OPTIMISATION OF POLYMER PARTICLES PROPULSION ON CAESIUM ION-EXCHANGED CHANNEL WAVEGUIDE FOR STEM CELLS SORTING APPLICATIONS

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ABSTRACT

Optical trapping of particles has become a powerful non-mechanical and non-destructive technique for precise particle positioning. The manipulation of particles in the evanescent field of a channel waveguide potentially allows for sorting and trapping of several particles and cells simultaneously. This paper describes the studies carried out, both theoretically and experimentally, to optimise the propulsion of polymer particles on caesium ion-exchanged channel waveguides, to ultimately allow for the trapping and separation of stem cells according to their size and refractive index. The propulsion of polymer particles was observed to increase with the supplied input power and with laser polarisation at transverse magnetic (TM) mode. The propulsion of particles was demostrated to peak on a 4μm channel width of an 8 hours ion-exchanged waveguide. The work carried out provides the optimal optical and waveguide parameters to be exploited for trapping and sorting stem cells on caesium ion-exchanged waveguides.

***KEYWORDS**: Waveguides, optical trapping, polymer particles, stem cells, evanescent field*

1.0 INTRODUCTION

There is a significant potential for stem cells to be exploited for regenerative medicine. Stem cells can be defined as cells with self-renewal and pluripotency properties (Siminovitch *et.al*., 1963), (Becker *et.al*., 1963), (Schöler *et.al*., 2007). Self-renewal in this case refers to the ability to maintain undifferentiated state after numerous cell division cycles. Pluripotency, on the other hand, is the capacity to differentiate into specialised cell types. Stem cells act as a repair system for the body by differentiating into specialised cells and replenishing cells in regenerative organs such as skin or intestinal tissues (Siminovitch *et.al*., 1963), (Becker *et.al*., 1963), (Schöler *et.al*., 2007). Hence stem cells can be utilised to develop into many different cell types in the body for medical therapies. Currently, the number of people needing a transplant for diseased or destroyed organs far exceeds the number of donated organs or tissues available for transplantation. Theoretically, stem cell therapy has the potential to dramatically change the treatment of a myriad of diseases, conditions, and disabilities including Parkinson's and Alzheimer's diseases, diabetes, leukaemia, spinal cord injuries, muscle damage and rheumatoid arthritis (Hall, 2008), (Goldman *et.al*., 2006), (Centeno *et.al*., 2008).

There has been extensive research on stem cell therapy, yet remarkably little is known about the molecular mechanisms that underlie the pluripotency of stem cells. Hence, there is a need for an approach to provide a pure population of stem cells that is free from mechanical (fluid sheer stress, cyclic stretch and pressure), electrical (field induced) or chemical (need for labelling) induced cellular response. Such an approach will be able to provide the effective characterisation and study of different stem cell populations and ultimately clearer strategies for regenerative medicine. Optical trapping and propulsion is seen as a potential candidate as a sorting technique that avoids detrimental effects on the stem cells.

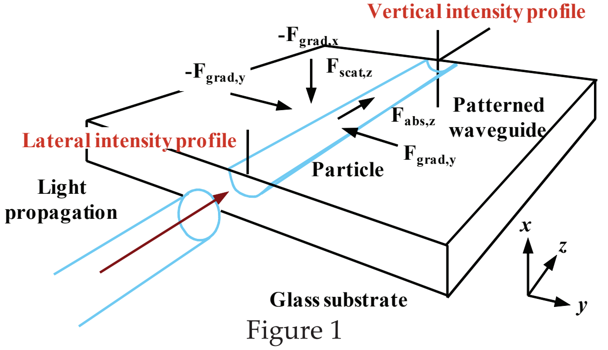

Figure 1

Schematic of optical forces acting on a particle on a channel waveguide.

