified by KL divergence.

(A) Schematic showing cellular consistency analysis and regional consistency analysis. (B) Schematic depicting the use of KL divergence to determine consistency between consecutive oscillations. Every β -cell in the islet is ranked, with near-zero KL divergence values indicating high consistency between oscillations and near-unity KL divergence indicating randomness. (C-D) Comparison of cellular vs. regional consistency of the network (C) and wave (D) by KL divergence. Data are displayed as mean $\pm$ SEM. **** $P < 0.0001$ by normality test followed by Paired Student's t -test or Wilcoxon Signed-Rank Test.

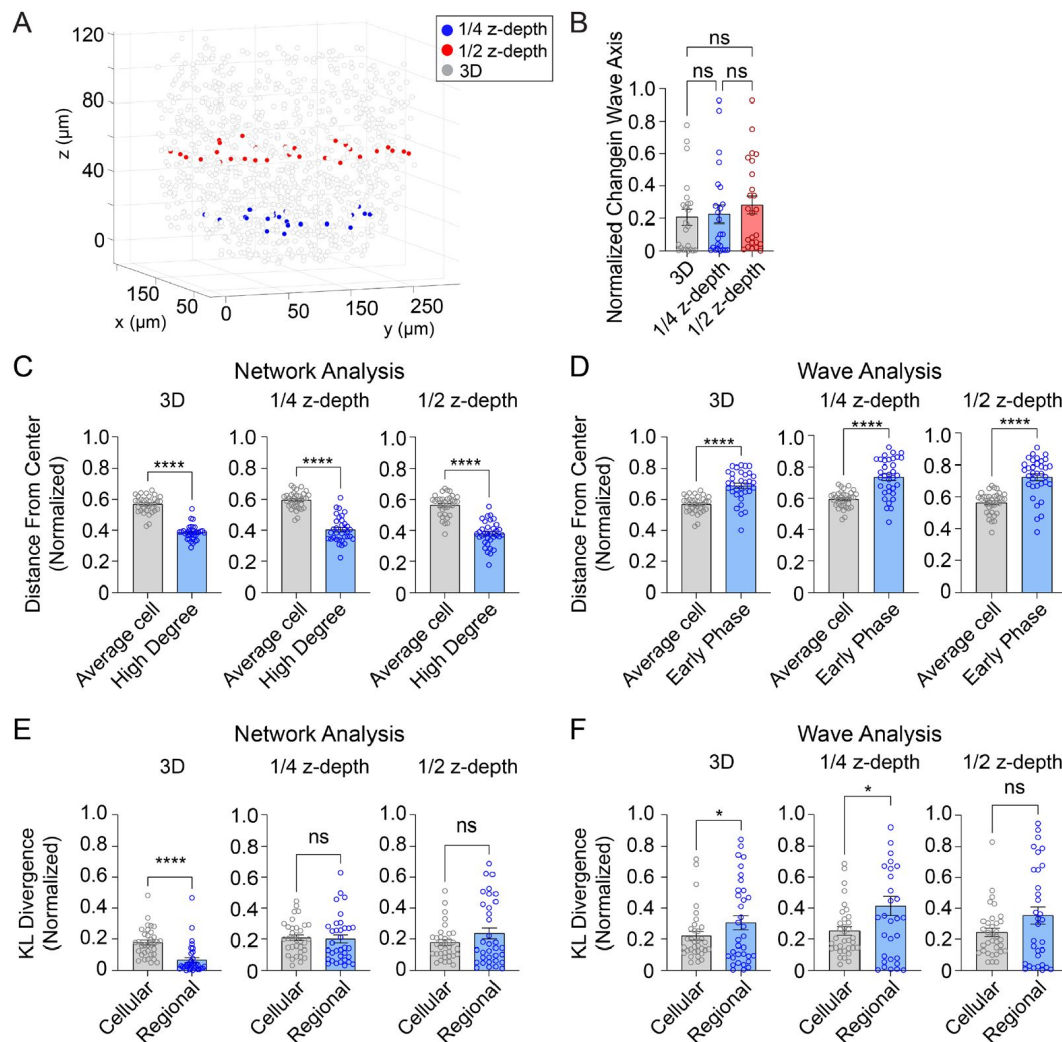


Fig. 5.

3D analysis is more robust than 2D analysis.

(A) Example islet showing the locations of the 1/4-depth (red) and 1/2-depth (blue) 2D planes used for analysis. (B) Comparison of wave axis change from 2D and 3D analysis. (C) Comparison of distance from center for average and high degree cells based on either 3D (left panel) or 2D planes (middle and right panels). (D) Comparison of distance from center for average and early phase cells based on either 3D (left panel) or 2D planes (middle and right panels). (E-F) Comparison of cellular and regional consistency of the network (E) and Ca^{2+} wave (F) based on either 3D (left panel) or 2D planes (middle and right panels). Data are displayed as mean $\pm$ SEM. * $P < 0.05$, **** $P < 0.0001$ by normality test followed by parametric or non-parametric 1-way ANOVA (B) or Student's t-test or Wilcoxon Signed-Rank Test (C-F).

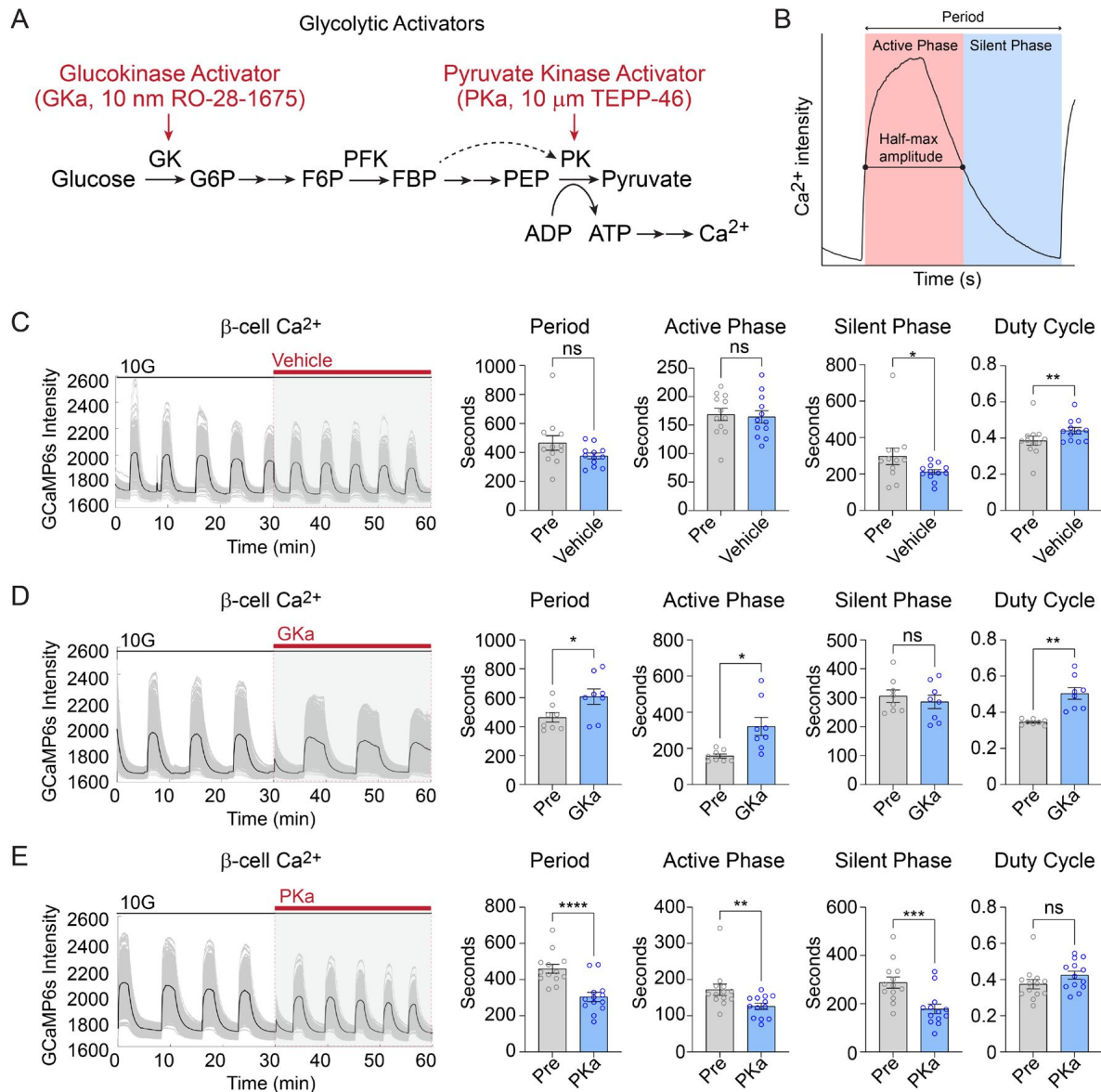


Fig. 6.

Effect of glycolytic activators on β -cell oscillations.

(A) Schematic of glycolysis showing the targets of glucokinase activator (GKa) and pyruvate kinase activator (PKa). (B) Illustration indicating the oscillation period, active phase duration, silent phase duration, and duty cycle (active phase/period) calculated at half-maximal Ca^{2+} . (C-E) Sample traces and comparison of period, active phase duration, silent phase duration and duty cycle before and after vehicle (0.1% DMSO) (n=11,284 cells, 13 islets, 7 mice) (C), GKa (50 nM RO-28-1675) (n=6871 cells, 8 islets, 7 mice) (D) and PKa (n=10,700 cells, 13 islets, 7 mice) (10 μ M TEPP-46) (E). Data are displayed as mean $\pm$ SEM. * P < 0.05, ** P < 0.01, *** P < 0.001, **** P < 0.0001 normality test followed by Paired Student's t-test or Wilcoxon Signed-Rank Test.

