

University of Groningen
Faculty of Mathematics and Natural Sciences
Zernike Institute for Advanced Materials

SUPER-RESOLUTION MICROSCOPY

Nanoscience Research Paper

Mykhailo Gerasymenko
Top Master in Nanoscience
m.gerasymenko@student.rug.nl

Supervisor:
Assistant Professor Dr. Thorben Cordes

31 August 2015

SUPER-RESOLUTION MICROSCOPY

Abstract

Eric Betzig, Stefan W. Hell plus William E. Moerner are generally given the particular Nobel Winning prize in Chemistry 2014 to have side stepped the suspected controlled issue stipulating that will an optical microscope can not render a resolution better as compared to 0.2 micrometers. Working with the fluorescence of molecules, research workers can certainly at this moment keep an eye on the particular interplay among individual molecules inside cellular material; they are able to see disease-related healthy proteins aggregate plus they can certainly keep track of mobile section with the nanolevel. Crimson blood vessels cellular material, microorganisms, thrush cellular material plus spermatozooids. Any time research workers within the 17 one hundred year regarding once examined located bacteria within an optical microscope, the marketplace opened just before his or her eyes. This is the particular entry into the world involving microbiology, plus from the time, the optical microscope continues to be a single of the biggest resources within the life-sciences toolbox. Other microscopy methods, for instance electron microscopy, involve basic steps that will sooner or later get rid of cell.

SUPER-RESOLUTION MICROSCOPY

Contents

Introduction.....	4
Discovery of Super-resolved Microscopy	6
Super-resolved Ensemble Microscopy	9
Super-resolved Single-Fluorophore Microscopy.....	10
A Single Fluorescent Molecule.....	11
Molecular-sized Lighting Fixtures.....	14
Abbe's Diffraction Limit	14
Conclusion	16
References.....	18

SUPER-RESOLUTION MICROSCOPY

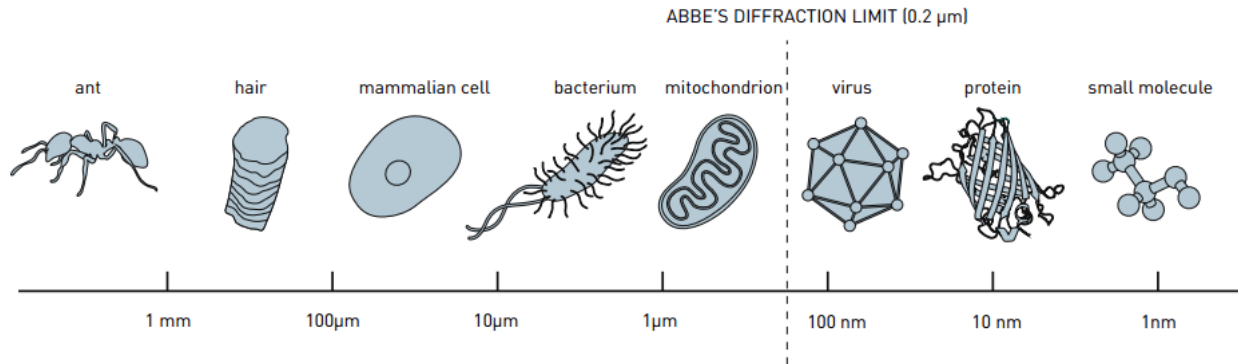
Introduction

Optical microscopy offers played a key position in biological and health care grounds since optical microscopy allows all of us to image and takes a look at organisms, tissues, cells as well as body organs within dwelling conditions. By making use of suitable fluorescent probes, incredibly tiny illustrations or photos give not only a constitutional data of the products, and also many different data via cellular atmosphere, like concentrations of Mitt, membrane prospective as well as signaling molecules. The particular non-invasiveness, as well as the plethora of available imaging modalities currently, have fascinated research workers within chemistry, medicine as well as relevant research fields (Huang et al., 2009).

The earliest mixture light microscopes constructed in the sixteenth as well as 17th generations enabled experts to make any difference and biological specimens within the incredibly tiny level. Within 1873, Ernst Abbe created significant reduces the resolution of the optical imaging system based upon the diffraction theory regarding light. At the same time a fabrication as well as progress of microscopes and contact lenses ended up being developed via empirical optimizations to help programs based upon quantitative data as well as theoretical considerations (Fernández-Suárez and Ting, 2008). Within the 20th 100 years, a variety of contrast modalities ended up being made which allow someone to find very small information and also to evaluate typical homes of your example of beauty with higher specificity. Finally, over the last twenty years numerous groundbreaking approaches ended up being formulated as well as experimentally confirmed, which in turn considerably elevated an optical resolution down towards the nanometer scale.