The optical trapping technique has proven to be a very useful tool that offers a non-contact method for precise particle handling. The pioneering work by Ashkin in 1970 showed that the forces of radiation pressure from focused laser beams could be used to significantly affect the dynamics of small transparent micrometer-sized neutral particles (Ashkin, 1970). It was shown experimentally that, using just these forces, small micrometer-sized neutral particles could be accelerated, decelerated and even stably trapped using focused laser beams. The utilisation of evanescent waves for optical trapping has so far been limited, as reviewed in (Shahimin, 2009). The most comprehensive work to date was done by Ng involving gold nanoparticles (Ng *et.al*., 2002). This motivates the use of the evanescent wave trapping technique to develop a novel method for sorting particles and biological cells according to their optical properties under optimised conditions. Using optical trapping and propulsion on a channel waveguide device allows the manipulation of several particles and cells simultaneously. This has a significant clinical advantage for biological applications where high throughput is required. Furthermore the channel waveguide configuration permits integration with microsystems for a lab-on-a-chip device. This is expected to pave the way for low cost, robust and simple integrated optical devices to be fabricated and optimised, allowing this technology to become applicable to a practical system.

In the evanescent field above an optical channel waveguide, a particle or a biological cell in the optical field experiences three main forces as illustrated in Figure 1; an axial scattering force, F_{scat}, a gradient force, F_{grad}, which can act in both the axial (due to losses along the propagation of light) and the radial direction (due to variation in the intensity profile), and an absorption force, F_{abs}, which is dependent upon the complex refractive index of the particle. A particle in the evanescent field will be propelled and trapped with a dependence on the intensity gradient (a property dependent upon the physical characteristic of the waveguide and the laser configurations). Thus the light reflected and absorbed by the particle will be a function of the relative intensity gradient, the particle size and refractive index of the particle. The particle is drawn into the region of highest light intensity and propelled in the direction of the propagating light. In this paper, we report our studies to establish the optimum optical and waveguide parameters for propulsion of polymer particles on caesium ion-exchanged waveguides.

2.0 EXPERIMENTAL PROCEDURES

Waveguides are fabricated using (50 x 50mm) sodalime glass substrates (UQG Optics) masked with aluminium film (photolithographically defined channels) and immersed in a molten caesium nitrate salt at 450°C for 4 to 17 hours. The channel regions in the glass substrate are thus doped with caesium ions resulting an ion-exchanged channel waveguides with varied effective refractive index as shown in Table 1. A polarised laser (1064nm, IPG Photonics) is coupled via a polarisation-maintaining single mode fiber onto the input facet of the channel waveguide. The resultant waveguides were monomode at the wavelength used.

A reservoir (50 x 10 x 2mm), formed in a moulded polydimethylsiloxane elastomer (PDMS, Dow Corning), is placed on the surface of the waveguide. A cooled charged-coupled device (CCD) camera (QImaging) attached to a microscope, operating in dark field mode, is used to image the particles on the waveguide. Polymer particles (polystyrene, refractive index 1.59, Polysciences Europe) of diameter 3μm, 6μm and 10μm, suspended in deionised water were pippetted into the PDMS reservoir. All polymer particle solutions used in this paper were prepared by diluting the particles in deionised water until a concentration of 1 x 106 particles per ml was reached. The concentration was such as to achieve a low density of particles in order to avoid the formation of long particle chains (Ng, 2000), (Hole, 2005). The propulsion of the particles was imaged and analysed using an in-house-generated tracking software. Unless stated otherwise, the waveguide channel used for the particle propulsion investigation has a width of 4μm and is single mode at 1064nm.

Table 1
Details of the waveguides fabricated using a soda-lime glass substrate. The refractive index, neff of the fundamental mode was measured at 632.8nm.

Ion-exchange time (h)	Fundamental n_{eff}
4	-
6.5	1.5151
8	1.5189
10	1.5219
17	1.5280

Each of the experimental data was compared with a theoretical model. The theoretical model was simulated by adapting the Arbitrary Beam Theory (ABT) developed by (Barton *et.al.*, 1988), (Barton, 1989). The simulation was made using the same model as in (Jaising *et.al.*, 2005), (Jaising *et.al.*, 2005) and carried out with the help of Dr Hitesh Jaising and Dr Olav Hellesø, of the University of Tromsø, Norway. Unless stated otherwise, the waveguide parameters used in the simulation were a 4μm channel width, a substrate index of 1.50, a waveguide index of 1.54 and a particle index of 1.59 dispersed in water (index of 1.33). The wavelength used in the simulation was 1064nm with an input power of 500mW. Note that the model assumed that there is no power loss due to the Fresnel scattering, modal mismatch or propagation loss along the channel waveguide. Furthermore, it is also assumed that the propulsion of particles is not affected by any non-optical forces.