Since biochemically distinct processes occur during the silent phase (i.e., the electrically-silent period when K_{ATP} channels close and Ca^{2+} remains low) and the active phase (i.e., the electrically-active period Ca^{2+} is elevated and secretion occurs)^{22,23}, we quantified the duration of each phase along with the oscillation period and duty cycle (the ratio of active phase to full cycle) (**Fig. 6B**). In the presence of vehicle control (0.1% DMSO), the Ca^{2+} duty cycle remained stable, although an outlier in the control group resulted in a small decrease in the silent phase duration (**Fig. 6C**). In 3 of 15 islets, GKa induced a Ca^{2+} plateau (duty cycle = 1.0); out of necessity these islets were removed from the oscillation analysis. In the majority of islets, GKa increased the oscillation period and duty cycle (**Fig. 6D**). The duty cycle increase was driven by an increase in the active phase duration, with no impact on the silent phase, the time when K_{ATP} channels close (**Fig. 6D**). In contrast with activation of glucokinase, PKa increased the oscillation frequency by reducing the silent phase duration and the active phase duration in equal proportions (**Fig. 6E**). The absence of any PKa effect on the duty cycle is expected since fuel input is controlled by glucokinase, whereas silent phase shortening is expected based on the ability of PKa to reduce the time required to close K_{ATP} channels and depolarize the plasma membrane^{22,23}. Thus, a single cell 3D analysis of β -cell Ca^{2+} oscillation upon GKa and PKa stimulation provides similar conclusions to prior 2D studies of intact islets.

Previous 2D studies have found metabolic differences along the Ca^{2+} wave, as measured by NAD(P)H fluorescence¹³. We measured the 3D position of early or late phase cells in response to glucokinase or pyruvate kinase activation. A positional analysis showed that GKa strongly reinforced the islet region corresponding to early phase and late phase cells, while vehicle and PKa had no discernable effect (**Fig. 7A**). The KL divergence for wave propagation was correspondingly reduced by GKa (**Fig. 7B**), indicating increased consistency, and the wave axis was significantly stabilized by GKa (**Fig. 7C**). Again, PKa had no discernable effect on the KL divergence for wave propagation or wave axis stability, a likely indication that the Ca^{2+} wave origin is primarily, if not exclusively, controlled by glucokinase patterning.

As a second approach, we examined the percentage of early phase or late phase cells maintained following activation of glucokinase or pyruvate kinase. Early phase cells were maintained to a greater degree upon GKa application, indicating greater consistency, but again showed no change upon vehicle or PKa application (**Fig. 7D**). Late phase cells showed no difference in their maintenance upon any of the treatments (**Fig. 7E**), suggesting that the earliest phase cells drive the consistency of the wave propagation. The time lag between early and late phase cells were increased upon GKa application (**Fig. 7F**), showing that GK activation can enlarge the differences between early and late phase cells.

While metabolic differences have been suggested to underlie functional heterogeneity in the β -cell network^{10,35}, we observed no changes in the consistency of the islet network upon either GKa or PKa application (Suppl. Fig. 4A). Similarly, the consistency of high degree cells or low degree cells also did not change upon either GKa or PKa application (Suppl. Fig. 4B and 4C). Collectively, these findings implicate glucokinase as the key determinant of the Ca^{2+} wave in three-dimensional space, whereas metabolic perturbations have little influence on the islet network.

We defined early phase cells as those that depolarized and repolarized first. We also assessed whether the results were consistent for cells that only depolarized first (while ignoring repolarization). Similar to early phase cells, GKa increased the retention of β -cells that depolarized first (Suppl. Fig. 5A) and their regional consistency (Suppl. Fig. 5B). However, GKa did not influence the wave axis change (Suppl. Fig. 5C), indicating that the cells that depolarize first are a more unstable population than those that depolarize and repolarize first.

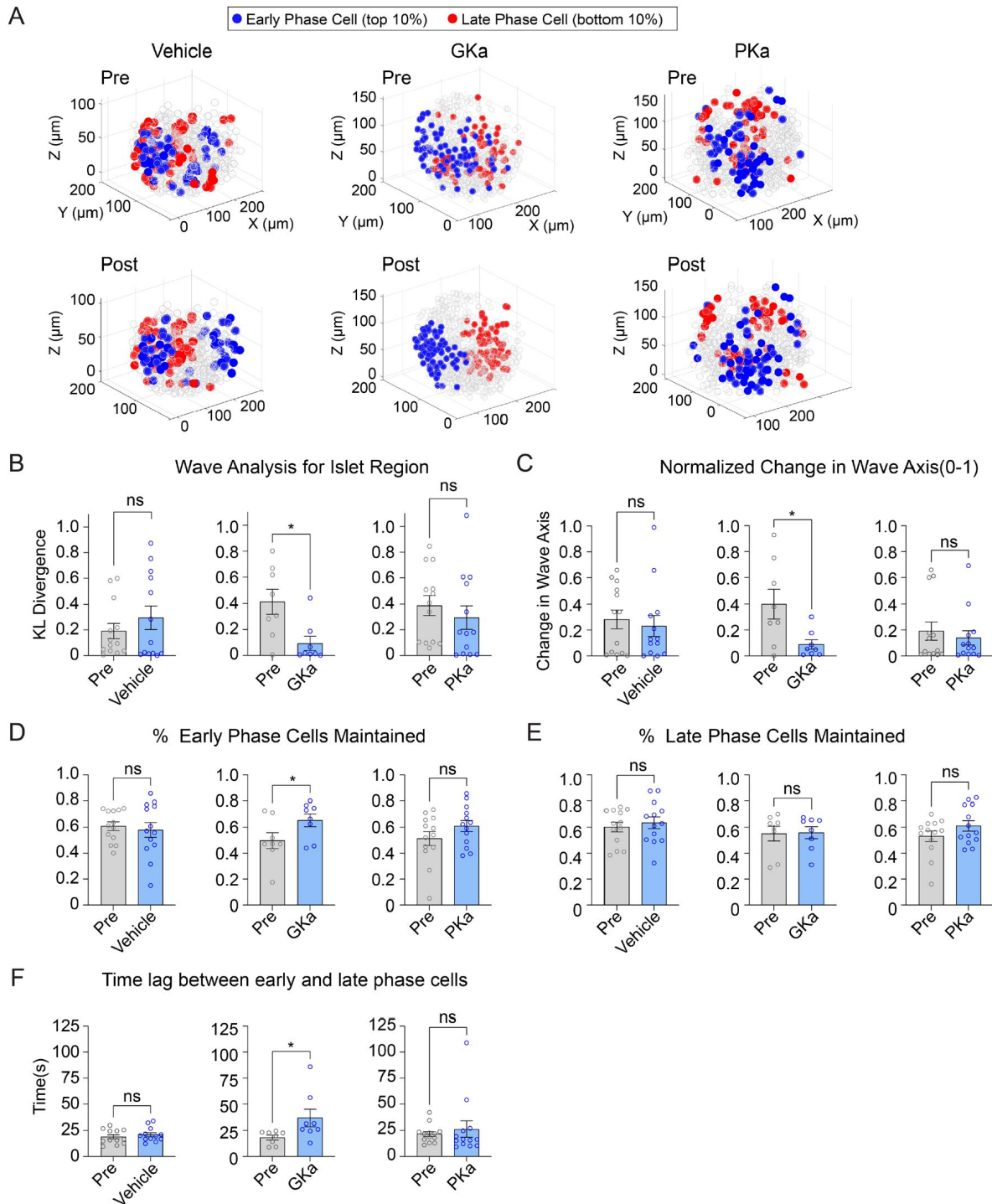


Fig. 7.

Glucokinase activity determines the origin of Ca^{2+} waves in 3D space.

(A) Illustrations showing the location change of early phase cells (blue) and late phase cells (red) before and after vehicle (left panel), GKa (middle panel) and PKa (right panel). (B-H) Effect of vehicle, GKa, and PKa on regional consistency of the Ca^{2+} wave (B), wave axis change (C), early phase cell retention (D), late phase cell retention (E), and the time lag between early and late phase cells(F). Data are displayed as mean $\pm$ SEM. * $P < 0.05$ by Student's t -test.

Discussion

In this study we used light-sheet microscopy of single mouse islets to provide a three-dimensional analysis of the β -cell subpopulations that initiate Ca^{2+} oscillations and coordinate the islet network. While this *ex vivo* approach might not precisely mimic the *in vivo* situation, our analyses show that 3D imaging is a more robust approach than 2D imaging, which does not accurately reflect heterogeneity and subpopulation consistency over the entire islet. Reinforcing the concept of distinct β -cell subpopulations, the most highly synchronized cells are located at the center of the islet, while those β -cells that control the initiation and termination of Ca^{2+} waves ('leaders') were located on the islet periphery. We further observed that different regions of the islet initiate the Ca^{2+} wave over time, challenging the view that leader cells are a fixed pacemaker population of cells defined by their biochemistry. As discussed below, technical advances in image capture and analysis provide several new insights into the features of β -cell subpopulation in 3D and illustrate how glycolytic enzymes influence the system.

β -cell Ca^{2+} imaging is an indispensable approach for understanding pulsatility. When studied by light-sheet imaging, islets exhibited similar ~ 3 -5-minute oscillations as *in vivo* 2-photon imaging of β -cell Ca^{2+} oscillations in live mice³⁶, as well as the high-speed confocal imaging used in prior *ex vivo* studies³⁷. Light-sheet imaging overcomes the speed and depth limitations, respectively, that prevent these approaches from single-cell analysis of the entire islet. Relative to spinning disk confocal, penetration depth increased >2 -fold with the light-sheet microscope (from 50-60 to 130-150 μm), allowing small and medium-sized islets to be imaged *in toto*. Abandoning confocal pinholes improved light collection, and therefore acquisition speed, ~ 3 -fold; this is an underestimate given the 0.4 e^- read noise cameras on the spinning disk microscope versus 1.6 e^- read noise cameras on the light-sheet microscope. The ~ 1.1 μm axial resolution of the light-sheet, while lower than spinning disk confocal, was easily sufficient for Nyquist sampling of 5-6 μm nuclei used to identify each β -cell in 3D space (β -cells themselves are 12-18 μm). Together these features allowed sampling the islet at >2 Hz, although future studies could be improved by employing a higher numerical aperture objective and a camera with lower read noise and higher quantum efficiency.

Phase and functional network analyses were used to understand the behavior of β -cell subpopulations and how they communicate. Importantly, in past heterogeneity studies, phase and network calculations were assessed over the entire time course^{10,15,27,38,39}. Here, we assessed over individual oscillations to compare subpopulation stability over time. One population of cells are those which we termed 'early phase cells' and lead the propagating Ca^{2+} wave. These have also been referred to as 'leader cells' or 'pacemaker cells' and regulate the oscillatory dynamics^{12,37,37}. To our surprise, the early phase cells (i.e. the leader cells) were not consistent over time. The late phase cells, located on the opposite end of the islet, showed a similar shift, with over half of the islets showing changes in the wave axis. Consequently, laser ablation of these early phase or late phase cells would be predicted to have little impact on islet function, as suggested previously by electrophysiological studies in which surface β -cells have been voltage-clamped with no impact on β -cell oscillations¹⁹, or computational studies in which removal of simulated β -cells had little impact on resulting oscillations^{15,40}.

