RSC Advances



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REVIEW

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Cite this: RSC Adv., 2021, 11, 9433

Received 5th January 2021 Accepted 24th February 2021

DOI: 10.1039/d1ra00074h

rsc.li/rsc-advances

1. Introduction

Recent advances in nanotechnology have contributed tremendously to the development and revolutionizing of the drug delivery system in the nanomedicine field. The application of nanoparticles has long been recognized as a controlled release formulation for delivering a therapeutic agent to a specific targeted site. Nanoparticles provide a high therapeutic effect against cancers, which has earned them remarkable research interest among researchers. Nanoparticles offer a highly efficient targeted therapy compared to traditional cancer therapies. This targeted therapy can be done easily on nanoparticles using an ideal targeting ligand. Thus, targeting nanoparticles based on biodegradable polymers have gained much interest for treating cancer cells with minimal systemic side effects.^{1,2}

Poly(lactic-*co*-glycolic acid) (PLGA) is a biodegradable polymer that has attractive properties as a nanocarrier for cancer therapy. PLGA is a hydrophobic copolymer and mainly

Cytotoxicity of targeted PLGA nanoparticles: a systematic review[†]

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Recent advances in nanotechnology have contributed tremendously to the development and revolutionizing of drug delivery systems in the field of nanomedicine. In particular, targeting nanoparticles based on biodegradable poly(lactic-co-glycolic acid) (PLGA) polymers have gained much interest. However, PLGA nanoparticles remain of concern for their effectiveness against cancer cells and their toxicity to normal cells. The aim of this systematic review is to identify a promising targeting PLGA nanoformulation based on the comparison study of their cytotoxicity potency in different cell lines. A literature search was conducted through the databases of Google Scholar, PubMed, ScienceDirect, Scopus and SpringerLink. The sources studied were published between 2009 and 2019, and a variety of keywords were utilized. In total, 81 manuscripts that met the inclusion and exclusion criteria were selected for analysis based on their cytotoxicity, size, zeta potential, year of publication, type of ligand, active compounds and cell line used. The half maximal inhibitory concentration (IC₅₀) for cytotoxicity was the main measurement in this data extraction, and the SI units were standardized to $\mu q m L^{-1}$ for a better view of comparison. This systematic review also identified that cytotoxicity potency was inversely proportional to nanoparticle size. The PLGA nanoparticles predominantly exhibited a size of less than 300 nm and absolute zeta potential ~20 mV. In conclusion, more comprehensive and critical appraisals of pharmacokinetic, pharmacokinetic, toxicokinetic, in vivo and in vitro tests are required for the investigation of the full value of targeting PLGA nanoparticles for cancer treatment.

composed of two monomers: lactic acid and glycolic acid (Fig. 1). PLGA is approved by the European Medicine Agency and the US Food and Drug Administration (FDA) as an ideal material for designing a drug delivery system due to its biocompatibility and biodegradability. PLGA is widely adapted for preparing nanoparticles encapsulating hydrophilic and hydrophobic anti-therapeutic agents.^{3,4} PLGA offers an enhanced permeability and retention (EPR) effect, sustained and controlled drug delivery for cancer therapy, enhanced accumulation of drugs in tumor vasculature and targeted delivery by surface conjugation with targeting ligands.⁵

Active and passive mechanisms are often practiced when targeting cancer cells using nanoparticles. Passive targeting is the application of polymeric nanoparticles owing to their size, shape and surface charge enabling them to be accumulated



Fig. 1 Chemical structure of PLGA.

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[†] Electronic supplementary information (ESI) available: Supplementary data for Fig. 3 and 4. See DOI: 10.1039/d1ra00074h

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predominantly in the microenvironment of cancer cells *via* the EPR effect. This EPR effect is amplified based on the exclusive presence of leaky vasculature and impaired lymphatic drainage in tumors. Active targeting is the attachment or grafting of targeting/biorecognizable ligands on nanoparticles to target specific receptors/biomarkers that are overexpressed in cancer cells, excluding normal cells.⁶ Since targeting ligands are highly selective towards overexpressed receptors in cancer cells, in which can result in enhanced cellular uptake of nanoparticles as well as excluding harm to normal cells. Both passive and targeting mechanisms are considered a gold standard in designing a drug delivery system.