3.0 RESULTS AND DISCUSSION

3.1 Optical Configurations

The laser power was varied from ≈400mW to ≈600mW by adjusting the supply current through the laser controller. A series of experiments with varying laser power were conducted on a 10 hours ceasium ion-exchanged waveguide before changing to another particle size. The experiments were repeated 3 times for each particle size. Theoretical estimation of the particles propulsion, as illustrated in Figure 2, shows that the propulsion velocity increased with the laser power. This is due to the fact that the intensity of the evanescent field and thus, the optical forces acting in the direction of the wave propagation increase linearly with the laser power. Figure 3 shows the increment of the particle velocity in relation to the laser power supplied to the 4μm channel width for all particle size used in the experiments. The laser power, however, was not increased over 650mW in order to avoid burning any of the components along the optical path as well as to preserve the waveguide's lifetime. An over exposure to high laser power has been recorded as the major factor in deteriorating the lifetime of the waveguide as discussed in (Barton *et.al.*, 1988).

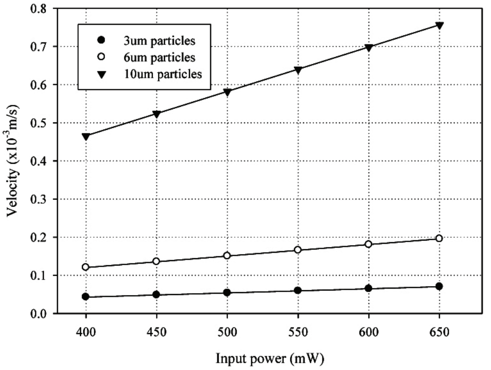

Figure 2
The theoretical estimation of the propulsion velocity of different sized particles for varying input laser power

There are discrepancies between the velocity observed experimentally and from the theoretical model due to limitation in the model as described in Section 0. However, the experimental data shows the same trend as expected from the model where the propulsion velocity increases with particle size. The highest velocity observed in the range tested was 3.44μm/s, obtained for a 10μm particle when the laser power was set to 617mW. The velocity then decreased as the power coupled to the waveguide was decreased. At 400mW, the 10μm particles moved at 1.14μm/s and at 0.53μm/s for the 6μm particles.

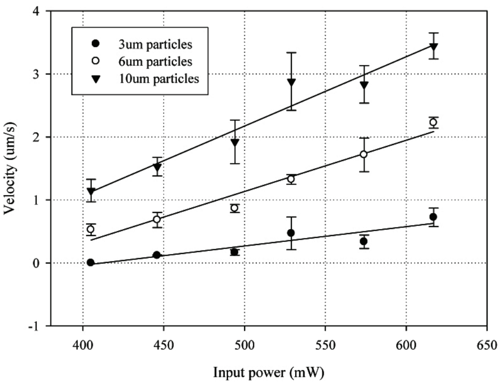

Figure 3
Velocity of different sized particles for varying input laser power

Another optical parameter that plays an important role in the particle trapping and propulsion is the laser polarisation. There are two polarisation modes, transverse electric (TE) and transverse magnetic (TM). TE mode signifies that the electric field vector is directed along the y-direction (parallel to the waveguide channel) as illustrated in Figure 1. Likewise, TM mode signifies that the magnetic field vector is directed along to the y-direction. In determining the effect of polarisation on particle velocity, the same 10 hour caesium ion-exchanged waveguide was used. A 10μm polystyrene particle solution was pipetted to the reservoir and the propulsion on a 4μm channel width was monitored. The nanorotator attached to the fibre holder and the utilisation of PM fibre allows control of the polarisation of the propagating light in the waveguide. A polariser was used to set the light to the correct mode before the beginning of each experiment. The nanorotator was set by fixing the polariser, for example to the TE mode. The nanorotator was rotated until the minimum output power was detected from the power meter. The laser polarisation was now set to TM mode. Output power from the PM fibre of both polarisations was recorded and a polarisation extinction ratio of about 30dB was obtained.