Studies have sought to define whether β -cell intrinsic or extrinsic factors determine the oscillations^{10,19,35,41}. Because of the shift in Ca^{2+} wave axis between consecutive oscillations, we conclude that β -cell depolarization is dominated by stochastic properties rather than a pre-determined genetic or metabolic profile. Previous experimental and modeling studies have suggested that the Ca^{2+} wave origin corresponds to the glucokinase activity gradient^{15,27}. Consistent with this prediction, pharmacologic activation of glucokinase reinforced the islet region of early phase cells and reduced the wave axis change. Pyruvate kinase activation, despite

increasing oscillation frequency, had no effect on leader cells, indicating the wave origin is patterned by fuel input. Importantly, there is no evidence that the glucokinase gradient is the result of intentional spatial organization. Rather, in computational studies the glucokinase gradient emerges stochastically due to randomly placed high and low glucokinase-expressing cells, with multiple competing glucokinase gradients determining the degree of wave axis rotation. Our findings suggest that when glucokinase is activated, the strongest gradient is amplified, which is why the Ca^{2+} wave axis is reinforced. Another compelling hypothesis for stochastic behavior, which is not mutually exclusive, is the heterogeneous nutrient response of neighboring α -cells influences the excitability of neighboring β -cells via GPCRs^{42–44}. The preponderance of α -cells on the periphery of mouse islets, which influence β -cell oscillation frequency⁴⁵, would be expected to disrupt β -cell synchronization on the periphery and stabilize it in the islet center – which is precisely the pattern of network activity we observed. In addition to α -cells, vasculature may also impact islet Ca^{2+} responses⁴⁶, and may induce additional heterogeneity *in vivo*.

Functional network studies of the islet revealed a heterogeneity in β -cell functional connections¹⁴. A small subpopulation of β -cells, termed ‘hub’ cells, was found to have the highest synchronization to other cells¹⁰. Optogenetic silencing of hub cells was found to disrupt network activity within that plane, however it should be noted that hub cells are defined as the most highly coordinated cells within a randomly selected plane of the islet. Debates exist over whether the hub cells can maintain electrical control over the whole islet^{19,47}. Because our study investigated the 3D β -cell functional network over individual oscillations, our top 10% of highly coordinated cells are not the exact same population as hub cells defined in¹⁰, however the subpopulations likely overlap. In contrast with leader cells, we found that the highly synchronized hub cells are both spatially and temporally stable. However, in conflict with the description of hub cells as intermingled with other cells throughout the islet¹⁰, the location of such cells in 3D space is close to the center. This observation could be explained by the peripheral location of α -cells as discussed above for the Ca^{2+} wave behavior.

Previous studies indicated that the intrinsic metabolic activity and thus oscillation profile may play a larger role in driving high synchronization than the strength of gap junction coupling^{35,41}. This included experimental 2D measurements but also computational 3D measurements. Nevertheless, we demonstrated here that perturbing glucokinase or pyruvate kinase had little effect on the consistency of the high degree or low degree cells within the 3D network. We further observed that the β -cell network was more regionally consistent than cellularly consistent, indicating a tendency for nearby cells within the islet center to ‘take over’ as high degree cells. The mechanisms underlying this are unclear. One explanation may be that paracrine communication within the islet determines which region of cells will show high or low degree⁴⁵. For example, more peripheral cells that are in contact with nearby δ -cells may show some suppression in their Ca^{2+} dynamics⁴⁸, and thus reduced synchronization. Alternatively, more peripheral cells may show increased stochastic behavior that reduces their relative synchronization. Modulating α/δ -cell inputs to the β -cell in combination with 3D islet imaging will be important to test this in the future. Our study emphasizes that 3D studies are critical to fully assess the consistency and spatial organization of the β -cell network.

Methods

Mice

Ins1-Cre mice⁴⁹ (Jax 026801) were crossed with *GCaMP6s* mice (Jax 028866), a Cre-dependent Ca^{2+} indicator strain, and *H2B-mCherry* mice, a Cre-dependent nuclear indicator strain⁵⁰. The resulting *Ins1-Cre:ROSA26^{GCaMP6s}/H2B-mCherry* mice were genotyped by Transnetyx. Mice were sacrificed by CO_2 asphyxiation followed by cervical dislocation at 12–15 weeks of age, and islets

were isolated and cultured as detailed in²⁴. All procedures involving animals were approved by the Institutional Animal Care and Use Committees of the William S. Middleton Memorial Veterans Hospital and followed the NIH Guide for the Care and Use of Laboratory Animals.

Light-sheet microscope

The stage of a Nikon Ti inverted epifluorescence microscope was replaced with a Mizar TILT M-21N lateral interference tilted excitation light-sheet generator²⁵ equipped with an ASI MS-2000 piezo z-stage and Okolab stagetop incubator. The sample chamber consisted of an Ibidi 4-well No. 1.5 glass bottom chamber slide with optically clear sides. Excitation from a Vortran Stradus VeraLase 4-channel (445/488/561/637) single mode fiber-coupled laser and CDRH control box (AVR Optics) was passed through the TILT cylindrical lens to generate a light-sheet with a beam waist of 4.3 μm directly over the objective's field of view. Similar to a wide-field microscope, the axial (z) resolution of the light-sheet microscope is dictated by the numerical aperture of the objective ($\sim 1.1 \mu\text{m}$ for our Nikon CFI Apo LWD Lambda S 40XC water immersion objective with a numerical aperture of 1.15). Fluorescence emission was passed through an optical beamsplitter (OptoSplit III, 89 North) and collected by an ORCA-Flash4.0 v3 digital CMOS camera (Hamamatsu C13440-20CU) equipped with a PoCL camera link cable. To achieve high-speed triggered acquisition, the laser and piezo z stage were triggered directly by the camera, which received a single packet of instructions from the NIS-Elements JOBS module via a PCI express NiDAQ card (PCIe-6323, National Instruments). Electronic components (DAQ card, camera, lasers, stage) were linked by a Nikon 'standard cable' via a Nikon BNC breakout box; cable assembly is diagrammed in Suppl. Fig. 1. Images were streamed to a Dell computer equipped with an Intel Xeon Silver 4214R CPU, 256 GB RAM, XG5 NVMe SSD, and NVIDIA Quadro Pro 8 GB graphics card and Bitplane Imaris Software (Andor).

Imaging of β -cell Ca^{2+} and nuclei

Reagents were obtained from Sigma-Aldrich unless indicated otherwise. Islets isolated from *Ins1-Cre:ROSA26^{GCaMP6s/H2B-mCherry}* mice were incubated overnight and loaded into an Ibidi μ -slide 4-well No. 1.5 glass bottom chamber slide and maintained by an Okolab stagetop incubator at 37°C. The bath solution contained, in mM: 135 NaCl, 4.8 KCl, 2.5 CaCl_2 , 1.2 MgCl_2 , 20 HEPES, 10 glucose, 0.18 glutamine, 0.15 leucine, 0.06 arginine, 0.6 alanine, pH 7.35. Glucokinase activator (50 nM RO 28-1675, Axon), pyruvate kinase activator (10 μM TEPP-46, Calbiochem), and vehicle control (0.1% DMSO) were added as indicated. GCaMP6s (488 nm, 5% power, 50 mW Vortran Stradus Versalase) and H2B- mCherry (561 nm, 20% power, 50 mW) were simultaneously excited and emission was simultaneously collected on a single camera chip using an optical beamsplitter (Optosplit III, 89 North) containing a dichroic mirror (ZT568rdc, Chroma) and emission filters for GCaMP6s (ET525/40, Chroma) and mCherry (ET650/60, Chroma). The exposure time was set to 15 ms in NIS-Elements JOBS, which includes ~ 10 ms camera integration time and ~ 5 ms stage dwell time. This was sufficiently fast to image intact islets an axial (z) depth of 132 μm at 2.02 Hz (33 z-steps every 4 μm). Raw NIS-Elements ND2 files were imported into Bitplane Imaris analysis software. The location of each cell was marked using H2B-mCherry nuclear signal and a sphere mask was created based on average β -cell nuclear diameter. Nuclear ROIs were mathematically expanded to 9.3 μm to avoid overlapping cells, which was determined by point-scanning confocal imaging³⁰. Masks were propagated to all the timepoints and mean Ca^{2+} levels were used to generate single cell traces that were exported from Imaris to Microsoft Excel. Quantitative analyses of the β -cell network and Ca^{2+} wave were performed in MATLAB as described below.

Identification of β -cell Ca^{2+} Oscillations

To compare β -cell subpopulations over multiple oscillations, we developed a semi-automated oscillation identifier to ensure that the results did not depend on manual identification of oscillation start and end times. First, the approximate time corresponding to the peak of each oscillation was manually identified based on the average islet signal. The time course around each

oscillation peak was automatically extracted as seconds before the islet begins depolarization $x/2$ seconds after the islet completes repolarization, where $x = 1/4$ oscillation duty cycle. Depolarization and repolarization were then automatically identified using the derivatives of the Ca^{2+} time course and MATLAB's findpeaks function. All oscillation time courses were manually confirmed. For studies of glycolysis, we ensured that all pre- and post-glycolytic activator treatments had the same number of oscillations. All islets analyzed exhibited slow Ca^{2+} oscillations (period = 6.77 ± 0.36 min).

Network analysis

Network analysis was conducted as described in³⁵, with the caveat that the functional network was recalculated for each oscillation. The correlation threshold was calculated such that the average degree was 7 when averaged over all oscillations³¹.

Wave analysis

Lagged cross correlation between the normalized Ca^{2+} dynamics of each cell and the islet mean was calculated for each oscillation. Each cell was assigned a cell phase, defined as the time lag that maximized the cross correlation.

Wave axis

Wave axis was defined as the primary axis between the early (top 10%) and late (bottom 10%) of cells in the Ca^{2+} wave. The primary axis was identified using principal component analysis. To ensure the axis was not confounded by spuriously located cells, cells were not included in the analysis if they were greater than $50 \mu\text{m}$ from the center of gravity (calculated using Euclidean distance) of their respective group (early or late phase). Variability of the wave axis over oscillations was defined as the squared Euclidean distance between each wave axis. To compare across islets of differences sizes, wave axis variability was normalized by the maximum variability possible for each islet. This maximum variability was identified by repeating the wave axis calculation 50,000 times for randomly selected early and late phase cells.