Recently, the use of PLGA nanoparticles for cancer therapy has received great interest due to the advantages offered and approval by the FDA. However, the safeness of PLGA nanoparticles containing cytotoxic therapeutic agent remains a huge concern. The anti-cancer drugs lack targeting specificity to cancer cells and could induce potent cytotoxic effects against both normal and cancer cells. In addition, the cellular concentration of the drugs is relatively low in cancer cells due to the low efficiency of non-targeting PLGA nanoparticles in delivering the drugs to the site of action. The cancer cell targeting of PLGA nanoparticles, enhanced cellular uptake of the drugs and low toxicity to normal cells are the most important criteria or measurements for chemotherapy. Therefore, it is vital for researchers to design a PLGA nanocarrier that, in addition to being biocompatible, biodegradable and cost-effective, can specifically release drugs at the target site with reduced systemic effects.

Hence, this systematic review is focused on a comparison study of the cytotoxicity potency of the targeting PLGA nanoparticles on the basis of published *in vitro* assessment findings from 2009 to 2019 in order to assess the PLGA nanoparticles with the ideal targeting ligands for specific cell lines – preferentially based on their IC_{50} cytotoxicity potency – and to correlate the size and zeta potential of nanoparticles with cytotoxicity potency.

The databases of Google Scholar, PubMed, ScienceDirect, Scopus and SpringerLink were searched for literature published between 2009 and 2019. Different combinations of keywords including PLGA nanoparticles, cytotoxicity, targeting ligands and anti-cancer - were used for the literature search (Fig. 2). The methodology for the study was based on the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P) 2015.7-9 The inclusion criteria for our study were: (1) PLGA nanoparticles with different types of targeting ligands; (2) PLGA with nanoencapsulated active compounds and exhibited cytotoxic effects on normal and cancer cells; (3) PLGA with coencapsulation of outer or inner polymers; (4) studies published between 2009 and 2019 (including in-press articles). Studies with the following criteria were omitted (exclusion criteria): (1) PLGA microparticles; (2) chemical conjugation of PLGA with other polymers to form nanoparticles; (2) all in vivo, ex vivo, in silico, clinical studies, and review articles; (4) studies without available cytotoxicity data; (5) articles that were not published in English. Based on the inclusion and exclusion criteria, the articles that fulfilled the requirements were selected for analysis. Screening of the articles was conducted by two independent reviewers. The data extraction involved analysis of



Fig. 2 Flowchart of the selection of studies, using PRISMA guidelines.

the selected articles based on the types of cells, IC_{50} for cytotoxicity, year of publication, treatment duration, types of active compounds used, types of targeting ligands, types of studies (*in vitro*) and the size and zeta potential of the nanoparticles. The data were described and presented in a table. The IC_{50} for cytotoxicity was the main measurement in this data extraction. The SI units were standardized to $\mu g m L^{-1}$ for a better view of comparison. The IC_{50} is the dose required to inhibit 50% of the cell viability. Based on the availability of the data of IC_{50} , size and zeta potential of the nanoparticles, PLGA nanoparticles with the active targeting properties were selected for the purpose of studying the correlation between the particle size/ zeta potential of PLGA nanoparticles and cytotoxicity potency.

2. Cytotoxicity of PLGA nanoformulations

The databases of Google Scholar, PubMed, ScienceDirect, Scopus and SpringerLink were searched. These produced 113, 32, 113, 20 and 5 articles, respectively. From all the databases, a total of 266 articles were retrieved after 17 duplicates were removed. Following this, 170 articles that were not compliant with the inclusion criteria were identified and excluded from the study. The 96 articles left were thoroughly assessed according to the exclusion criteria defined in Introduction. After critical assessment, 15 articles were omitted due to the methodology and cytotoxicity data being insufficiently described. Hence, 81 studies have been integrated into the qualitative synthesis involving assessment of the data of *in vitro* studies.