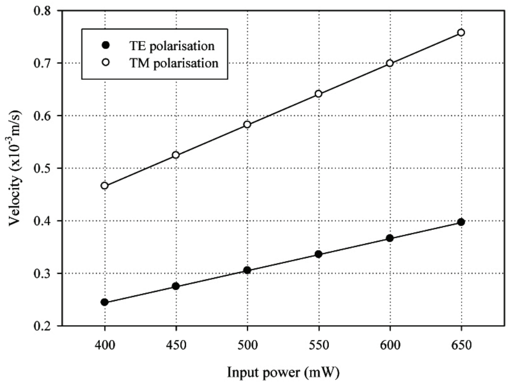

Figure 4
The theoretical estimation of the propulsion velocity of 10μm particles with varying input laser power for both polarisations

Propulsion velocity of particles for each polarisation was investigated by varying the laser power coupled to the waveguide. Figure 4 illustrates a significant difference for the velocity of particles according to the polarisation from the theoretical model. Particles propelled in the direction of wave propagation were observed to be propelled at a higher average velocity in the TM mode as shown in Figure 5. For example the velocity of particles propelled at 500mW was 1.92μm/s in the TM mode and 0.87μm/s in the TE.

The velocity for TM and TE modes was in accordance with the results observed in [10, 11]. The greater overall gradient for the TM mode indicates that the mode exhibits a higher surface intensity, as expected from several published papers (Ng, 2002), (Ng, 2000), (Jaising, 2005), (Hole, 2005). Hence, the TM mode was used for all subsequent experiments unless stated otherwise. Note that if the gradients for both polarisations are extrapolated, both cross the x-axis at approximately 300mW. This may indicate that 300mW was the threshold power needed for creating the surface intensity to propel 10μm polystyrene particles. A similar extrapolation on Figure 3 shows a possible threshold power for 3μm and 6μm particles of about 400mW and 350mW respectively. A higher threshold power is needed for smaller particles and this may be due to the fact that smaller particle motion is more influenced by Brownian motion. Thus stronger gradient force is needed to stably trap smaller particles.

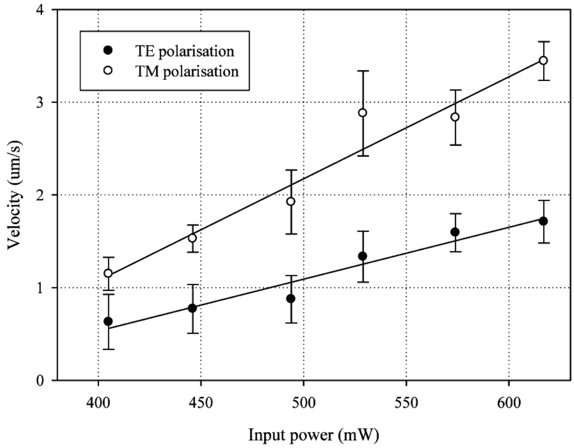

Figure 5
Velocity of 10μm particles against power for both polarisations

3.2 Waveguide Parameters

Several waveguides have been fabricated to investigate the effect of ion-exchange time on the particle propulsion. By varying ion-exchange time, the waveguide depth is also varied. Two polystyrene particles, 3μm and 6μm were used for this investigation. Each particle size was diluted in deionised water before being pipetted into the reservoir. The same optical and imaging setup was used as described in previous sections.

