Strongly enhanced bacterial bioluminescence with the ilux operon for single-cell imaging

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Bioluminescence imaging of single cells is often complicated by the requirement of exogenous luciferins that can be poorly cell-permeable or produce high background signal. Bacterial bioluminescence is unique in that it uses reduced flavin mononucleotide as a luciferin, which is abundant in all cells, making this system purely genetically encodable by the lux operon. Unfortunately, the use of bacterial bioluminescence has been limited by its low brightness compared with other luciferases. Here, we report the generation of an improved lux operon named ilux with an approximately sevenfold increased brightness when expressed in Escherichia coli; ilux can be used to image single E. coli cells with enhanced spatiotemporal resolution over several days. In addition, since only metabolically active cells produce bioluminescent signal, we show that ilux can be used to observe the effect of different antibiotics on cell viability on the single-cell level.

Bacterial bioluminescence cells generate light by a chemical reaction. The bioluminescence reaction is catalyzed by an enzyme called luciferase, with a luciferin required as substrate. Molecules of luciferin are converted into products in an electronically excited state and emit a photon on return to the ground state, with visible light emitted in the process. There are many different luciferases and corresponding luciferins found in nature, indicating that bioluminescence has evolved more than 40 times independently during evolution (1), although in several cases, its biological function remains not fully understood. Most luciferins are only produced by organisms that express the corresponding luciferase, with the exception of the bacterial luciferin FMNH₂, reduced flavin mononucleotide (FMN), which is abundant in all cells.

The bacterial bioluminescence reaction is catalyzed by an αβ-heterodimeric luciferase coded by the genes luxC and luxD. In addition to FMNH₂, the luciferase binds molecular oxygen and a long-chain fatty aldehyde. The fatty aldehyde is oxidized to the corresponding fatty acid, and FMNH₂ is oxidized to FMN, thereby emitting a blue photon with a wavelength around the spectral emission maximum λmax of ~490 nm:

\[

\text{FMNH}_2 + \text{RCOOH} + \text{O}_2 \rightarrow \text{FMN} + \text{RCOOH} + \text{H}_2\text{O} + \text{hv}.

\]

To keep this reaction ongoing, the fatty aldehyde must be continuously regenerated. This is performed by the fatty acid reductase complex, which consists of a fatty acid reductase, transerase, and synthetase coded by luxC, luxD, and luxE, respectively. Since an FMN reductase that generates FMNH₂ is present in Escherichia coli, introduction of the luxCDABE operon is sufficient to produce a bioluminescent output in these cells.

Due to its very low light levels compared with fluorescence, bioluminescence imaging is not routinely applied so far. However, bioluminescence provides several benefits compared with fluorescence measurements. First, there is virtually no background because of the lack of autofluorescence. Bioluminescence background levels in living cells are extremely low, making bioluminescence up to 50 times more sensitive than fluorescence (ref. 2 and references therein). Second, no excitation light source and filters are required, making the setup very simple. In addition, it is possible to study processes where the intense excitation light required for fluorescence measurements would be disturbing, such as circadian rhythms or Ca²⁺ activity in the retina (3, 4). Third, no phototoxicity or bleaching occurs, allowing image acquisition over arbitrary timespans. Furthermore, bioluminescence is dependent on metabolic energy, and hence, only metabolically active cells are visible, preventing artifacts due to the observation of severely damaged or dead cells.

In addition to the limitation by their low brightness, the luciferases that are most commonly used exhibit several drawbacks, as the luciferin must be externally supplied. Limited solubility, stability, or cell permeability of the luciferin may, in some cases, hamper its usability (5–7). Administering of excess amounts of the luciferin is readily done for standard single-layered cell cultures, but luciferin consumption within larger collections of cells, such as tumors, is more rapid. In these situations, the luciferin concentration is not constant over time, and the signal decays sometimes within minutes (8, 9). Therefore, the luciferin has to be applied repeatedly for long-term imaging, which complicates quantification of the signal. Moreover, autooxidation of coelenterazine, the substrate of commonly used Renilla and Gaussia luciferase, can produce luminescence background signal (6, 10). Bacterial luciferase is the only luciferase to circumvent all of these problems, since FMN is present in all cell types and can be converted into free FMNH₂ by additional expression of an FMN reductase. Its main limitation is the poor brightness that is several orders of magnitude lower than that of other luciferases (11). Several attempts have been made to improve the brightness of bacterial bioluminescence, including splitting the lux operon for enhanced expression, codon optimization and additional expression of an operon for enhanced fluorescence. This work was supported by grants from the Max Planck Society and grants of the German Research Foundation (DFG: SFB 1060).}