2.1 In vitro studies

The data of the cytotoxicity of PLGA nanoparticles conjugated with particular targeting ligands that deliver specific active

compounds against different types of cells – such as brain, breast, lung, colon, stomach, gastric, liver, ovary, cervix, prostate, uterus, pancreas, skin, umbilical vein endothelial, esophagus, bladder, head, neck and kidney cells – are shown in Table 1. From the table, it can be seen that PLGA nanoparticles are time/dose-dependent on cytotoxicity.

2.1.1 Brain. Magnetic silica PLGA nanoparticles conjugated with transferrin showed the most potent cytotoxic effect against brain cancer cells (U-87) with an IC_{50} of 0.13 µg mL⁻¹.¹⁰ This could be due to the dual drug delivery of doxorubicin and paclitaxel designed for the PLGA nanoparticles, compared to the single drug carriers listed in Table 1. The application of targeting ligands can improve the bioavailability of drug-loaded nanoparticles. In this study, transferrin was actively targeted to the overexpressed transferrin receptors in brain capillary endothelium and glioma cells. The IC_{50} was much lower when the treatment duration was prolonged from 48 h (1.03 µg mL⁻¹) to 96 h (0.13 µg mL⁻¹), showing the time-dependent effect of the treatment.

2.1.2 Breast. Transferrin-conjugated lipid-coated PLGA nanoparticles carrying the aromatase inhibitor 7α -(4'-amino) phenylthio-1,4-androstadiene-3,17-dione (7α -APTADD) exhibited the greatest anti-proliferative effect against SKBR-3 breast cancer cells. The IC₅₀ value of the nanoparticles was less than 0.00049 µg mL⁻¹ for 24 h of treatment.¹¹ These findings indicate that the inhibitory activity of nanoparticles has been improved in comparison with the non-targeted nanoparticles, accounting for the transferrin receptor-mediated endocytosis.

2.1.3 Lung. Arginine–glycine–aspartic acid (RGD) peptidemodified and paclitaxel-loaded PLGA-chitosan nanoparticles (PTX-PLGA-CSNP-RGD) had the most potent cytotoxic effect against H1975 lung cancer cells with an IC₅₀ of 0.0017 µg mL⁻¹.¹² The PTX-PLGA-CSNP-RGD nanoparticles showed enhanced uptake due to the nature of RGD peptide, which is highly targeted to the overexpressing integrin $\alpha_v\beta_3$ receptor specifically found in lung cancer cells. In addition, less toxicity was received by the normal lung cells due to the weak expression of integrin $\alpha_v\beta_3$ in normal lung cells.

2.1.4 Colon. PLGA nanoparticles loaded with paclitaxel and conjugated with WGA wheat germ agglutinin (WNP) showed the most promising cytotoxic potency against colon cancer cells (HT-29) with an IC_{50} of 0.028 µg mL⁻¹.¹³ WGA actively binds to the highly expressed *N*-acetyl-D-glucosamine-containing glycoprotein found in the membrane of colon cancer cells, thus increasing the cellular uptake of WNP in colon cancer cells. Since WGA tends to bind to the glycoprotein in colon cancer cells, WNP is more effective in delivering paclitaxel to colon cancer cells to enhance the bioavailability of paclitaxel compared to non-targeted nanoparticles.

2.1.5 Stomach. Only one study about nanoparticles targeting stomach cancer cells was included for review after the databases were screened. PLGA nanoparticles modified with polyethylene glycol and conjugated with an engineered antihuman CD44v6 Fab (AbD15179) were developed to specifically target human CD44 isoforms containing exon v6 (CD44v6) present in stomach cancer cells. The PLGA nanoparticles were reported to exhibit anti-proliferative potency against GP202,

MKN74-CD44v6+ and MKN74 stomach cancer cells. The cytotoxicity of the PLGA nanoparticles was 50 μ g mL⁻¹ and highly stable against fluid-mimicking gastrointestinal conditions.¹⁴ No IC₅₀ data were reported in this study.