Details of the waveguides fabricated are tabulated in Table 1. Out of all 5 waveguides tested in this investigation, the 4 hour ion-exchanged waveguide shows no guiding at all. This indicates that the ion-exchange time was not enough to create a waveguide depth that permits light to propagate in a confined mode. The 17 hour ion-exchanged waveguide has the highest effective refractive index and was observed to show a considerably higher loss. No propulsion of 3μm and 6μm particles was observed on this waveguide. Hence these observations signify that there is an optimal waveguide effective index (and hence ion-exchange time) for particle propulsion. The 17 hour ion-exchanged waveguide was determined to be multimoded from the simulation data and the rest were single mode waveguides when operating at 1064nm wavelength. In order to establish the optimal waveguide effective index, based upon the fabrication condition used, the propulsion velocity of the 3μm and 6μm particles was compared on all fabricated waveguides. Mesh plots of particle velocity against ion-exchange time, for both the 3μm and 6μm particles, are illustrated in Figure 7. The maximum velocities achieved for the 3μm and 6μm particles using the 4μm channel width were 2.16μm/s and 0.75μm/s respectively at 500mW input. Both of the maximum velocities were observed using the 8 hour ion-exchanged waveguide. The theoretical propulsion velocity distribution as illustrated in Figure 6, also shows maximum velocity on 8 hour ion-exchanged waveguide. The maximum velocity for different channel width is also shown in the figures; this will be discussed further in the next section. Using the longer ion-exchange time waveguides, the velocity of both particles is lower. This corresponds to the shorter range of the evanescent field of deeper waveguide depth and hence reduces the intensity on the waveguide surface. Reduction in velocity was also apparent on the short ion-exchange time waveguide. Such an effect is due to the fact that the field penetrates deeper into the substrate layer and consequently lowers the surface intensity. From these general observations, it can be concluded that there is an optimum ion-exchange time for producing the maximum surface intensity for the propulsion of particles. From the range of waveguides tested, the 8 hour ion-exchange waveguide is the optimum sample.

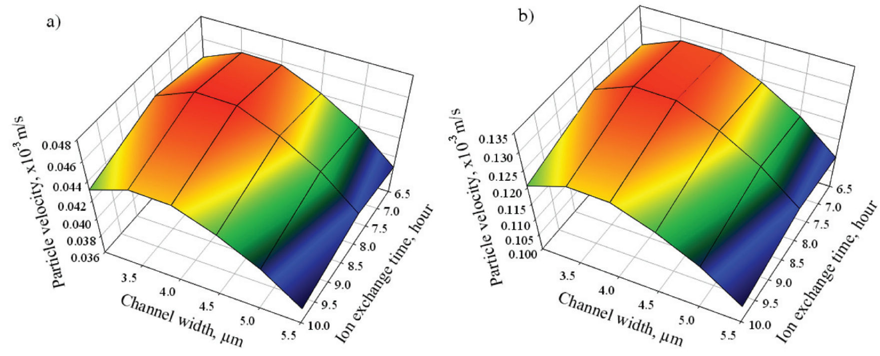

Figure 6
The theoretical estimation of the propulsion velocity of a) 3μm particle and b) 6μm particle against ion-exchange time and channel width

Another waveguide property that plays an important role in particle trapping and propulsion is the waveguide channel width. The laser power was coupled into the 10 hour caesium ion-exchanged waveguide channels with the nominal width varying from 3μm to 10μm. The same waveguide was used to ensure that the velocity of the particle's propulsion is affected by the channel width alone. Particles of diameter 3μm, 6μm and 10μm were used in a series of experiments to investigate the effect of channel width on the particle propulsion.

Experimental results for each particle size were compiled and are illustrated in Figure 9. On average, the propulsion velocity increases with size for all waveguide widths as observed from previous sections. All particle sizes show a peak in the propulsion velocity on the 4μm nominal channel width. Smaller particle sizes (3μm and 6μm) however show a less significant peak. Smaller particle sizes have longer settling times and they are easily affected by Brownian motion. Hence the optical force acting on the particle is believed to cause the particle to move in three dimensions away from the evanescent field. Consequently, this reduces the propulsion velocity. Nonetheless, the experimental observation agrees strongly with the theoretical waveguide simulation that 4μm channel width produces the optimum surface intensity, as suggested in Figure 8. At waveguide widths smaller than the optimum point, the velocity reduces with decreasing width, indicating a near cut-off point where the channel is no longer guiding and the light is totally propagating in the substrate layer.