The particular giving of the 2014 Nobel Winning prize within Chemical make up to help Eric Betzig, Stefan W. Hell as well as William E. Moerner for their landmark work in "super-resolution" fluorescence microscopy corroborates the promises for many advanced. Fluorescence microscopy straight down towards the single molecule level is researched in several current articles as well as books. In spite of the astounding achievements of fluorescence microscopy, the following method has numerous fundamental shortcomings. Consequently, numerous constant works strive to get alternate pregnant settings of microscopy based upon other contrast mechanisms (Leung and Chou, 2011).

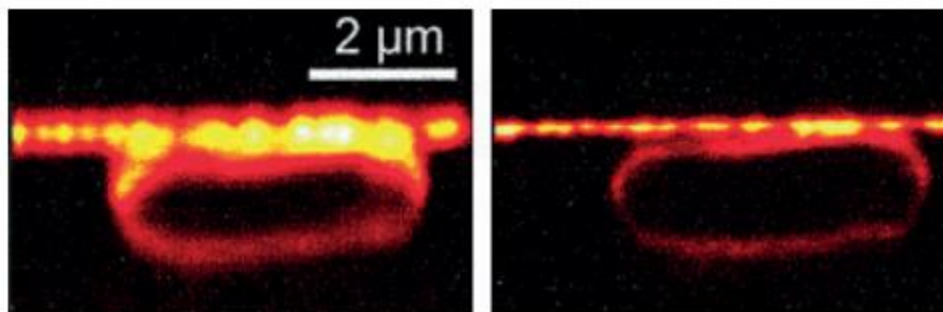
SUPER-RESOLUTION MICROSCOPY



Fluorescence microscopy is usually probably the most widespread gear in biological research. This particular is a result of the great level of sensitivity, specificity (ability specifically label molecules and buildings regarding interest), as well as convenience (compared to incredibly tiny techniques), and it may apply to dwelling tissues as well as organisms. For example, the invention of fluorescent proteins, as well as its vast usage, offers brought about to your emerging trend within the application forms of fluorescence microscopy within biology. The only one fundamental limitation of fluorescence microscopy (and optical microscopy within general) that has been unchallenged for more than 100 many years appeared to be the constrained spatial resolution, which happens to be dictated simply by the wave nature of light and consequently dependent upon its wavelength, which in turn usually is placed in the vary in between 300 as well as 800 nm (Shtengel et al., 2009). This example almost all altered in the 90's of the last century any time Stefan W. Hell, as well as peers, initially described a possibility to go around the diffraction limit by using the inherent quantum-mechanical homes of fluorescence emission by fluorescent molecules. Consequently, a whole new industry of fluorescence microscopy, super resolution microscopy, offers blossomed, which in turn takes advantage of diverse physical doing the job principles. This line of business continues to quickly evolving these days, which in turn can be seen in the big as well as continually being the quantity of papers endorsing ever before more sophisticated strategies to super resolution microscopy. You will find right now numerous outstanding evaluations as well as book sections conveying any a great number of new super resolution methods, its technological facts, uses, as well as investments as well as drawbacks.

SUPER-RESOLUTION MICROSCOPY

Moreover, owing get over a dogma regarding the resolution limit, experts at this point give attention to other critical factors like photo toxicity as well as if it is compatible by using live imaging, greater speed, multiscale imaging and correlative microscopy. Considering the light propagates as being an electromagnetic wave, the item should not be concentrated to help a region smaller compared to a fifty percent of the light wavelength, which in turn specifically determines the dimensions of resolvable test structures (Mortensen et al., 2010).



The fluorescence microscope is the key device regarding checking out the spatial organization with bio-molecular processes. Nevertheless, due to building in components of light, optical resolution is constrained by diffraction to $\sim 1/2$ the wavelength of fluorescent light. Almost, consequently things small compared to 200–300 nm should not be precisely resolved. Various techniques have been recently created to over-come this particular limit. Electron microscopy exploits your extremely short wavelength of electron cross-bow supports to attain file sizes about your subwoofer nanometer place even so, test planning is definitely onerous plus precludes live imaging, and then there is simply constrained potential for molecular identification. Single molecule tracking, talked over in greater detail in another place within this difficulty, requires sparsely labels bio-components with fluorescent dyes letting individual molecules end up being followed inside dwell skin cells by using preciseness with 1–50 nm. Even though Single molecule tracking brings very helpful findings with molecular character, brought on are generally limited by a smaller sub-set of molecules such of which sub-cellular components won't be able to make sure plus pursuing numerous varieties inside the same test is still challenging (Kner et al., 2009).