2.1.6 Gastric. Dual-targeting hybrid nanoparticles made of PLGA and a lipoid shell prepared by conjugating the anti-HER2/ neu peptides (AHNP) and *n*-hexadecylamine (HDA) to the carboxyl groups of hyaluronic acid (HA) were reported to deliver 7-ethyl-10-hydroxycamptothecin (SN38 agent) specifically to gastric cancer cells (HGC27 cells) with overexpression of (1) CD44 cluster determinant 44 and (2) HER2 (human epidermal growth factor receptor 2). An IC₅₀ of 0.05 μ g mL⁻¹ was reported for the dual-targeting nanoparticles.¹⁵ Studies on the cytotoxicity mechanism have indicated that the enhanced cellular uptake of dual-targeting nanoparticles and suppression of CD44 and HER2 expression by HA and AHNP inhibit the growth of HGC27 cells.

2.1.7 Liver. LFC131 peptide-conjugated PLGA nanoparticles composed of $D-\alpha$ -tocopheryl polyethylene glycol succinate (TPGS) moieties were prepared to deliver epirubicin and specifically bind with CXCR4-overexpressing human hepatic carcinoma cells (HepG2). TPGS is a vitamin E derivative and was used to stabilize the PLGA nanoparticles. It was also used as an inhibitor of P-glycoprotein in overcoming multi-drug resistance.¹⁶ LFC131 peptide-conjugated nanoparticles exhibited a threefold higher cellular uptake in HepG2 cells than non-targeted nanoparticles. CX-EPNP showed a promising antiproliferative effect against HepG2 cells with an IC₅₀ of 0.78 and 0.38 μ g mL⁻¹ for 24 and 48 h of treatment, respectively.¹⁷ Herein, LFC131 peptide-conjugated nanoparticles showed a time-dependent effect on the cytotoxicity studies.

2.1.8 Ovarian. The potential use of PLGA nanoparticles as a paclitaxel carrier for ovarian cancer stem cells (OCSCs) was reported. PLGA nanoparticles loaded with paclitaxel were developed by an emulsion solvent evaporation method and then conjugated with a targeting ligand: folic acid (FA). Cytotoxicity results reveal that FA-conjugated nanoparticles had an IC₅₀ of 0.00075 μ g mL⁻¹.¹⁸ Folate receptors (FR) are biomarkers that are over-expressed in human cancer cells, such as ovarian cancer cells. Therefore, FA was applied as the targeting ligand in the study to target paclitaxel to FR-positive OCSCs over the normal cells.

2.1.9 Cervical. Magnetic PLGA nanoparticles with surface modified with folate–chitosan conjugate, which served as an anti-cancer and magnetic resonance imaging (MRI) contrast agent, were reported in one study. Docetaxel and super paramagnetic iron oxide nanoparticles (SPIONs) were loaded into the PLGA nanoparticles for delivery to folate-positive KB cancer cells. The folate–chitosan conjugate was prepared using the carbodiimide method and then used as a shell for the loaded PLGA nanoparticles to target the FR in KB cells. This specific targeting of FA in PLGA nanoparticles improved the cellular uptake by FR-positive KB cancer cells with an IC₅₀ of 0.0057 μ g mL⁻¹.¹⁹

2.1.10 Prostate. Theragnostic PLGA nanoparticles loaded with superparamagnetic iron oxide (SPIO) nanocrystals and docetaxel were prepared for both ultrasensitive MRI and cancer

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Table 1 The cytotoxicity of PLGA nanoparticles on different types of cells