KL-divergence

To calculate consistency over oscillations of the entire islet, network and wave analysis were conducted and cells were ranked for each oscillation (i) based on (a) their degree or phase and (b) their Euclidean distance to the center of gravity of the high degree or early phase cells. The probability density functions (p_i) of these rankings was calculated using the MATLAB normpdf function. The KL-divergence⁵¹ (D_{KL}) was defined by equation (1), where n is the index of each cell, and i, j are indices for each oscillation.

$$D_{KL}(P_i||P_j) = \sum_n P_i \log \frac{P_i}{P_j} \quad (1)$$

To compare across islets of differences sizes, we normalized the KL divergence by the maximum KL divergence for each islet identified by shuffling the distribution and calculating KL divergence 100 times.

Comparison of 2D and 3D analyses

Quarter- and half-depth 2D planes were selected from each 3D islet. Cells were included in the 2D plane if their location on the z-axis was within $3 \mu\text{m}$ of the plane.

Statistical analysis

Statistical analysis was conducted using GraphPad PRISM 9.0 software. Significance was tested by first testing normality using Anderson-Darling and Kolmogorov-Smirnov normality tests and then using paired Wilcoxon tests, Student's two-tailed t-tests or ANOVA as indicated. $P < 0.05$ was considered significant and errors signify $\pm$ SEM.

Data and code availability

All data analyzed during this study will be included in this published article and its supplementary information files. All code is publicly available at https://github.com/jenniferkbriggs/Lightsheet_BetaCell_Identity 

Acknowledgements

We thank Barak Blum at the University of Wisconsin-Madison for providing *Rosa26^{H2B-mCherry}* mice and the University of Wisconsin Optical Imaging Core for use of the spinning disk confocal. The Merrins laboratory gratefully acknowledges support from the NIH/NIDDK (R01DK113103 and R01DK127637 to M.J.M., and R01DK106412 to R.K.P.B.) and the United States Department of Veterans Affairs Biomedical Laboratory Research and Development Service (I01BX005113 to M.J.M.). The Benninger laboratory gratefully acknowledges support from the NIH/NIDDK (R01DK106412, R01DK102950, R01DK140904 to R.K.P.B.) and the University of Colorado Diabetes Research center (P30 DK116073). Jennifer K Briggs acknowledges support from NSF GRFP (DGE-1938058_Briggs).

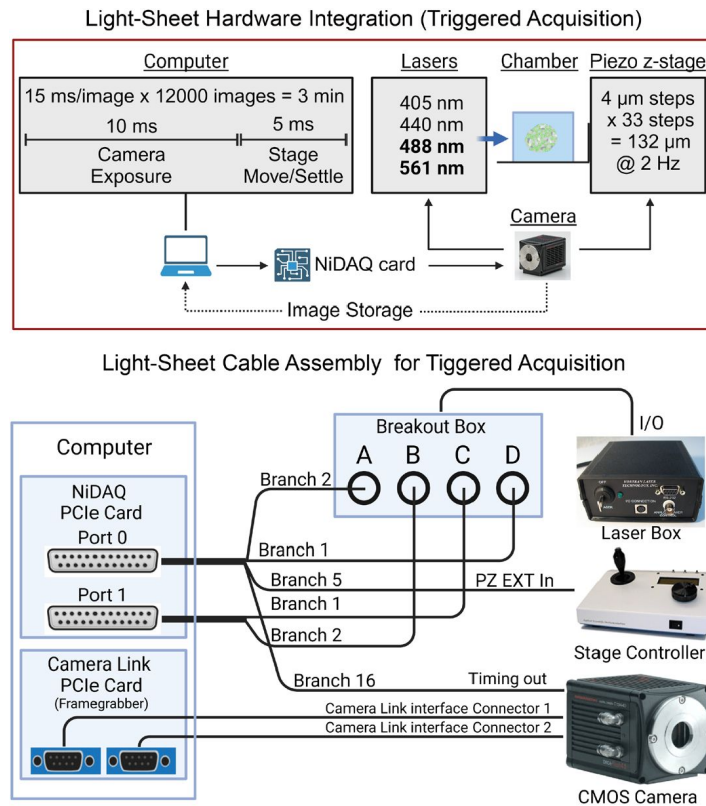
Author Contributions

E.J. constructed the microscope and performed islet imaging experiments. J.K.B. and E.J. analyzed the data and created the figures. E.J. and M.J.M. drafted the paper and all authors edited the paper. M.J.M. and R.K.P.B. provided resources.

Competing interests

The authors declare no competing interests.

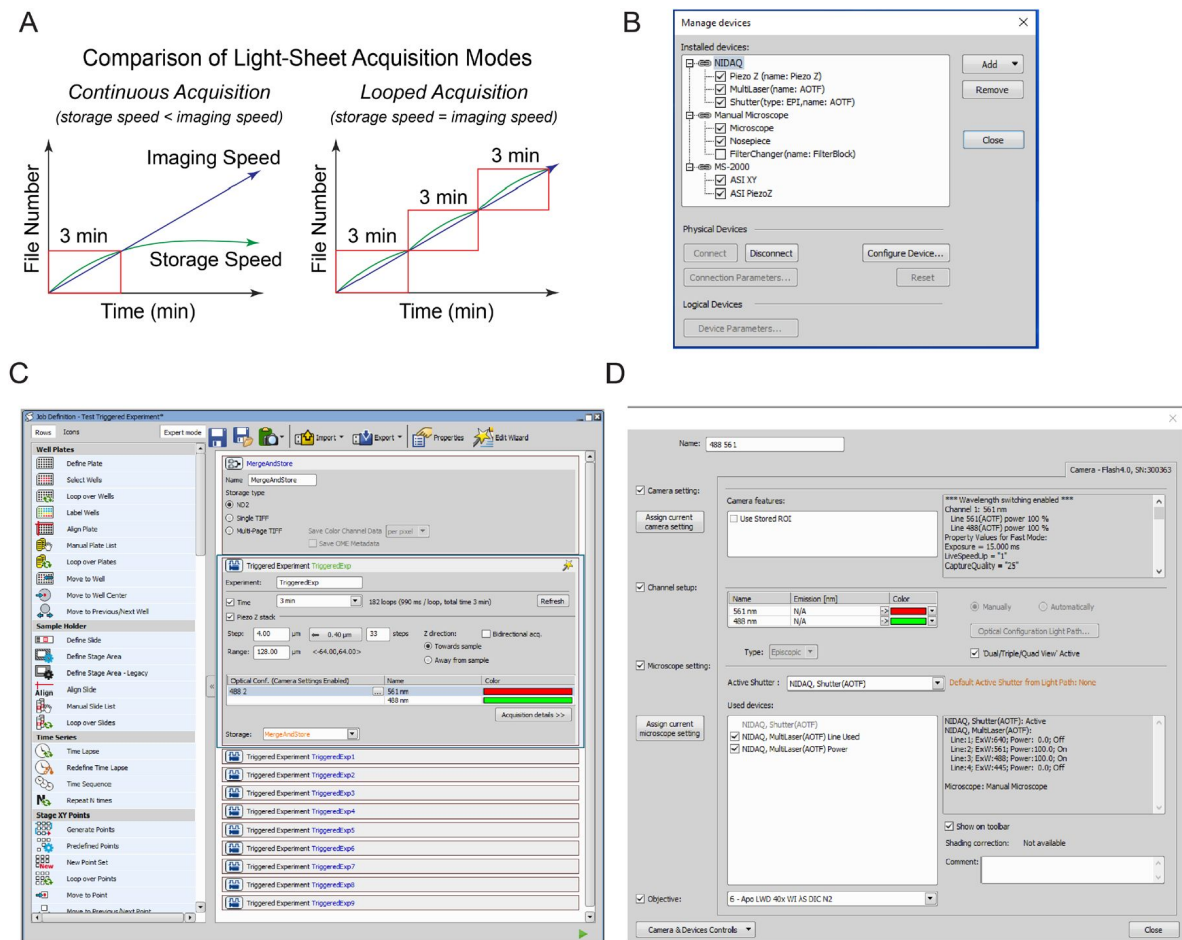
Correspondence and requests for materials should be addressed to Matthew J. Merrins and Richard K.P. Benninger.



Suppl. Fig. 1.

Hardware wiring diagram of the light-sheet microscope.

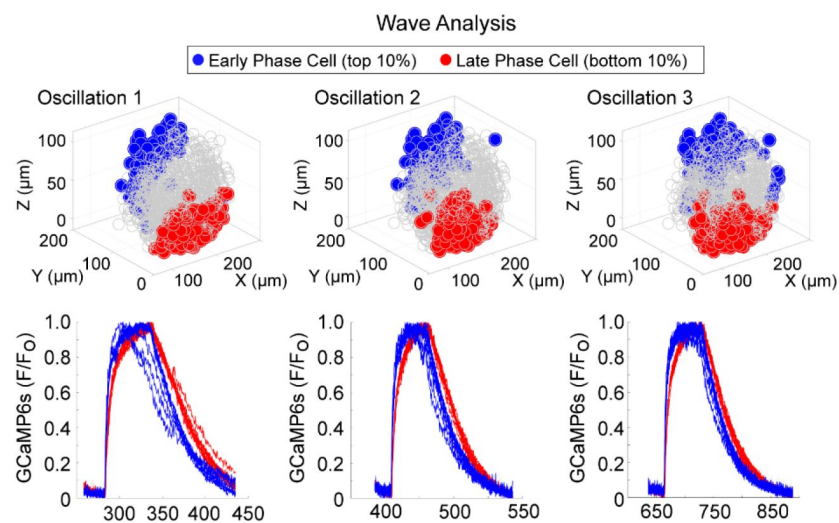
Hardware integration (top panel) for camera-triggered activation of the excitation lasers and piezo z-stage that limits communication to a single instruction from the computer every 3 minutes. Wiring diagram (bottom panel): two Nikon 'standard cables' connect to the NiDAQ card installed in the computer. These two cables link to the laser control box, stage controller and camera. The images captured are received by the computer through a camera link PCIe card. and



Suppl. Fig. 2.

NIS-Elements software configuration.