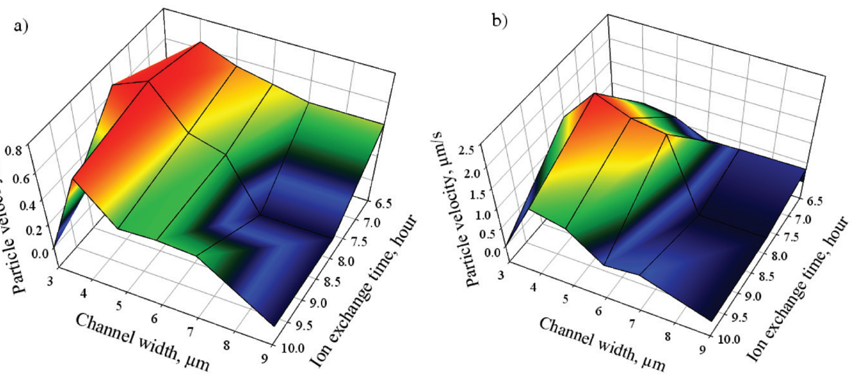

Figure 7
The propulsion velocity of a) 3μm particle and b) 6μm particle against ion-exchange time and channel width

In the experimnets, there is also a general trend of increasing particle velocity as the channel widths approach 4μm although these velocities fluctuated. Discrepancy from the simulation can be due to several reasons, such as inconsistent surface friction, a variation in particle size distribution or a fluctuation in the supplied input power. From the experiments discussed so far, it can be shown that the optimum channel width in the range tested is 4μm on an 8 hour caesium ion-exchanged waveguide. In terms of optical properties, propulsion was observed to be higher with a higher laser power and at the TM mode, as indicated in the simulations.

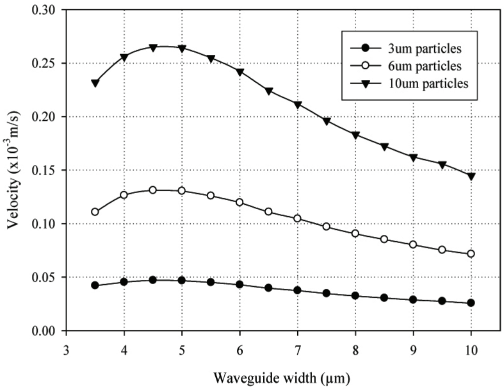

Figure 8
The theoretical estimation of the propulsion velocity of different sized particles with varying channel widths

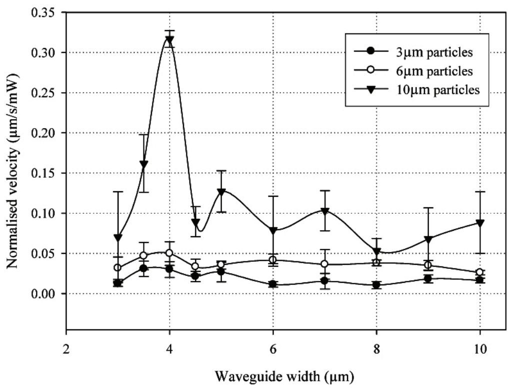

Figure 9
Velocity of different sized particles with varying channel widths

4.0 CONCLUSION

The optical trapping and propulsion of polymer particles, namely polystyrene were presented in this paper. Characterisation of particle propulsion against optical and waveguide parameters is used to investigate the optimum parameters for propulsion on caesium ion-exchanged waveguides. The effects of laser power and laser polarisation upon propulsion were investigated. 10µm polystyrene particles were observed to propel at a rate of $1.1 x 10^{-2} µms^{-1}mW^{-1}$ as laser power increased and in the TM polarisation. The rate of propulsion velocity of 10µm particles in the TE polarisation is $5.6 x 10^{-3} µms^{-1}mW^{-1}$. This observation confirms the theoretical evaluation and experimental findings of several papers(Ng, 2000), (Ng, 2002), (Grujic, 2004). Experimental characterisation of the waveguide parameters of caesium ion-exchanged waveguides was also carried out. Propulsion of polystyrene particles was conducted on several waveguides, investigating the effect of waveguide width and the waveguide ion-exchanged time (which is related to the waveguide depth). Results from this research found that the optimum propulsion is observed on an 8 hour caesium ion-exchanged waveguide (n_{eff} =1.5189). Variation in propulsion velocity of particles with different channel widths concludes that the optimum propulsion is observed on a 4μm nominal caesium ion-exchanged channel waveguide width (normalised to modal output power). Propulsion on a 10μm channel width shows the highest output power. The work carried out here determined the optimum optical and waveguide parameters to be further exploited for trapping and sorting of stem cells on caesium ion-exchanged channel waveguides. These studies will continue with a view to developing a new stem cell sorting device.