Type of cel	l line	IC_{50}	Cell viability assay	Size (nm)	Zeta potential (mV)	Active compound	Exposure duration	Response relationship	Targeting ligand	Ref.	Year
Brain	U87	1.03 $\mu g m L^{-1}$	TTM	${\sim}150$	-18.1 ± 0.5	Doxorubicin and paclitaxel	48 h	Dose-	Transferrin	10	2013
		$0.13~{ m \mug~mL^{-1}}$					96 h	dependent Time-			
		Not available (NA)	SRB	${\sim}190$	$+38.6 \pm 4.1$	Doxorubicin and EGFR siRNA	48 h	dependent Dose-	Angiopep-2	34	2015
	U87MG	NA	XTT	$181.9 \pm$	$+40.212 \pm$	Etoposide	6, 12, 24 and 48 h	dependent Time-	Lactoferrin and FA	35	2015
	C6	NA	TTM	$\begin{array}{c} 4.5\\ 182.8 \pm \end{array}$	$\begin{array}{c} 2.844 \\ -11.72 \pm 2.27 \end{array}$	Paclitaxel	24, 48 and 72 h	dependent Time-	Transferrin	36	2009
		7.28 $\mu g m L^{-1}$	WST-1	$\begin{array}{c} 3.78\\ 138.5 \pm \end{array}$	-43.03 ± 0.38	Paclitaxel	24 h	dependent Dose-	Vitamin E TPGS	37	2019
	GI-1	NA	TTM	7.0 85.5	-26.5 ± 2.1	Paclitaxel	24, 48 and 72 h	dependent Time-	AS1411	38	2012
		NA	TTM	${\sim}200$	NA	Paclitaxel	24, 48 and 72 h	dependent Time-	AS1411	39	2012
	U251	$0.185 \ \mu g \ m L^{-1}$	CCK-8	$137.3 \pm$	-17.63 ± 3.10	Doxorubicin	48 h	dependent Dose-	Chondroitin	40	2019
	SH-SY5Y	NA	TTM	$\begin{array}{c} \textbf{8.6} \\ \textbf{257.10} \end{array} \\$	-5.51 ± 0.73	Doxorubicin	26 h	dependent Dose-	sulphate Rabies virus-derived	1 41	2017
				22.39				dependent	peptide		
	DKMG/EGFRvIII	NA	TTM	251 ± 3	-2.9 ± 1.2	Curcumin	24 h	Dose- dependent	Anti-EGFRvIII monoclonal	42	2018
Breast	DOF2	>0.114o mL ⁻¹	STM	124.2.+	+12 + 7	DE38KDEL	48 h	Dose-	antibody Fah' fraøments of	43	2009
	D2F2/E2	0.00078 ± 0.00024 ug mL ⁻¹		21.2				dependent	a humanized anti- HER2 monoclonal		
		0							antibody (rhu- MAbHER2)		
	SKBR-3	$0.00497 \pm$	STM	$124.2 \pm$	+12 \pm 7	PE38KDEL	48 h	Dose-	Fab' fragments of	43	2009
		0.000176 µg mL ⁻¹		21.2				dependent	a humanized anti- HER2 monoclonal antibody (rhu- MAbHER2)		
		0.00031 to 0.00049	STM ($170.3 \pm$	-18.9 ± 1.5	Aromatase inhibitor, 7α -(4'-amino)	24 h	Dose-	Transferrin	11	2010
		µg mL⁻¹		7.6		phenylthio-1,4-androstadiene-3,17-dione (7a-APTADD)	Ð	dependent			
		NA	STM	180 ± 1	-1.0 ± 0.1	Paclitaxel	24 h	Dose- denendent	Herceptin	44	2013
	MCF-7	$6.71 \ \mu g \ m L^{-1}$	TTM	110	-32	DDP prodrug (c,c, t-	24 h	Dose-	Folate	45	2012
)				[Pt(NH ₃) ₂ Cl ₂ (O ₂ CCH ₂ CH ₂ CH ₂ CH ₂ CH ₃) ₂]	([dependent			
		NA	Alamar blue	218	-27 ± 3	Paclitaxel	120 h	Dose- denendent	AS1411	46	2013
		NA	MTS		$+24.21 \pm 2.31$	Epirubicin				47	2016

 $+24.21 \pm 2.31$ Epirubicin

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Table 1 (Contd.)