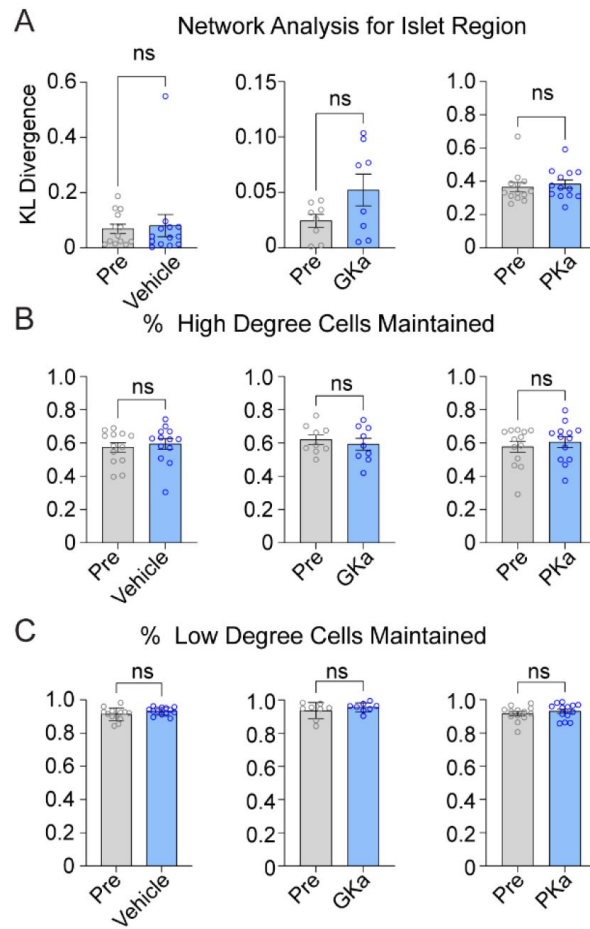
(A) Schematic for comparing continuous acquisition and looped acquisition. The red box indicates the 3-minute window where storage speed is higher than imaging speed. (B) Devices linked to NIS-Elements. (C) NIS-Elements JOBS module configured for looped acquisition. (D) Optical configuration for simultaneous GCaMP6s/H2B-mCherry excitation.



Suppl. Fig. 3.

Location of early and late phase cells in an islet with stable wave axis.

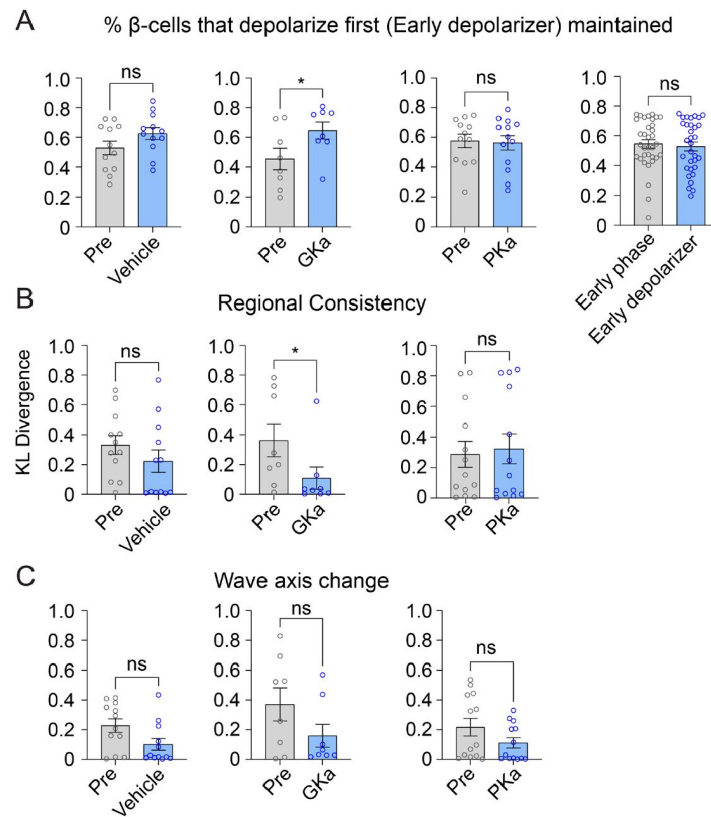
3D representation of the islet showing the location of early phase cells (blue) and late phase cells (red) over three consecutive oscillations (top panel) and their corresponding Ca^{2+} traces (bottom panel).



Suppl. Fig. 4.

Effect of glycolytic activators on the β -cell network.

(A-C) Effect of vehicle, glucokinase activator (GK α), and pyruvate kinase activator (PK α) on regional consistency of the β -cell network (A), high degree cell retention (B), and low degree cells retention (C). Data are displayed as mean $\pm$ SEM.



Suppl. Fig. 5.

Effect of glycolytic activators on the β -cells that depolarize first.

(A-C) Effect of vehicle, glucokinase activator (GKa), and pyruvate kinase activator (PKa) on the retention (A), regional consistency (B), and wave axis change (C) of the β -cells that depolarize first (Early depolarizer). The retention of β -cells that depolarize first (Early depolarizer) is similar to cells that depolarize and repolarize first (Early phase). Data are displayed as mean $\pm$ SEM.

References

1. Satin L. S., Butler P. C., Ha J., Sherman A. S (2015) **Pulsatile insulin secretion, impaired glucose tolerance and type 2 diabetes** *Mol Aspects Med* **42**:61–77
2. Merrins M. J., Corkey B. E., Kibbey R. G., Prentki M (2022) **Metabolic cycles and signals for insulin secretion** *Cell Metab* :223–6 <https://doi.org/10.1016/j.cmet.2022.06.003>
3. Benninger R. K., Kravets V (2022) **The physiological role of β -cell heterogeneity in pancreatic islet function** *Nature Reviews Endocrinology* **18**:9–22
4. Hiriart M., Ramirez-Medeles M. C (1991) **Functional subpopulations of individual pancreatic B-cells in culture** *Endocrinology* **128**:3193–3198
5. Kiekens R., et al. (1992) **Differences in glucose recognition by individual rat pancreatic B cells are associated with intercellular differences in glucose-induced biosynthetic activity** *The Journal of clinical investigation* **89**:117–125
6. Pipeleers D. G (1992) **Heterogeneity in pancreatic β -cell population** *Diabetes* **41**:777–781
7. Rutter G. A., Gresch A., Delgadillo Silva L., Benninger R. K. P (2024) **Exploring pancreatic beta-cell subgroups and their connectivity** *Nat Metab* <https://doi.org/10.1038/s42255-024-01097-6>
8. Wojtusciszyn A., Armanet M., Morel P., Berney T., Bosco D (2008) **Insulin secretion from human beta cells is heterogeneous and dependent on cell-to-cell contacts** *Diabetologia* **51**:1843–1852
9. Xavier G. D. S., Rutter G. A (2020) **Metabolic and functional heterogeneity in pancreatic β cells** *Journal of molecular biology* **432**:1395–1406
10. Johnston N. R., et al. (2016) **Beta cell hubs dictate pancreatic islet responses to glucose** *Cell metabolism* **24**:389–401
11. Kravets V., et al. (2022) **Functional architecture of pancreatic islets identifies a population of first responder cells that drive the first-phase calcium response** *PLoS Biol* **20**
12. Salem V., et al. (2019) **Leader beta-cells coordinate Ca²⁺ dynamics across pancreatic islets in vivo** *Nature Metabolism* **1**:615–629
13. Westacott M. J., Ludin N. W., Benninger R. K (2017) **Spatially organized β -cell subpopulations control electrical dynamics across islets of Langerhans** *Biophysical journal* **113**:1093–1108
14. Stožer A., et al. (2013) **Functional connectivity in islets of Langerhans from mouse pancreas tissue slices** *PLoS Comput Biol* **9**
15. Dwulet J. M., Briggs J. K., Benninger R. K. P (2021) **Small subpopulations of beta-cells do not drive islet oscillatory [Ca²⁺] dynamics via gap junction communication** *PLOS Computational Biology* **17**

16. Nasteska D., et al. (2021) **PDX1LOW MAFALOW β -cells contribute to islet function and insulin release** *Nat Commun* **12**
17. Briggs J. K., Kravets V., Dwulet J. M., Albers D. J., Benninger R. K. P (2022) **Beta-cell Metabolic Activity Rather than Gap Junction Structure Dictates Subpopulations in the Islet Functional Network** *bioRxiv* <https://doi.org/10.1101/2022.02.06.479331>
18. Peercy B. E., Sherman A. S (2022) **Do oscillations in pancreatic islets require pacemaker cells?** *Journal of Biosciences* **47**:1–11
19. Satin L. S., Zhang Q., Rorsman P (2020) **“Take Me To Your Leader”: An Electrophysiological Appraisal of the Role of Hub Cells in Pancreatic Islets** *Diabetes* **69**:830–836
20. Dwulet J. M., et al. (2019) **How heterogeneity in glucokinase and gap-junction coupling determines the islet $[Ca^{2+}]$ response** *Biophysical journal* **117**:2188–2203
21. Jetton T. L., Magnuson M. A (1992) **Heterogeneous expression of glucokinase among pancreatic beta cells** *Proceedings of the National Academy of Sciences* **89**:2619–2623
22. Lewandowski S. L., et al. (2020) **Pyruvate Kinase Controls Signal Strength in the Insulin Secretory Pathway** *Cell Metab* **32**:736–750
23. Foster H. R., et al. (2022) **β -cell deletion of the PKm1 and PKm2 isoforms of pyruvate kinase in mice reveals their essential role as nutrient sensors for the KATP channel** *Elife* **11**
24. Ho T., Potapenko E., Davis D. B., Merrins M. J (2023) **A plasma membrane-associated glycolytic metabolon is functionally coupled to KATP channels in pancreatic α and β cells from humans and mice** *Cell Rep* **42**
25. Fadero T. C., et al. (2018) **LITE microscopy: Tilted light-sheet excitation of model organisms offers high resolution and low photobleaching** *J. Cell Biol* **217**:1869–1882
26. Benninger R. K., Zhang M., Head W. S., Satin L. S., Piston D. W (2008) **Gap junction coupling and calcium waves in the pancreatic islet** *Biophysical journal* **95**:5048–5061
27. Hraha T. H., et al. (2014) **Phase transitions in the multi-cellular regulatory behavior of pancreatic islet excitability** *PLoS computational biology* **10**
28. Skyggebjerg O. (1999) **Acquisition and analysis of complex dynamic intra-and intercellular signaling events**. Denmark: Technical University of Denmark
29. Stožer A., Dolenšek J., Rupnik M. S (2013) **Glucose-stimulated calcium dynamics in islets of Langerhans in acute mouse pancreas tissue slices** *PloS one* **8**
30. Briggs J., Jin E., Merrins M. J., Benninger R (2024) **K CRISP: Correlation-Refined Image Segmentation Process** <https://doi.org/10.1101/2024.08.23.609461>
31. Šterk M., et al. (2024) **Network representation of multicellular activity in pancreatic islets: Technical considerations for functional connectivity analysis** *PLOS Computational Biology* **20**
32. Tornheim K (1997) **Are metabolic oscillations responsible for normal oscillatory insulin secretion?** *Diabetes* **46**:1375–1380