SUPER-RESOLUTION MICROSCOPY

New advancements inside photochemistry, optical engineering plus info research include in the roll-out of numerous alternative fluorescence microscopy techniques that prevent the diffraction limit. The following, so named, super-resolution microscopy has showed the doorway for you to correct nano range applying of biological components, furnishing a good unheard of taking a look at malware duplication and it is main cellular biology. Nevertheless, since fluorescence labeling is an essential look at biological imaging, your qualification with labels regarding super resolution is certainly not a large disadvantage. Within these areas, all of us express the notion plus components with the super-resolution microscopes. So next benefits, all of us express your guidelines with various kinds super-resolution microscopes and their imaging properties plus applications.

After this great article, we go over views with regards to the long run progression of super-resolution microscopes and similar techniques. Will certainly super-resolution microscopes are produced for a declaration of fluorescent samples; all of us reduce your account underneath for you to inside modality of fluorescence imaging.

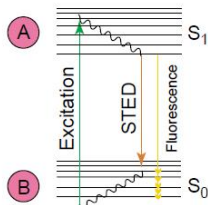
Discovery of Super-resolved Microscopy

Thus far the two main far-field guidelines that lead for you to fluorescence-based microscopy with a resolution far past Abbe's well-known limit. The foremost is below called "super-resolved ensemble fluorophore microscopy" plus the subsequent seeing that "super-resolved single fluorophore microscopy. The earliest rule has been initially created seeing that plus carried out by way of induced exhaust depletion (STED) of fluorescence from all molecules in an example with the exception of these in a tiny place of your analyzed object. Having fulling induced exhaust, the actual "active" place can be created randomly small compared to the actual diffraction-limited size. Through integrating the light spot determining the actual fluorescing place through the analyzed subject plus supervising the fluorescence emission frequently some computer renovation associated with the article can be had (Schemmelleh et al., 2010). The key can certainly be carried out by way of Saturated Structured-Illumination microscopy (SSIM). They can be employed once the fluorescing zones incorporate outfits of fluorophores as nicely seeing that single fluorophores and, therefore, are generically called "Super-resolved ensemble fluorophore microscopy. The popular denominator is that often saturation of your excitation

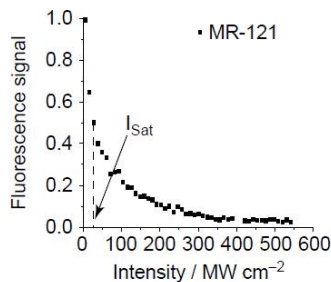
SUPER-RESOLUTION MICROSCOPY

high spatial frequencies better as opposed to runners authorized by way of Abbe's limit. The finding acquired a pair of unique phases. The earliest pertains towards the theoretical types associated with the ways plus the subsequent for their fresh implementation (Bates et al., 2008).