Significance

The emission of light generated in a process referred to as bioluminescence can be used for imaging of living cells over long timespans without phototoxicity or bleaching. The amounts of light produced in the bioluminescence process are very low, and exogenous substrate molecules are often required. We improved the brightness of bacterial bioluminescence, a system that features the advantage that all of the required molecular components are genetically encoded within a single operon. Consequently, we have engineered an improved operon ilux, which enables long-term visualization of single bacterial cells while simultaneously providing information about cellular viability.

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FMN reductase in mammalian cells, and exogenous addition of the fatty aldehyde (12–15). However, to our knowledge, introduction of mutations in the luxCDABE operon to increase the brightness has so far been unsuccessful. Here, we show that bioluminescence from the lux operon from Photobacterium phosphoreum expressed in E. coli can be substantially enhanced by coexpression of an additional FMN reductase and subsequent error-prone mutagenesis of the complete lux operon. The improved lux operon dubbed ilux can be used to image single E. coli cells for extended time periods and to assay cell viability in the presence of different antibiotics.

Results

Engineering and Characterization of the ilux Operon. To engineer a bacterial bioluminescence system with improved brightness at 37 °C, we chose the luxCDABE operon from P. phosphoreum, as its luciferase has been reported to be more thermostable than Vibrio harveyi luciferase (ref. 16 and references therein). The P. phosphoreum luxCDABE operon was cloned into the vector pGEX-6P-1. Details of all primers used for cloning and error-prone PCR are contained in Table S1. Expression in E. coli DH5α cells resulted in only weakly luminescent colonies. Since the function of the fatty acid reductase coded by the luxC gene may be affected by the N-terminal GST tag contained in pGEX-6P-1, we expressed the luxCDABE operon from a GST-deleted version of this vector, dubbed pGEX(−). This increased the brightness by ∼40% at room temperature and ∼20-fold at 37 °C (Fig. 1A), suggesting that the activity of the fatty acid reductase is strongly inhibited by the relatively large GST tag at elevated temperature, possibly by inhibiting assembly of the fatty acid reductase complex. In addition, we observed that the bioluminescence signal increases with temperature, yielding two to three times more signal at 37 °C compared with room temperature (22 °C) (Fig. 1A).

To further enhance the bioluminescence intensity, we sought to identify the rate-limiting enzymes of the bioluminescence reaction by cloning a second copy of luxAB, luxCD, and luxE as well as two different FMN reductases downstream of the luxCDABE operon and comparing the brightness with the original construct. The FMN reductase from E. coli coded by the frp gene and the NADPH-flavin oxidoreductase from Vibrio campbellii coded by the fpr gene resulted in 1.5- and 2.3-fold increases in brightness, respectively (Fig. 1A). This suggested that the endogenous FMN reductase in E. coli does not regenerate sufficient amounts of FMNH₂ for maximum levels of bioluminescence. We chose luxCDABE+fpr pGEX(−) for mutagenesis and performed multiple rounds of error-prone PCR in the luxAB, luxCD, luxE, and fpr genes. The resulting clones were screened for enhanced luminescence in DH5α cells on LB agar plates at 37 °C. We identified several mutations in luxA, luxB, luxC, and fpr that resulted in higher bioluminescence signal, whereas no beneficial mutations in luxD and luxE were found. The final improved operon called ilux contains the mutations listed in Table 1 (complete amino acid sequences of the ilux proteins are in Fig. S1). E. coli cells expressing the WT lux operon (luxCDABE WT) and ilux exhibited identical bioluminescence emission spectra (Fig. S2). The brightness of ilux compared with luxCDABE WT was increased not only at 37 °C but also at room temperature (Fig. 1A). Maximum levels of bioluminescence from E. coli cells were observed at ∼37 °C for both

Table 1. Mutations contained in ilux

| Gene | Mutations |
|------|-----------|
| luxA | K22E, T119A, S178A |
| luxB | S13P, V121A, N259D |
| luxC | N10T, N59D, E74D, S256P, M355T, N360D |
| luxD | — |
| luxE | — |
| frp | M213L, R242L, K256R |