33. Matschinsky F. M., Ellerman J. E (1968) **Metabolism of glucose in the islets of Langerhans** *J. Biol. Chem* **243**:2730–2736
34. Quesada I., Nadal A., Soria B (1999) **Different effects of tolbutamide and diazoxide in alpha, beta-, and delta-cells within intact islets of Langerhans** *Diabetes* **48**:2390–2397
35. Briggs J. K., et al. (2023) **β -cell intrinsic dynamics rather than gap junction structure dictates subpopulations in the islet functional network** *Elife* **12**
36. Adams M. T., et al. (2021) **Reduced synchronicity of intra-islet Ca^{2+} oscillations in vivo in Robo-deficient β cells** *Elife* **10**
37. Peng X., et al. (2024) **Readily releasable β cells with tight Ca^{2+} -exocytosis coupling dictate biphasic glucose-stimulated insulin secretion** *Nat Metab* **6**:238–253
38. Stožer A., et al. (2022) **From Isles of Königsberg to Islets of Langerhans: Examining the function of the endocrine pancreas through network science** *Frontiers in Endocrinology* **13**
39. Stožer A., et al. (2013) **Functional connectivity in islets of Langerhans from mouse pancreas tissue slices** *PLoS computational biology* **9**
40. Korošak D., et al. (2021) **Autopoietic influence hierarchies in pancreatic β cells** *Physical Review Letters* **127**
41. Šterk M., Barać U., Stožer A., Gosak M (2023) **Both electrical and metabolic coupling shape the collective multimodal activity and functional connectivity patterns in beta cell collectives: A computational model perspective** *Physical Review E* **108**
42. Capozzi M. E., et al. (2019) **β Cell tone is defined by proglucagon peptides through cAMP signaling.** *JCI Insight* **4**
43. El K., et al. (2021) **GIP mediates the incretin effect and glucose tolerance by dual actions on α cells and β cells** *Sci Adv* **7**
44. Kang G., Leech C. A., Chepurny O. G., Coetzee W. A., Holz G. G (2008) **Role of the cAMP sensor Epac as a determinant of KATP channel ATP sensitivity in human pancreatic beta-cells and rat INS-1 cells** *J Physiol* **586**:1307–1319
45. Ren H., et al. (2022) **Pancreatic α and β cells are globally phase-locked** *Nat Commun* **13**
46. Jevon D., et al. (2022) **Local activation of focal adhesion kinase orchestrates the positioning of presynaptic scaffold proteins and Ca^{2+} signalling to control glucose-dependent insulin secretion** *Elife* **11**
47. Satin L. S., Rorsman P, et al. (2020) **“Take me to your leader”: An electrophysiological appraisal of the role of hub cells in pancreatic islets** *Diabetes* **69**:830–836
48. Dickerson M. T., et al. (2022) **Gi/o protein-coupled receptor inhibition of beta-cell electrical excitability and insulin secretion depends on Na^+/K^+ ATPase activation** *Nat Commun* **13**
49. Thorens B., et al. (2015) **Ins1(Cre) knock-in mice for beta cell-specific gene recombination** *Diabetologia* **58**:558–565

- 50. Blum B., et al. (2014) **Reversal of β cell de-differentiation by a small molecule inhibitor of the TGF β pathway** *Elife* 3
- 51. Kullback S., Leibler R. A. (1951) **On information and sufficiency.** *The annals of mathematical statistics* 22:79–86

Author information

Erli Jin*

Department of Medicine, Division of Endocrinology, Diabetes & Metabolism, University of Wisconsin- Madison, Madison, United States
ORCID iD: [0009-0002-9410-9738](https://orcid.org/0009-0002-9410-9738)

*Equal contribution

Jennifer K Briggs*

Department of Bioengineering, University of Colorado Anschutz Medical Campus, United States; Barbara Davis Center for Childhood Diabetes, University of Colorado Anschutz Medical Campus, Aurora, United States
ORCID iD: [0000-0002-8737-2215](https://orcid.org/0000-0002-8737-2215)

*Equal contribution

Richard KP Benninger

Department of Bioengineering, University of Colorado Anschutz Medical Campus, United States; Barbara Davis Center for Childhood Diabetes, University of Colorado Anschutz Medical Campus, Aurora, United States
ORCID iD: [0000-0002-5063-6096](https://orcid.org/0000-0002-5063-6096)

For correspondence: richard.benninger@cuanschutz.edu

Matthew J Merrins

Department of Medicine, Division of Endocrinology, Diabetes & Metabolism, University of Wisconsin- Madison, Madison, United States
ORCID iD: [0000-0003-1599-9227](https://orcid.org/0000-0003-1599-9227)

For correspondence: mmerrins@medicine.wisc.edu

Editors

Reviewing Editor

Show-Ling Shyng

Oregon Health & Science University, Portland, United States of America

Senior Editor

Felix Campelo

Institute of Photonic Sciences, Barcelona, Spain

Reviewer #1 (Public review):

Summary:

Jin, Briggs and colleagues use light sheet imaging to reconstruct the islet three-dimensional Ca^{2+} network. The authors find that early/late responding (leader) cells are dynamic over time, and located at the islet periphery. By contrast, highly connected or hub cells are stable, and located toward the islet center. Suggesting that the two subpopulations are differentially regulated by fuel input, glucokinase activation only influences leader cell phenotype, whereas hubs remain stable.

Strengths:

The studies are novel in providing the first three-dimensional snapshot of the beta cell functional network, as well as determining the localization of some of the different subpopulations identified to date. The studies also provide some consensus as to the origin, stability and role of such subpopulations in islet function.

Weaknesses:

Experiments with metabolic enzyme activators do not take into account the influence of cell viability on the observed Ca^{2+} network data. Limitations of the imaging approach used need to be recognised and evaluated/discussed.

Comments on revisions:

The authors have addressed the majority of the points raised.

<https://doi.org/10.7554/eLife.103068.2.sa3>

Reviewer #2 (Public review):

The manuscript by Erli Jin and Jennifer Briggs et al. utilizes light sheet microscopy to image islet beta cell calcium oscillations in 3D and determine where beta cell populations are located that begin and coordinate glucose-stimulated calcium oscillations. The light sheet technique allowed clear 3D mapping of beta cell calcium responses to glucose, glucokinase activation, and pyruvate kinase activation. The manuscript finds that synchronized beta-cells are found at the islet center, that leader beta cells showing the first calcium responses are located on the islet periphery, that glucokinase activation helped maintain beta cells that lead calcium responses, and that pyruvate kinase activation primarily increases islet calcium oscillation frequency. The study is well-designed, contains a significant amount of high quality data, and the conclusions are largely supported by the results.

Comments on revisions:

The manuscript by Erli Jin et al. has been improved with the revisions, which have addressed my previous concerns. The manuscript significantly improves the mechanistic underpinnings of islet calcium oscillations and resulting pulsatile insulin secretion.

<https://doi.org/10.7554/eLife.103068.2.sa2>

Reviewer #3 (Public review):

Summary:

Jin, Briggs et al. made use of light-sheet 3D imaging and data analysis to assess the collective network activity in isolated mouse islets. The major advantage of using whole islet imaging, despite compromising on a speed of acquisition, is that it provides a complete description of the network, while 2D networks are only an approximation of the islet network. In static-incubation conditions, excluding the effects of perfusion, they assessed two subpopulations of beta cells and their spatial consistency and metabolic dependence.

Strengths:

The authors confirmed that coordinated Ca^{2+} oscillations are important for glycemic control. In addition, they definitively disproved the role of individual privileged cells, which were suggested to lead or coordinate Ca^{2+} oscillations. They provided evidence for differential regional stability, confirming the previously described stochastic nature of the beta cells that act as strongly connected hubs as well as beta cells in initiating regions (doi.org/10.1103/PhysRevLett.127.168101). This has not been a surprise to the reviewer.

The fact that islet cores contain beta cells that are more active and more coordinated has also been readily observed in high-frequency 2D recordings (e.g. DOI: 10.2337/db22-0952), suggesting that the high-speed capture of fast activity can partially compensate for incomplete topological information.

They also found an increased metabolic sensitivity of mantle regions of an islet with subpopulation of beta cells with a high probability of leading the islet activity and which can be entrained by fuel input. They discuss a potential role of alpha/delta cell interaction, however relative lack of beta cells in the islet border region could also be a factor contributing to less connectivity and higher excitability.

The Methods section contains a useful series of direct instructions on how to approach fast 3D imaging with currently available hardware and software.

The Discussion is clear and includes most of the issues regarding the interpretation of the presented results.

Taken together it is a strong technical paper to demonstrate the stochasticity regarding the functions subpopulations of beta cells in the islets may have and how less well-resolved approaches (both missing spatial resolution as well as missing temporal resolution) led us to jump to unjustified conclusions regarding the fixed roles of individual beta cells within an islet.

Weaknesses:

There are a few relevant issues that need to be addressed.

(1) The study is not internally consistent regarding the Results section. In the text the authors discuss changes in membrane potential (not been measured in this study), while in the figures they exclusively describe Ca^{2+} oscillations (which were measured). Examples are on lines 149, 150, 153, 154, 263... It is recommended that the silent and active phase in the Results section describe processes actually measured in this study as shown 6A.

(2) There are in fact no radially oriented networks in the core of an islet (l. 130, Fig. 4) apart from the fact that every hub has somewhat radially oriented edges. For radially to have some general meaning, the normalized distance from the geometric center would need to be lower than 0.4. The networks are centrally located, which does not change the major conclusions of the study.

(3) The study would profit from acknowledging that Ca^{2+} influx is not a sole mechanism to drive insulin secretion and that KATP channels are not the sole target sensitive to changes in

the cytosolic (global or local) ADP and ATP concentration or that there is an absolute concentration-dependence of these ligands on KATP channels. The relatively small conductance changes that have been found associated to active and silent phases (closing and opening of the KATP channels as interpreted by the authors, respectively, doi: 10.1152/ajpendo.00046.2013) and should be due to metabolic factors, could be also associated to desensitization of KATP channels to ATP due to the increase in cytosolic Ca^{2+} changes after intracellular Ca^{2+} flux (DOI: 10.1210/endo.143.2.8625) as they have been found to operate also at time scales, significantly faster (DOI: 10.2337/db22-0952) than reported before (refs. 21,22). Metabolic changes influence intracellular Ca^{2+} flux as well.