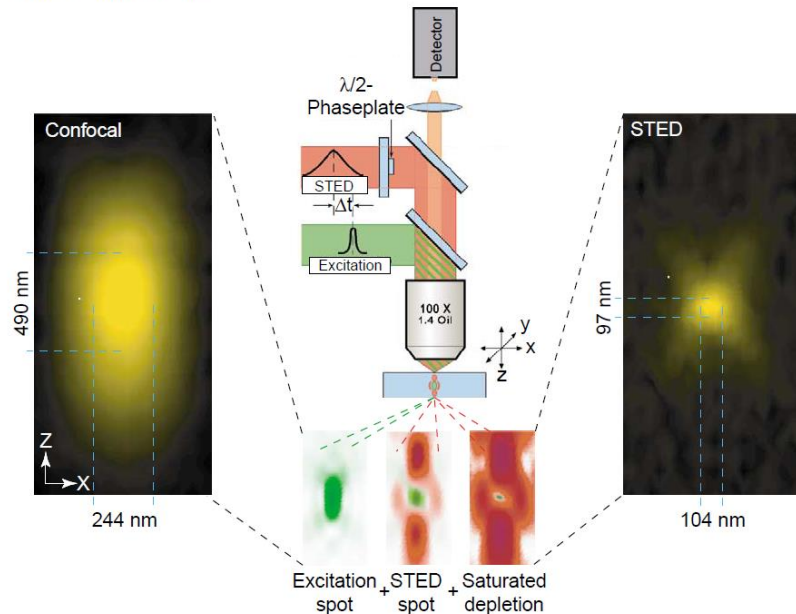
(a) STED principle



(b) Saturated depletion of state A



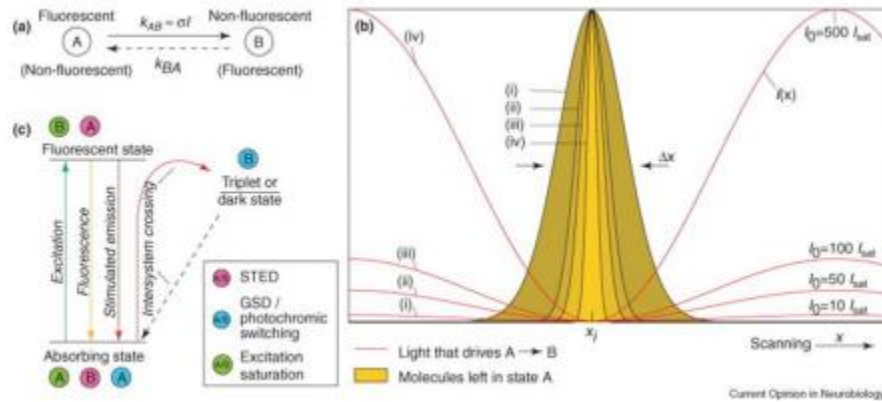
(c) STED microscope



Current Opinion in Neurobiology

The other rule is actually using the prior awareness that almost all photons from a product noticed in a time result from single fluorophores that usually are taken away from via the other by way of kilometers bigger Abbe's minimize (Eq. 1). This post is in that case accustomed to approximation the location of those giving off place methods using a preciseness that is better as compared with of which authorized by way of Abbe's diffraction limit. The other rule will be here generically called "Super-resolved single fluorophore microscopy. Its finding could be termed a few unique steps. The earliest pertains towards the finding associated with single fluorophore spectroscopy around thick media channels, the other towards the theoretical explanation associated with the key plus the 3rd to the fresh implementation (Huang, 2010).

SUPER-RESOLUTION MICROSCOPY



Super-resolved Ensemble Microscopy

Within the introduction of the nineteen nineties, Stefan A W. Hell relocated being a post-doc coming from Belgium for the School associated with Turku with Finland to get area plus a possibility to build their, right at that moment, suspect strategy that it hadn't been simply achievable but, in addition, possible go beyond Abbe's diffraction limit with far-field light microscopy. By two theoretical forms this individual shown the particular concepts as well as defined, with quantitative terminology, the particular trial and error disorders for that groundbreaking story notion of Stimulated Emission Depletion (STED) microscopy and comparable techniques (van de Linde et al., 2012). The government financial aid Belgium this individual appeared to be sooner or later having the ability to gather your adequately sophisticated fluorescence microscope to supply the particular trial and error evidence of concept associated with STED microscopy. Inside STED, two lasers are used. A decreased depth laser light irradiates the fluorophores that outline the dwelling of your researched object.

This particular ray showcases an easy key district seeing that based on Abbe's diffraction limit. A different, high-intensity STED ray, red-shifted in connection with the earliest ray, contains an absolutely no depth bare minimum inside the key district as well as its depth develops everywhere through the focus. That quickly brings fluorophores that are fired up through the earliest ray, through the vibrational floor condition associated with the earliest fired up singlet condition, S1, to a very high vibrational electricity condition of your electric floor condition in which these people quickly transfer for the vibrational floor condition (Patterson et al., 2010).

SUPER-RESOLUTION MICROSCOPY

At this layout, in partnership with exceptional heart series for that excitation as well as STED cross-bow supports, light emission can be switched off in all places other than with a small sector of your diffraction-limited key region. Aforementioned district reduces consistently along with growing power of the particular maximum cost, I_0 , of your STED beam. This fullness, Δ_{\min} , of your correctly fluorescing district influences side airplane approximated through.