The listed mutations were introduced by error-prone PCR into the luxCDABE operon from P. phosphoreum supplemented with the frp gene from V. campbellii, resulting in the improved operon ilux.
**luxCDABE WT** and **ilux**, with a slightly broader temperature curve for **ilux** (Fig. 1B). Since we were not able to further improve the cellular signal intensity enabled by the **ilux** operon (“brightness of **ilux**”) by error-prone mutagenesis, we attempted to increase its brightness by bioluminescence resonance energy transfer from the luciferase to an acceptor with high fluorescence quantum yield. For this purpose, we chose the fluorescent protein EYFP \( \Phi_0 = 0.61 \) (17) and fused it N- and C-terminally to both the luciferase \( \alpha \) and \( \beta \) subunit. However, this did not improve the brightness (Fig. 1C).

To investigate whether the increase in brightness of **ilux** is due to enhanced enzymatic activity or elevated expression of the **lux** proteins, we quantified protein levels by Western blot analysis of cell lysates (Fig. S3). Since antibodies for the **lux** proteins from *P. luminescens* were not available, single proteins in the **luxCDABE WT** and **ilux** operon were expressed with a C-terminal His tag and detected with an anti-His antibody. To control whether the His tag itself affects protein expression, the brightness of cells expressing the His-tagged **lux** operons was compared with the **lux** operon without His tag. The brightness of **ilux** **luxC**-His and **frp**-His was strongly reduced (Fig. S4), whereas for the other His-tagged proteins the brightness remained comparable with the nontagged operon (Fig. 2A). Therefore, **luxC** and **frp** were instead expressed with an N-terminal His tag, which influenced the brightness less strongly (Fig. 2A). However, the His antibody failed to detect His-**frp** (Fig. S3). Expression of the detectable functional fusion proteins **luxA**-His, **luxB**-His, **luxC**-His, **luxD**-His, and **luxE**-His in both **luxCDABE**+**frp** and **ilux** was quantified by Western blot (Fig. 2B). Whereas expression of **luxA**-His and His-**luxC** was increased by 30% and 25%, respectively, expression of **luxB**-His, **luxD**-His, and **luxE**-His remained unaffected. Therefore, the increased brightness of **ilux** seems to be partly due to enhanced expression and partly due to increased activity of the **lux** proteins.

**Imaging of Single E. coli Cells.** To obtain a higher brightness for imaging of single *E. coli* cells, the **ilux** operon was cloned into the vector **pOE**(-) and expressed in *E. coli* Top10 cells. **pOE**(-) was generated from **pQE30** by deletion of the His tag. Expression of **ilux** from **pOE**(-) in Top10 cells resulted in a 2.0-fold higher signal at room temperature compared with **ilux** **pGEX**(-) in DH5\( ^\alpha \) on LB agar plates (Fig. S5). Although bioluminescence emission was two- to threefold higher at 37 °C, the imaging was performed at room temperature for technical simplicity. Single Top10 cells could already be discriminated after exposure times of only 10–20 s (Fig. 3). Longer exposure times resulted in significantly improved signal-to-noise ratio. A calibration of the camera indicated that 100–200 photons per pixel were detected during a 10-min exposure time, corresponding to \( 10^2–10^4 \) detected photons per cell per minute.

We compared the brightness of single Top10 cells expressing **ilux** and **luxCDABE WT**. Whereas cells expressing **ilux** could clearly be discriminated after exposure times of 10 min (Fig. 4A), **luxCDABE WT** provided only little signal above background both in the fluorescence and in the bioluminescence images (Fig. 4B). In addition, we compared the brightness of **ilux** with the widely used firefly luciferase (FLuc) (Fig. 4 C and D). High concentrations of \( \alpha \)-Luciferin of 1 mg/mL were required to visualize the cells, presumably because of low penetration through the bacterial cell wall and membrane. Still, the brightness of FLuc was six to eight times lower than that of **ilux**. In addition, the brightness of FLuc was not constant over time, but single cells sometimes became suddenly much brighter (Fig. 4E). The reason for this is not clear but may be due to increased uptake of the luciferin, since a similar effect was
not observed for ilux. Together, this shows that ilux outperforms both luxCDABE WT and FLuc for imaging of single E. coli cells due to its superior brightness and stability of the signal.