(4) There is no explanation for why KL divergence is so different between the pre-test regional consistency of the islets used to test the vehicle compared to those where GKα and PKα have been tested.

<https://doi.org/10.7554/eLife.103068.2.sa1>

Author response:

The following is the authors' response to the original reviews.

Public Reviews:

Reviewer #1 (Public Review):

Summary:

Jin, Briggs, and colleagues use light sheet imaging to reconstruct the islet threedimensional Ca^{2+} network. The authors find that early/late responding (leader) cells are dynamic over time, and located at the islet periphery. By contrast, highly connected or hub cells are stable and located toward the islet center. Suggesting that the two subpopulations are differentially regulated by fuel input, glucokinase activation only influences leader cell phenotype, whereas hubs remain stable.

Strengths:

The studies are novel in providing the first three-dimensional snapshot of the beta cell functional network, as well as determining the localization of some of the different subpopulations identified to date. The studies also provide some consensus as to the origin, stability, and role of such subpopulations in islet function.

We thank the reviewers for their positive assessment.

Weaknesses:

Experiments with metabolic enzyme activators do not take into account the influence of cell viability on the observed Ca^{2+} network data. Limitations of the imaging approach used need to be recognized and evaluated/discussed.

We worked very hard to make sure the islets remained stable and healthy over the duration of imaging time course. We imaged the islet in 3D and observed that all betacells displayed glucose-dependent oscillations, which can only arise from functioning cells. From the raw calcium traces (displayed in the figures) we observed no detectable loss of signal over 60 min of continuous imaging regardless of drug treatment; this is because the laser excitation is below the bleach threshold for GCaMP6s, and it is bleaching that generates phototoxicity. To demonstrate this clearly, we performed a bleach test using 6x laser power; in this case calcium amplitude dropped 30% over a 60 min of imaging, however islet calcium oscillatory

behavior was preserved. Light-sheet is well documented to be 1000x more gentle than other optical sectioning techniques, which is why it was chosen for this application.

Regarding the limitations of imaging approach, we recognized studying islets *ex vivo* is necessarily performed in the absence of native surrounding tissue, as highlighted in the discussion.

Reviewer #2 (Public Review):

The manuscript by Erli Jin, Jennifer Briggs et al. utilizes light sheet microscopy to image islet beta cell calcium oscillations in 3D and determine where beta cell populations are located that begin and coordinate glucose-stimulated calcium oscillations. The light sheet technique allowed clear 3D mapping of beta cell calcium responses to glucose, glucokinase activation, and pyruvate kinase activation. The manuscript finds that synchronized beta-cells are found at the islet center, that leader beta cells showing the first calcium responses are located on the islet periphery, that glucokinase activation helped maintain beta cells that lead calcium responses, and that pyruvate kinase activation primarily increases islet calcium oscillation frequency. The study is well-designed, contains a significant amount of high-quality data, and the conclusions are largely supported by the results.

It has recently been shown that beta cells within islets containing intact vasculature (such as those in a pancreatic slice) show different calcium responses compared to isolated islets (such as that shown in PMID: 35559734). It would be important to include some discussion about the potential in vitro artifacts in calcium that arise following islet isolation (this could be included in the discussion about the limitations of the study).

Although isolated islets reproduce the slow oscillatory calcium behavior observed *in vivo*, we agree that missing elements such as blood flow, cholinergic innervation, and surrounding tissues may each impact islet calcium responses. Pancreatic regional blood flow also links the endocrine and exocrine signaling which can directly influence the behavior of beta cells. We have highlighted some of these issues in the discussion “In addition to α -cells, vasculature may also impact islet Ca^{2+} responses, and may induce additional heterogeneity *in vivo*.” (see line 375, Ref. 46).

Reviewer #3 (Public Review):

Summary:

Jin, Briggs et al. made use of light-sheet 3D imaging and data analysis to assess the collective network activity in isolated mouse islets. The major advantage of using whole islet imaging, despite compromising on the speed of acquisition, is that it provides a complete description of the network, while 2D networks are only an approximation of the islet network. In static-incubation conditions, excluding the effects of perfusion, they assessed two subpopulations of beta cells and their spatial consistency and metabolic dependence.

Strengths:

The authors confirmed that coordinated Ca^{2+} oscillations are important for glycemic control. In addition, they definitively disproved the role of individual privileged cells, which were suggested to lead or coordinate Ca^{2+} oscillations. They provided evidence for differential regional stability, confirming the previously described stochastic nature of the beta cells that act as strongly connected hubs as well as beta cells in initiating regions (doi.org/10.1103/PhysRevLett.127.168101).

The fact that islet cores contain beta cells that are more active and more coordinated has also been readily observed in high-frequency 2D recordings (e.g. DOI: 10.2337/db22-0952), suggesting that the high-speed capture of fast activity can partially compensate for incomplete topological information.

They also found an increased metabolic sensitivity of mantle regions of an islet with a subpopulation of beta cells with a high probability of leading the islet activity which can be entrained by fuel input. They discuss a potential role of alpha/delta cell interaction, however relative lack of beta cells in the islet border region could also be a factor contributing to less connectivity and higher excitability.

The Methods section contains a useful series of direct instructions on how to approach fast 3D imaging with currently available hardware and software.

The Discussion is clear and includes most of the issues regarding the interpretation of the presented results.

Some issues concerning inconsistencies between data presented and statements made as well as statistical analysis need to be addressed.

Taken together it is a strong technical paper to demonstrate the stochasticity regarding the functions subpopulations of beta cells in the islets may have and how less well-resolved approaches (both missing spatial resolution as well as missing temporal resolution) led us to jump to unjustified conclusions regarding the fixed roles of individual beta cells within an islet.

We thank the reviewers for the comments on the many strengths of the manuscript and address the specific critiques below.

Recommendations for the authors:

Reviewing Editor Comments:

Essential revisions:

(1) How useful is GK activation as a subpopulation-level perturbation, given that all beta cells would be affected? Previous studies by the authors have shown that GK gradients likely dictate subpopulation behaviour, so the concern here is that GK activation across all cells might mask the influence of such gradients i.e. a U-shaped effect. Also, does the GK activator differentially penetrate the islet such that first responders/leaders are more vulnerable than hubs?

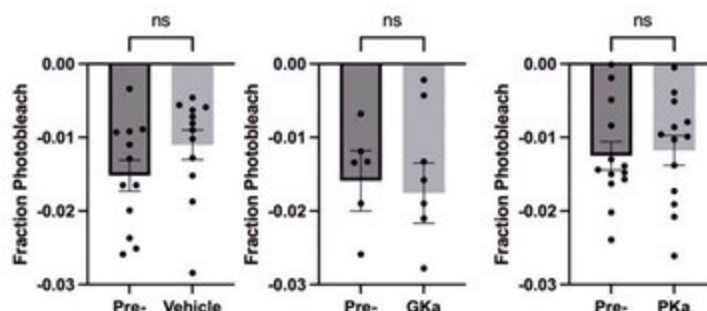
As we previously published, non-saturating concentrations of GK activator (as used here) have the same effect on calcium oscillations as raising glucose (PMID:33147484). In other words, the activator boosts the activity of the endogenous GK. To the second point, recent ex vivo islet studies (PMID: 28380380) document the islet penetration of a fluorescent glucose analogue within seconds even under static conditions, and in our study the islets calcium oscillations reached steady state, so we are not concerned about drug penetration. The real limitation with any drug study in the islet is that non-beta cells are also activated; this limitation is included in the discussion along with the recommendation that genetic tools are needed to assess the effect of GK activation in the various endocrine subpopulations.

An additional concern with the GK activation experiment is that GK activation might push beta cells into a more stressed state such that they are more susceptible to phototoxicity. Although the authors state that photobleaching is low, they provide no data to support such a statement. Given the long duration of imaging and acquisition rate, phototoxicity

might be more of an issue, especially with GK activation. Some further analysis (e.g. apoptosis) would be useful here to exclude an effect of beta cell viability versus GK activation on the observed phenotype of the different subpopulations.

Acute GK activation (for 30min) does not stress the islet; the drug has the same effect as raising glucose (PMID: 33147484). To determine whether photobleaching was impacted by GK activation, we examined the peak of consecutive oscillations in response to vehicle and GK activator. The average photobleaching was less than 2% of the calcium fluorescence over 30min of continuous imaging. Furthermore, GKa activation did not significantly increase photobleaching (see Author response image 1).

Author response image 1.



To the reviewer's second point, apoptosis cannot occur on the timescale of the drug treatment (30min), and raw calcium traces are included showing that all beta cells display oscillatory behavior throughout the course of the experiment.

(2) The authors show that glucokinase activation increases the duration of islet calcium oscillations and in some islets (3 of 15 islets) causes "a Ca²⁺ plateau." The authors indicate that "Glucokinase, as the 'glucose sensor' for the β -cell, controls the input of glucose carbons into glycolysis, and opens KATP channels." It would be nice to have some experimental evidence that the change in oscillation rate caused by the glucokinase activator is due to KATP activation. This could be accomplished by treating islets with subthreshold KATP activators (e.g., diazoxide) or subthreshold KATP inhibitors (e.g., tolbutamide).

The statement that glucokinase activation opens KATP channels was a typo; glucose metabolism closes KATP channels by raising the ATP/ADP ratio. We now include additional citations that document the relationship between GK and KATP and the oscillatory behavior. See Ref 22 (PMID: 33147484) and Ref 34 (PMID: 33147484).

The manuscript finds that "Early phase cells were maintained to a greater degree upon GKa application." Yet GKa is proposed to activate KATP. Some discussion about how the early phase is maintained in cell populations by GKa activation in the context of KATP activity would be useful.

As discussed above, we meant to say that GKa will close KATP and apologize for the confusion. As we mentioned in the discussion, early phase cells are most likely maintained to a great degree following GK activation as result of enhanced GK gradient and reduced effect of stochastic alpha cell input.

(3) Membrane potential depolarization precedes calcium channel activation and subsequent calcium entry. In many cases, electrical coupling across beta cells happens on millisecond timescale. It would be good to confirm that the calcium is showing the same time scale in terms of elevation following beta cell membrane potential depolarization. One concern is that the islet beta cells could be depolarizing at the same speed and lagging in terms of calcium channel activation and calcium entry.

We thank the reviewer for making this point, which is almost certainly true, particularly since plasma membrane calcium influx is not the sole source of intracellular calcium. Previously published “simultaneous” recordings of Vm and calcium show their same phase relationship but do not have sufficient time resolution to capture depolarization of each cell. A quantification of phase lag would require the field to generate mice with voltage sensors expressed in beta cells; these tools are not yet available.