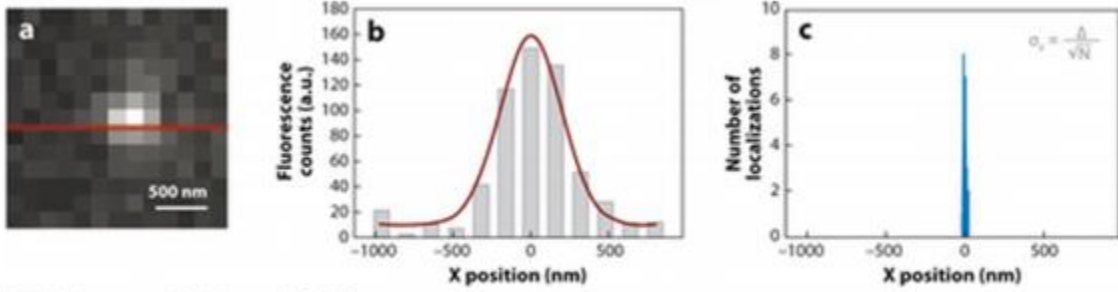
$$\Delta_{\min} \approx \frac{\lambda}{2n \sin \alpha (\sqrt{1 + I_0 / I_{\text{sat}}})}$$

The result is made by this concept that will the resolution limit caused by Abbe's requirement is taken out: the resolution measure Δ_{\min} strategies absolutely no seeing that I_0 develops indefinitely. Without a doubt, the particularly lighted district will certainly solution your Dirac well-designed along with I_0 growing further than reducing Employing STED, the particular commonly diffraction-limited key location can be created much small. That is apparent that will there will probably be other troubles, for example, photo-damage to biological tissues, along with really rigorous STED beams (Ha and Tinnefeld, 2012). It's important, on the other hand, why these limitations are certainly not the effect of a difficult actual physical reduce and might as a result often be successively taken out, e.g. through the creation of various other floor condition depletion parts as compared to ignited exhaust, which usually not one of them this kind of large intensity.

Super-resolved Single-Fluorophore Microscopy

Super-resolved single-fluorophore microscopy should right here often be recognized for a school of techniques for that the super resolution is received by way of the possibility to "super-localize" a place supply of photons. While laid out throughout part 1 previously, photons from a place origin can click the particular microscopic lenses sensor with spatial probability occurrence driven by the factor distributed function.

SUPER-RESOLUTION MICROSCOPY



Thompson MA, et al. 2012.
Annu. Rev. Biophys. 41:321–42

Failing background pixelation, the particular possibility occurrence, $p(x, y)$, associated with photon recognition inside the side airplane is around Gaussian:

$$p(x, y) \approx C e^{-\frac{(x-\mu_x)^2}{2\Delta^2} - \frac{(y-\mu_y)^2}{2\Delta^2}}$$

C is normalization regular, μ_x and μ_y establish the horizontal middle of the PSF and Δ is corresponding to Abbe's diffraction limit in Eq. 1 above. From the data that the photon circulation on the detector stalks from a spot resource, the middle of the purpose distribute purpose could be projected with a regular error, Δ_{\min} , in both x and y coordinates, written by

$$\Delta_{\min} = \frac{\Delta}{\sqrt{N}} = \frac{1}{\sqrt{N}} \frac{\lambda}{2n \sin \alpha}$$

It is actually the entire variety of photons registered by way of the sensor, and it's viewed the spatial resolution of the particular microscopic lense, used seeing that its capability to localize a place origin, Δ_{\min} , has enhanced via Abbe's initial control by way of the element $1/\sqrt{N}$. Which means that by using 100 detected photons from the only factor origin Δ_{\min} is really an element associated with 10 smaller compared to Abbe's control is actually more and more detected photons there isn't any stringent downfall to be able to the amount the resolution can often be improved. Just for this, the dwelling appealing need to be and so sparsely referred to as with fluorophores that the splitting up is bigger the diffraction limit. This issue, even so, triggers just one more problem. Good choosing theorems by way of (Huang et al., 2010) a new spatial resolution, Δ_{\min} , inside the renovation of any design involves the design is actually evenly experienced by using a spatial frequency over $2/\Delta_{\min}$. This issue, even so, is actually at odds