Next, we aimed at investigating the utility of ilux for the observation of single bacteria for extended periods of time. Most cells remained viable over the whole recording time of 12 h and

![Fig. 4. Comparison of ilux with luxCDABE WT and FLuc. (A and B) Comparison of brightness of E. coli Top10 cells expressing (A) ilux or (B) luxCDABE WT. The same color map was used for both bioluminescence images. (C and D) Comparison of brightness of E. coli Top10 cells expressing (C) ilux or (D) FLuc. The same color map was used for both bioluminescence images. (E) E. coli Top10 cells expressing FLuc. A cell with a sudden increase and decrease of brightness between three consecutive images is indicated. The same color map was used for all three bioluminescence images. All bioluminescence images were taken with an exposure time of 10 min. Fluorescence (fluo) images excited with a 405-nm laser are shown in gray. For FLuc, fluorescent beads were used for focusing. In the bioluminescence images, the color map was scaled to the minimum and maximum pixel values of A and C and the third column in E. Fig. S6 shows B and D scaled to the minimum and maximum pixel values. (Scale bar: 2 μm.)](image)

![Fig. 5. E. coli Top10 cells expressing ilux in the presence of different antibiotics. E. coli Top10 cells expressing ilux were imaged under an LB agar pad containing 50 μg/mL ampicillin and (A) no additional antibiotics, (B) 100 μg/mL timentin, or (C) 100 μg/mL kanamycin. Single images were taken with 10-min exposure time. Fluorescence (fluo) images excited with a 405-nm laser are shown in gray. The same color map was used for all bioluminescence images in each row. Complete time series are shown in Movies S1–S3. (Scale bar: 2 μm.)](image)
divided several times while maintaining an almost constant bioluminescence signal (Fig. 5A). Subsequently, we investigated the effect of different antibiotics on cell viability. Since continuous supply of ATP and NADPH is required for the regeneration of fatty aldehyde and FMNH₂ to keep the bioluminescence reaction ongoing, the signal is expected to disappear on cell death. We imaged Top10 cells in the presence of timentin, a mixture of the β-lactame antibiotic ticarcillin and clavulanic acid. Since pOE(−) contains a β-lactamase resistance marker, cells expressing ilux are expected to be resistant to ticarcillin. However, since the β-lactamase is inhibited by clavulanic acid, the cells become susceptible for the cell wall-disrupting effects of ticarcillin and ampicillin. On cell division, this leads to the formation of small holes in the cell wall. As a result, the inner membrane occasionally forms large protrusions due to osmotic pressure (Fig. 5B). This finally leads to cell lysis. After 12 h, all cells in the field of view had died.

The second antibiotic that we examined was kanamycin, an inhibitor of protein synthesis (Fig. 5C). The brightness decreased continuously, consistent with a reduction of protein levels of the ilux enzymes. Most cells died within the 48-h observation time; nevertheless, bioluminescence was still detectable from a few cells. This shows that, even at high kanamycin concentrations of 100 μg/mL, cellular metabolism continues for relatively long timespans, although cell division is prevented immediately.

Interestingly, we often observed “blinking” of cells before cell death. The signal from cells that had already disappeared often recovered, sometimes even between two 10- or 3-min frames (Fig. 6A, Fig. 5B, and Movies S1–S4). This effect was most pronounced in kanamycin-treated cells, where blinking often occurred repeatedly (Movies S3 and S4), but it was also occasionally observed in dying cells without additional antibiotics (Movie S1). Blinking was not affected by the presence of ampicillin and was not observed on kanamycin treatment of kanamycin-resistant cells (Movie S5). Blinking cells often continued living for many hours. To determine if blinking results from altered levels of the ilux proteins or variations in substrate concentrations, we imaged cells expressing ilux with an EYFP-tagged version of luxB in the presence of kanamycin. Fluorescence images of EYFP were taken between the bioluminescence images to determine possible alterations of the luxB-EYFP protein concentration. Some of the cells that irreversibly lost their bioluminescence signal also exhibited a loss of EYFP fluorescence, whereas other cells retained EYFP fluorescence (Fig. S8A). Blinking cells always retained EYFP fluorescence (Fig. S8B), showing that the protein concentration remains constant. Therefore, we conclude that blinking is caused by rapid fluctuations in metabolite concentrations, most likely ATP or NADPH. To test this hypothesis, we coexpressed the fluorescent ATP biosensor QUEEN-2m with the ilux proteins (18). QUEEN-2m fluorescence excited at 405-nm increases with ATP concentration, whereas its fluorescence excited at 490-nm decreases (18). Although QUEEN-2m was designed as a ratiometric ATP sensor, we used its indicator properties at just one excitation wavelength of 491 nm. This allowed us to disentangle the ATP signal from the fluorescence from ilux-expressing cells on excitation at 405 nm, while additionally reducing phototoxicity and bioluminescence bleaching. Bioluminescence and fluorescence images were recorded alternately (Fig. 6B). When the bioluminescence signal declined during blinking, the fluorescence signal simultaneously increased. This indicates that the loss of bioluminescence