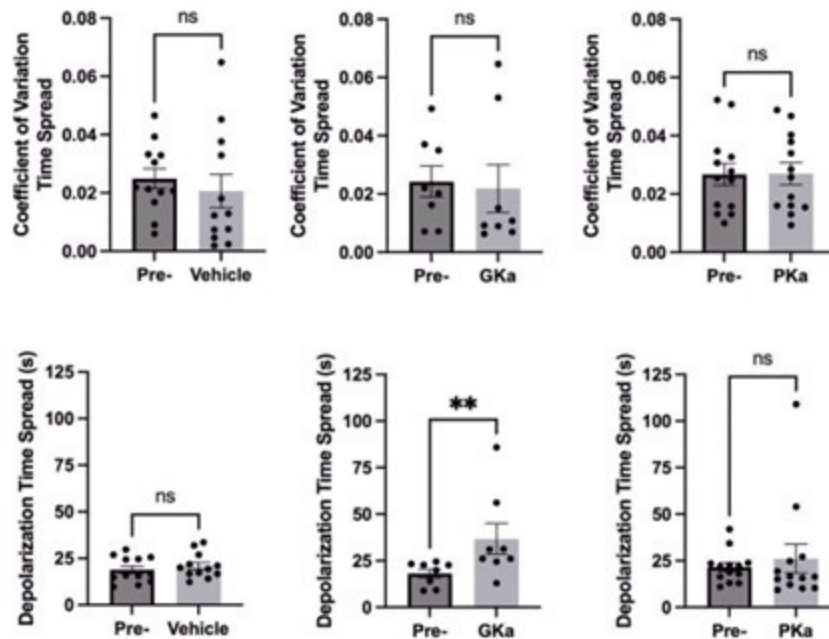
A related issue: in the text, the authors discuss changes in membrane potential (not been measured in this study), while in the figures they exclusively describe Ca²⁺ oscillations (which were measured). Examples are on lines 149, 150, 153, 154, 263. It is recommended that the silent and active phases in the Results section describe processes actually measured in this study as shown in 6A.

To clarify, we did not use the term ‘membrane potential’ anywhere in the manuscript. We do sometimes refer to calcium influx as a proxy for membrane depolarization; we think this is valid given the abundant evidence that these processes are interdependent in beta cells.

(4) It would be good to include the timing of the phases of calcium entry. When was the beta cell calcium entry monitored for the response time? Were the response times between the late and early phases consistent for each oscillation? It looks as if the start of the calcium upstroke was similar for many beta cells (such as for the Figure 2I traces). It would be nice to include a shorter time duration graph of calcium oscillation traces right when the upstroke starts. This would allow the community to observe the differences in the start time of calcium entry.

We agree this is an important point. We now include an inset showing the expanded time scale of the calcium upstroke in Fig.2I. The response time spread between early and late phase cells is now shown in Fig.7F (and in Author response image 2). We also quantified the coefficient of variation in the response time spread (0 = no variation and 1 = maximal variation) and found no significant differences between metabolic activators (Author response image 2).

Author response image 2.



Also, for most of the GCaMP6s traces shown, the authors indicate that they are plotted as F/F_0 . However, this normalization (F/F_0) is not done for the actual traces shown. For example, Figure 2D shows the traces starting from what looks to be 0 to 0.3 F/F_0 , but the traces for an F/F_0 group should all start at 1. Please change this for all representative oscillations so the start of calcium entry for example traces all line up.

This has been corrected in Fig. 2D, I and Fig. 3B. Also Fig.6 should be F not F/F_0

Reviewer #1 (Recommendations for the authors):

(1) Line 53: "Silencing the electrical activity of these hub cells with optogenetics was found to abolish the coordination within that plane of the islet". The authors should acknowledge that studies also showed that beta cell transcription factor (*Pdx1/Mafa*) dosage was important for hub cell phenotype and islet function.

Thank you, this reference to Nasteska et al. (PMID: 33514698, Ref. 16) has been added to the discussion.

(2) Light sheet imaging is used to image the 3D islet volume. Whilst speed is undoubtedly an advantage of this technique, axial resolution is $\sim 1.1 \mu\text{m}$ over $4 \mu\text{m}$ z-step size. How confident are the authors that single nuclei can be reliably identified given their $\sim 6 \mu\text{m}$ size in a beta cell (e.g. do some elongated nuclear appear, which could be "doublets")?

The axial resolution of $1.1 \mu\text{m}$ exceeds the resolution needed for the Nyquist criterion (i.e. sampling every $2\text{--}3 \mu\text{m}$). As a practical matter, it is not possible to doublecount nuclei because the software will exclude nuclei that occupy the same volume. Only a very elongated nucleus ($>10 \mu\text{m}$) would be double counted and this does not occur.

(3) The authors discuss the advantages of the light sheet imaging approach used, including speed and phototoxicity. Some more balance is needed here since other

approaches such as two-photon excitation achieve similar speeds with much better axial resolution (see dozens of neural circuit studies).

We are careful to point out that two-photon excitation has better axial resolution, better tissue penetration, and often higher speeds (kHz using linescans) – however these neuronal studies are limited to the cells in a few planes and the laser power is orders of magnitude higher than lightsheet. For this reason, two photon imaging has not been used to image islet calcium in three dimensions. The bottom line is lightsheet trades axial resolution for gentle volumetric imaging.

(4) Line 340: "Laser ablation or optogenetic inactivation of these early phase cells would be predicted to have little impact on islet function, as suggested previously by electrophysiological studies in which surface β -cells have been voltage-clamped with no impact on β -cell oscillations". This statement is slightly ambiguous since the authors showed in their previous studies that laser ablation of first responder cells/leaders was able to influence the Ca^{2+} network. Do the authors mean that laser ablation would only temporarily influence islet function before another cell picked up the role of a first responder/leader? As written, the sentence seems to imply that first responders/leaders are unimportant for the islet function.

We intended to imply that the oscillatory system is sufficiently robust that a new cell take over when leader cells are ablated. We also cite Korosak et al. (PMID:34723613, Ref. 40) and Dwulet et al. (PMID: 33939712, Ref. 15) to make this point, although to clarify we are not examining first responders in this study.

(5) Line 369: "In contrast with leader cells, we found that the highly synchronized cells are both spatially and temporally stable." The sentence needs qualifying- what would spatiotemporal stability be expected to confer on such a subpopulation?

We believe that the spatiotemporal stability of highly synchronized cells is a consequence of beta cells in the center of the islet lacking the stochastic input of nearby alpha cells; we raise this point in the discussion: "The preponderance of α -cells on the periphery of mouse islets, which influence β -cell oscillation frequency, would be expected to disrupt β -cell synchronization on the periphery and stabilize it in the islet center – which is precisely the pattern of network activity we observed." (see line 372).

(6) Line 370: "However, in conflict with the description of hub cells as intermingled with other cells throughout the islet, the location of such cells in 3D space is close to the center." The study by Johnston et al did not have the axial resolution to exclude that some cells might have been grouped together.

We agree and have included the reviewer's comment in the text (See line 384); that's an important reason for conducting this 3D study.

(7) Line 380: "One explanation may be that paracrine communication within the islet determines which region of cells will show high or low degree. For example, more peripheral cells that are in contact with nearby δ -cells may show some suppression in their Ca^{2+} dynamics, and thus reduced synchronization." A potentially exciting future study. Should however probably cite DOI s41467-022-31373-6 here.

We thank the reviewer for their input. This reference to Ren et al. (PMID:35764654) was previously included as Ref. 42 (now Ref. 45)

Reviewer #3 (Recommendations for the authors):

(1) There are in fact no radially oriented networks in the core of an islet (l. 130, Figure 4) apart from the fact that every hub has somewhat radially oriented edges. For radially to have some general meaning, the normalized distance from the geometric center would need to be lower than 0.4. The networks are centrally located, which does not change the major conclusions of the study.

Thank you for pointing out this imprecise language. We did not intend to imply that the functional network is orientated radially. We corrected the text (see line 131, 145) to indicate that the cells with high and low synchronization are distributed in a radial pattern.

(2) The study would benefit from acknowledging that Ca^{2+} influx is not a sole mechanism to drive insulin secretion and that KATP channels are not the sole target sensitive to changes in the cytosolic (global or local) ADP and ATP concentration or that there is an absolute concentration-dependence of these ligands on KATP channels. The relatively small conductance changes that have been found to be associated with active and silent phases (closing and opening of the KATP channels as interpreted by the authors, respectively, doi: 10.1152/ajpendo.00046.2013) and should be due to metabolic factors, could be also associated to desensitization of KATP channels to ATP due to the increase in cytosolic Ca^{2+} changes after intracellular Ca^{2+} flux (DOI: 10.1210/endo.143.2.8625) as they have been found to operate also at time scales, significantly faster (DOI: 10.2337/db22-0952) than reported before (refs. 21,22). Metabolic changes influence intracellular Ca^{2+} flux as well.

The reviewer is absolutely correct that there are amplifying factors and other sources of calcium beyond plasma membrane influx and there are other mechanisms that regulate insulin secretion beyond calcium levels. These alternative mechanisms are introduced in Refs. 1-2, however they are not the focus of this study.

(3) There is no explanation for why KL divergence is so different between the pre-test regional consistency of the islets used to test the vehicle compared to those where GKα and PKα have been tested.

We thank the reviewer for their careful observation. This arises because there are larger differences between preparations than within a preparation. This has been described previously (PMID: 16306370 and 20037650) and could be expected to account for the differences in KL divergence between animals.

(4) Statistical analysis would profit from testing the normality of the data distribution before choosing the statistical test and then learning the difference between parametric and nonparametric tests. For example, in Figures 3CD and 5EF, the data density is lower at the calculated mean than below and above this value and there are other examples in other figures too.

We thank the reviewer for this very important comment, and we apologize for the oversight on our part. To address this comment, we conducted two normality tests: Anderson-Darling and Kolmogorov-Smirnov on all statistical analyses in the manuscript. If the data were not normally distributed, we changed the analysis to Wilcoxon matchedpairs signed rank test (non-parametric version of t-tests) or the Friedman test (nonparametric version of ANOVA). Three results were changed based on this statistical correction: Figure 4D, also 5F 3D (from $P=0.01$ to $P=0.0526$), Figure 5F ¼ z-depth ($P = 0.005$ to $P = 0.012$). We have updated the manuscript methods, results, and figures accordingly. Importantly, these results did not change the main points of the paper.

<https://doi.org/10.7554/eLife.103068.2.sa0>