SUPER-RESOLUTION MICROSCOPY

while using affliction that will closest next door neighbor long distance in between music labels is bigger Abbe's diffraction limit. The truth is, what exactly is essential is definitely the dichotomy of any really thin supply of fluorescence labels to conserve the particular idea that will almost all separable factor resources along with quite a compacted supply in order to reach the particular choosing theorems associated with Nyquist along with Shannon. Your conceptual means to fix this particularly reasonable problem was offered by Erik Betzig. Irrespective of the achievements of Betzig develop near-field fluorescence microscopy, that it was getting increasingly apparent the confinement to be able to work surface experiments as well as the complicated rendering constrained the utilization of these kinds of methods(Dertinger et al., 2009). Betzig made the decision to exit instructional research, however, ongoing to consider super-resolved fluorescence microscopy. Your dog at some point recognized a different way to accomplish super-resolution without worrying about flaws associated with near-field microscopy. The remedy, your dog, proposed, ended up being to look for the placements associated with many factor resources by using noticeable spectral homes in 2 steps. With an initial stage, the particular PSF of each and every spectral school ended up being identified separately. So that each and every spectral school established a new thin placed in room, it will be achievable to look for the placements in their associates by using super resolution by calculating the particular facilities in their PSFs while using precision. Through along with the placements of the instruction alongside one another, a new super-resolution image of a new largely experienced design could be obtained. A unique rendering associated with this process ended up being therefore utilized in tests by way of G.J. Braken hoff along with collaborators; however the best approach to experimentally comprehend Betzig's perspective had been lacking. 2 years just after Betzig's offer, Moerner ended up being understanding the light emission homes associated with single molecules of mutants associated with saving money fluorescent protein (GFP) stripped away from Roger Tsien's laboratory(Jungmann et al., 2010).

SUPER-RESOLUTION MICROSCOPY

As soon as Betzig delivered to be able to instructional research just after her post-near-field exile throughout individual market, your dog knowledgeable in relation to Lippincott-Schwartz mutant along with recognized it could potentially fix the condition associated with acquiring the best approach to mix thin models of fluorophores with specific spectral homes into a compacted complete range of fluorophores. The straightforward remedy is always to switch on quite a small, and so thin, hit-or-miss part associated with GFP mutant molecules in a biological structure by way of low-level irradiation with 413 nm. Following irradiation with 488 nm would certainly subsequently be familiar with figure out the particular placements from the people in the particular thin part with super-resolution (Jungmann et al., 2010).

As soon as the earliest part has been irreversibly inactivated by way of lightening, an additional tiny part could possibly be triggered as well as the placements of their associates identified with high resolution, and many others until finally all of the subsets have been experienced along with utilized to look for the design beneath genuine superresolution conditions. This kind of satisfied the two the health of only one thin part becoming seen at the same time, along with the health of high-frequency (dense) spatial sampling so that you can match the Nyquist along with Shannon theorems.

SUPER-RESOLUTION MICROSCOPY

A Single Fluorescent Molecule

Practically in most substance procedures, by way of example computing intake and fluorescence, people examine thousands and thousands of molecules simultaneously. The outcomes of the tests symbolize a type of regular, regular molecule. People have experienced to accept simply this particular considering hardly anything else may be feasible, nevertheless for a long period that they wished you could be computing single molecules, considering that the thicker in addition to more in-depth the information, the higher the possible ways to fully grasp, by way of example, the way illnesses develop(Galbraith and Galbraith, 2011).

Consequently, throughout 1989, whenever W. E. Moerner while the primary researchers on the earth managed to assess the light absorption of the single molecule, the item became a vital achievement. At that time, your dog had been functioning on the IBM homework center throughout San Jose, California. Your try opened up it to a different foreseeable future, in addition, to influencing several apothecaries to make the focus to sole molecules. One too had been Eric Betzig, who are accomplishments will likely be insured below(Galbraith and Galbraith, 2011).

Molecular-sized Lighting Fixtures

Around 1997 W. E. Moerner became members of your School involving Los Angeles throughout San Mikka, the place Roger Tsien, Nobel Reward Laureate for being, had been looking to get GFP to be able to fluoresce in the shades in the rainbow. Your green protein was singled out coming from a fluorescent jelly-fish and power is in being able to produce different healthy proteins on the inside existing tissues visible. Working with gene technological innovation people several saving money fluorescent protein to different proteins. Your green light subsequently unveils specifically where your mobile phone your marked protein is positioned (Lippincott-Schwartz and Patterson, 2009).

SUPER-RESOLUTION MICROSCOPY

W. E. Moerner learned that the fluorescence of a single version involving GFP might very well be flipped on / off during will. As he ecstatic the protein with a light of wavelength 488 nanometers the protein began to be able to fluoresce, nevertheless eventually the item faded. In spite of the sum of light, he subsequently presented to the protein, the fluorescence was dead. This ended up, nonetheless, that light of wavelength 405 nanometers may get the protein back alive again. Whenever the protein was reactivated, the item again fluoresced during 488 nanometers.