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**Fig. 6.** Blinking of E. coli Top10 cells during kanamycin-induced cell death. E. coli Top10 cells were imaged under an LB agar pad containing 50 μg/mL ampicillin and 100 μg/mL kanamycin. (A) Bioluminescence of ilux-expressing cells was imaged with 10-min exposure time. A fluorescence (fluor) image excited with a 405-nm laser is shown in gray. The same color map was used for all bioluminescence images. For the indicated cells, the normalized signal is plotted over time. The complete time series is shown in Movie S4. (B) Bioluminescence (BL) images of Top10 cells expressing ilux and the ATP sensor QUEEN-2m were taken with 3-min exposure time. Fluor of QUEEN-2m was excited at 491 nm and recorded between the bioluminescence images. The first fluor and BL images are displayed. For the indicated cell, the normalized signal after subtraction of the background signal outside the cell area is plotted over time. (Scale bars: 2 μm.)
signal during kanamycin-induced cell death in blinking cells is accompanied by a decrease in ATP concentration.

Discussion and Conclusions

Our results show that bacterial bioluminescence from *E. coli* cells can be enhanced by mutagenesis of the *luxCDABE* genes in combination with introduction of an additional FMN reductase. This allows imaging of single *E. coli* cells with improved spatio-temporal resolution in comparison with previous approaches of single-cell imaging using bacterial bioluminescence (3, 15, 19) without the need of exogenous aldehyde supply. Since the brightness of *ilux* is increased two- to threefold at 37 °C compared with cells with improved spatio-

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by providing information about the metabolic state of the cell. Correlating the change in the signal during kanamycin-induced cell death in blinking cells is accompanied by a decrease in the cellular ATP concentration. A possible explanation for this observation is a breakdown of the proton gradient due to the transient formation of membrane defects, which might inhibit ATP synthesis. Indeed, it has been described that aminoglycoside antibiotics can increase cellular permeability by the incorporation of mistranslated membrane proteins (21, 22). Therefore, cell death in kanamycin-treated cells might be the final result of pronounced membrane damage. This would also explain the rapid loss of EYFP fluorescence observed in some kanamycin-treated cells expressing *luxB-EYFP*, as membrane defects might lead to leakage of cellular proteins. Although different explanations for the blinking cannot be excluded, this effect points at interesting applications of *ilux* by providing information about the metabolic activity of the cell.

The independence from exogenous luciferin makes the *lux* system particularly interesting for long-term imaging studies, although its utility has so far been limited by its low brightness compared with other luciferases. Codon-optimized versions of the *lux* proteins have been shown to be functional in eukaryotic cells (13, 14), facilitating observation of bacterial bioluminescence from cell types other than bacteria. Therefore, *ilux* holds promise as a valuable future tool for the observation of mammalian cells as well. In addition, it might be possible to image cellular structures by fusing the luciferase to a protein of interest, allowing its usage in a similar way as fluorescent proteins.

Materials and Methods

Details of the cloning and mutagenesis of the *lux* constructs, measurement of temperature curves, Western blot analysis, and the imaging are described in SI Materials and Methods. Briefly, bioluminescence imaging was performed on a custom microscopy setup (Fig. S9) equipped with an oil immersion objective (1.4 N.A.) and an electron multiplying charge-coupled device (EMCCD) camera. The setup additionally contained laser sources for wide-field fluorescence excitation at 405 and 491 nm and a focus lock system for long-term imaging.

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