5.0 ACKNOWLEDGMENT

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6.0 REFERENCES

A. J. Becker, E. A. McCulloch, and J. E. Till. 1963. Cytological Demonstration of the Clonal Nature of Spleen Colonies Derived from Transplanted Mouse Marrow Cells. Nature. Vol. 197. pp. 452-454.

Ashkin A. 1970. Acceleration and trapping of particles by radiation pressure. Physical Review Letters. Vol. 24. pp. 156-159.

C. J. Centeno, D. Busse, J. Kisiday, C. Keohan, M. Freeman, D. Karli. 2008. Increased Knee Cartilage Volume in Degenerative Joint Disease using Percutaneously Implanted. Autologous Mesenchymal Stem Cells. Pain Physician. Vol. 11. pp. 343-353.

H. Jaising, K. Grujic, O. G. Hellesø. 2005. Simulations and velocity measurements for a microparticle in an evanescent field. Optical Review. Vol. 12. pp. 4.

H. R. Schöler. 2008. The Potential of Stem Cells: An Inventory: Ashgate Publishing Ltd.

H. Y. Jaising, O. G. Hellesø. 2005. Radiation forces on a Mie particle in the evanescent field of an optical waveguide. Optics Communications. Vol. 246. pp. 373-83.

J. P. Barton, D. R. Alexander, S. A. Schaub. 1988. Internal and near-surface electromagnetic fields for a spherical particle irradiated by a focused laser beam. Journal of Applied Physics. Vol. 64. p. 1632.

J. P. Barton, D. R. Alexander, S. A. Schaub. 1989. Theoretical determination of net radiation force and torque for a spherical particle illuminated by a focused laser beam. Journal of Applied Physics, Vol. 66. p. 4594.

J. P. Hole, J. S. Wilkinson, K. Grujic, O. G. Hellesø. 2005. Guiding and sorting of micro and nano particles with integrated optics. In Conference on Lasers and Electro-Optics (CLEO 2005).

J. P. Hole, J. S. Wilkinson, K. Grujic, O. G. Hellesø. 2005. Velocity distribution of gold nanoparticles trapped on an optical waveguide.Optics Express. Vol. 13. pp. 3896-3901.

J. P. Hole. 2005. The Control of Gold and latex Particles on Optical Waveguide. In Optoelectronics Research Centre. Vol. PhD thesis Southampton: University of Southampton. pp. 1-204.

K. Grujic, O. G. Hellesø, J. S. Wilkinson, J. P. Hole. 2004. Optical propulsion of microspheres along a channel waveguide produced by Cs+ ion-exchange in glass. Optics Communications. Vol. 239. pp. 227-235.

L. N. Ng, B. J. Luff, M. N. Zervas, J. S. Wilkinson. 2000. Forces on a Rayleigh particles in the cover region of a planar waveguide. Journal of Lightwave Technology. Vol. 18. pp. 388-400.

L. N. Ng, B. J. Luff, M. N. Zervas, J. S. Wilkinson. 2002. Propulsion of gold nanoparticles on optic s. Journal of Cellular and Comparative Physiology. Vol. 62. pp. 327-336.

M. M. Shahimin. 2009. Propulsion of polymer particles on ceasium ion-exchanged channel waveguides for stem cell sorting applications. In School of Electronics and Computer Sciences. Vol. PhD Thesis Southampton: University of Southampton. pp. 1-206.

S. A. Goldman and M. S. Windrem. 2006. Cell replacement therapy in neurological disease. Philosophical Transactions of the Royal Society B-Biological Sciences. Vol. 361. pp. 1463-1475.

V. J. Hall. 2008. Embryonic stem cells and Parkinson's disease: Cell transplantation to cell therapy. Annals Academy of Medicine Singapore. Vol. 37. pp. 163-164.