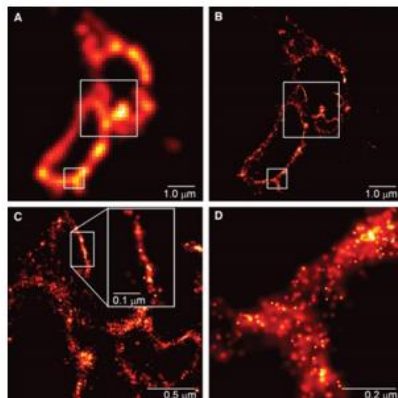
Moerner dispersed all these excitable healthy proteins in the carbamide peroxide gel, for the long distance in between each protein was higher than Abbe's diffraction limit involving 0.2 micrometers. Ever since they were sparsely dispersed, some regular optical microscope may notice your shine coming from individual molecules – that they were really like minor lighting fixtures using switches. Your outcome was revealed within the clinical diary Design throughout 1997.

Through this uncovering, Moerner established that you'll be able to control optically fluorescence of sole molecules. This particular sorted a difficulty that will Eric Betzig acquired made 24 months earlier(Lippincott-Schwartz and Patterson, 2009).

Abbe's Diffraction Limit

The same as Stefan W. Hell, Eric Betzig had been addicted using the thought of skipping Abbe's diffraction limit. Inside addition of the nineteen nineties, they ran a brand new sort of optical microscopy termed near-field microscopy at your Bell Labs around Innovative Jersey. Throughout near-field microscopy, the light ray is spewed coming from a remarkably narrow suggestion located not many nanometers from your sample. Through the years of microscopy can additionally go around Abbe's diffraction limit, while the technique has got important weaknesses. For example, the light emitted has got this kind of a brief vary of which it's difficult to just imagine houses beneath the mobile phone surface (Greenfield et al., 2009).

SUPER-RESOLUTION MICROSCOPY



Throughout 1995, Eric Betzig figured that near-field microscopy could stop enhanced significantly further. Also, they failed to come to feel in your house around academia as well as determined to terminate the analysis profession; not knowing what to do following, they give up Bell Labs (Greenfield et al., 2009).

Empowered using W. E. Moerner, a few, Eric Betzig acquired previously detected fluorescence in single molecules using near-field microscopy. He soon started to think if a frequent microscopic lense may render exactly the same high resolution if different molecules glowed with various colors, for instance, crimson, orange as well as green. The concept had been to get the microscopic lense apply for one image per color. When all molecules of just one coloration ended up dispersed but not deeper to one another compared to 0.2(Markaki et al., 2012) micrometers specified by means of Abbe's diffraction limit, his or her posture could possibly be decided pretty precisely. Subsequent, whenever these kinds of pictures ended up superimposed, your complete image would have a resolution far greater than Abbe's diffraction limit, as well as crimson, orange as well as green molecules would always be noticeable even though his or her range had been only a few nanometers. In this fashion, Abbe's diffraction limit could be circumvented. Nevertheless, there have been several functional challenges, by way of example a new shortage of molecules with a respectable level of distinguishable optical properties.

SUPER-RESOLUTION MICROSCOPY

Conclusion

Particularly put together by Eric Betzig, Stefan W. Hell in addition to W. E. Moerner get brought about to a few nanoscopy techniques and are employed throughout the world. Several Laureates continue to be effective scientists while in the big in addition to developing area involving researchers spearheading technology while in the area involving nanoscopy. Whenever they strong its impressive nanoscopes when it comes to the actual parts of life time additionally create cutting-edge knowledge. Stefan W. Hell possesses peered inside of located lack of feeling cellular material so as to have an understanding of head synapses. W. E. Moerner possesses learned protein with regards to Huntington's disease. Eric Betzig possesses followed mobile or portable split inside of embryos. There are just some of lots of examples. A very important factor is bound; the particular Nobel Laureates around Hormone balance 2014 get set the particular reason for improvement of info of the most effective benefits for you to mankind.

SUPER-RESOLUTION MICROSCOPY

References

1. BATES, M., HUANG, B. & ZHUANG, X. 2008. Super-resolution microscopy by nanoscale localization of photo-switchable fluorescent probes. *Current opinion in chemical biology*, 12, 505-514.
2. DERTINGER, T., COLYER, R., IYER, G., WEISS, S. & ENDERLEIN, J. 2009. Fast, background-free, 3D super-resolution optical fluctuation imaging (SOFI). *Proceedings of the National Academy of Sciences*, 106, 22287-22292.
3. FERNÁNDEZ-SUÁREZ, M. & TING, A. Y. 2008. Fluorescent probes for super-resolution imaging in living cells. *Nature Reviews Molecular Cell Biology*, 9, 929-943.
4. GALBRAITH, C. G. & GALBRAITH, J. A. 2011. Super-resolution microscopy at a glance. *Journal of cell science*, 124, 1607-1611.
5. GREENFIELD, D., MCEVOY, A. L., SHROFF, H., CROOKS, G. E., WINGREEN, N. S., BETZIG, E. & LIPHARDT, J. 2009. Self-organization of the Escherichia coli chemotaxis network imaged with super-resolution light microscopy. *PLoS biology*, 7, 1453.
6. HA, T. & TINNEFELD, P. 2012. Photophysics of fluorescence probes for single molecule biophysics and super-resolution imaging. *Annual review of physical chemistry*, 63, 595.
7. HUANG, B. 2010. Super-resolution optical microscopy: multiple choices. *Current opinion in chemical biology*, 14, 10-14.
8. HUANG, B., BABCOCK, H. & ZHUANG, X. 2010. Breaking the diffraction barrier: super-resolution imaging of cells. *Cell*, 143, 1047-1058.
9. HUANG, B., BATES, M. & ZHUANG, X. 2009. Super resolution fluorescence microscopy. *Annual review of biochemistry*, 78, 993.
10. JUNGSMANN, R., STEINHAUER, C., SCHEIBLE, M., KUZYK, A., TINNEFELD, P. & SIMMEL, F. C. 2010. Single-molecule kinetics and super-resolution microscopy by fluorescence imaging of transient binding on DNA origami. *Nano letters*, 10, 4756-4761.
11. KNER, P., CHHUN, B. B., GRIFFIS, E. R., WINOTO, L. & GUSTAFSSON, M. G. 2009. Super-resolution video microscopy of live cells by structured illumination. *Nature methods*, 6, 339-342.
12. LEUNG, B. O. & CHOU, K. C. 2011. Review of super-resolution fluorescence microscopy for biology. *Applied spectroscopy*, 65, 967-980.

SUPER-RESOLUTION MICROSCOPY

13. LIPPINCOTT-SCHWARTZ, J. & PATTERSON, G. H. 2009. Photoactivatable fluorescent proteins for diffraction-limited and super-resolution imaging. *Trends in cell biology*, 19, 555-565.
14. MARKAKI, Y., SMEETS, D., FIEDLER, S., SCHMID, V. J., SCHERMELLEH, L., CREMER, T. & CREMER, M. 2012. The potential of 3D-FISH and super-resolution structured illumination microscopy for studies of 3D nuclear architecture. *Bioessays*, 34, 412-426.
15. MORTENSEN, K. I., CHURCHMAN, L. S., SPUDICH, J. A. & FLYVBJERG, H. 2010. Optimized localization analysis for single-molecule tracking and super-resolution microscopy. *nature methods*, 7, 377-381.
16. PATTERSON, G., DAVIDSON, M., MANLEY, S. & LIPPINCOTT-SCHWARTZ, J. 2010. Superresolution imaging using single-molecule localization. *Annual review of physical chemistry*, 61, 345.
17. SCHERMELLEH, L., HEINTZMANN, R. & LEONHARDT, H. 2010. A guide to super-resolution fluorescence microscopy. *The Journal of cell biology*, 190, 165-175.
18. SHTENGEL, G., GALBRAITH, J. A., GALBRAITH, C. G., LIPPINCOTT-SCHWARTZ, J., GILLETTE, J. M., MANLEY, S., SOUGRAT, R., WATERMAN, C. M., KANCHANAWONG, P. & DAVIDSON, M. W. 2009. Interferometric fluorescent super-resolution microscopy resolves 3D cellular ultrastructure. *Proceedings of the National Academy of Sciences*, 106, 3125-3130.
19. VAN DE LINDE, S., HEILEMANN, M. & SAUER, M. 2012. Live-cell super-resolution imaging with synthetic fluorophores. *Annual review of physical chemistry*, 63, 519-540.