		Cell viabilitv		Zeta			Response			
Type of cell line	IC_{50}	assay	Size (nm)	potential (mV)	Active compound	Exposure duratior	ı relationship	Targeting ligand	Ref.	Year
	$\sim 0.043~\mathrm{\mu g~mL^{-1}}$	STM	$268.0 \pm$	-22	Paclitaxel and combretastatin A4	24,148, 72, 96 and	Dinne-	Bjøtinførtedly-Asp	- 48	2010
			23.4			120 h	dependent	ohittasatuys)		
	NA	TTM	85.5	-26.5 ± 2.1	Paclitaxel	24, 48 and 72 h	Time- denondant	AS1411	38	2012
	NA	TTM	222.7	+10.2	Epirubicin	72 h	uepenuent Dose-	5TR1 DNA aptamer	49	2017
				-	- - - - -	-	dependent	(Apt)	1	
	NA	TTM	245.8 ± 7.8	-8.57 ± 0.6	Gold nanorods and doxorubicin	28 h	Dose- denendent	Human serum albumin	50	2019
	0.02611 $\mu g m L^{-1}$	TTM	274 ± 1.6	013.8 ± 5.1	Rapamycin	120 h	Dose-	EGFR antibody	51	2009
	$0.42\pm0.15~\mu\mathrm{g}$	TTM	$141 \pm$	-2.61 ± 1.37	Epirubicin	24 h	dependent Dose-	Trastuzumab	52	2019
	mL^{-1}		58.41				dependent	:		
	$1.84 \pm 1.30 \ \mu m g m m L^{-1}$	TTM	$\begin{array}{c} 153.41 \pm \\ 4.78 \end{array}$	$+49.1\pm1.2$	Salinomycin and paclitaxel	24 h	Dose- dependent	Hyaluronic acid	53	2016
	$0.053 \pm 0.0065 $ µg mL ⁻¹ (48 h), 0.03 ± 0.0052 µg mL ⁻¹ (72 h)	g MTT 19	184.6 ± 4.1	-28.6 ± 2.4	Docetaxel, silibinin and SPIONs	48 and 72 h	Time- dependent	LHRH decapeptide hormone	54	2016
	NA	TTM	$210.4 \pm$	$\textbf{+9.7}\pm\textbf{0.2}$	Antimir-21 and epirubicin	72 h	Dose-	MUC1 Apt	55	2018
	8.12 $\mu g m L^{-1}$	TTM	$\begin{array}{c} \textbf{10.14} \\ \textbf{151.7} \pm \end{array}$	-1.00 ± 0.11	Paclitaxel	48 h	uepenuent Dose-	Glutamate	56	2016
	1		4.9				dependent			
HER2-negative	NA	TTM	268.4 ± 6.6	$+11.80 \pm 0.75$	Paclitaxel	24, 48 and 72 h	Time- denendent	Herceptin	57	2016
HER2-positive	NA	TTM	$268.4 \pm$	$+11.80 \pm 0.75$	Paclitaxel	24, 48 and 72 h	Time-	Herceptin	57	2016
B1474 DT 20	2000 + 62 C	MTT	6.6 111 ⊥	767 + 73 C	Dnimhiain	4 60	dependent	Tweeturningh	C L	0100
07-10	2.73 ± 0.20 μg mL ⁻¹	TIM	141 ± 58.41	/C'I I 10.7-	Epitubiciii	24 II	dependent	11 astužulijaD	70	6107
MDA-MB-453	$3.11 \pm 0.19 \ \mu g^{-1}$	TTM	$141 \pm$	-2.61 ± 1.37	Epirubicin	24 h	Dose-	Trastuzumab	52	2019
MDA-MB-231	mL ⁻¹ NA	STM	$\begin{array}{c} 58.41 \\ 286.20 \pm \end{array}$	-15.97 ± 1.28	Docetaxel	24, 48, 72 h	dependent Time-	Hyaluronic acid	58	2014
			4.35	-			dependent	ceramide	C L	
	4 µg mL	III	150 ±	$-21.5/ \pm 2.93$	Quercetin	24 N	Dose- denendent	Iransterrin	9C	2018
	$0.048\pm0.004~\mu\mathrm{g}$	WST-1	$91.2 \pm$	-60.7 ± 1.0	Doxorubicin and irinotecan	240 h	Dose-	Hyaluronic acid	60	2015
MBA-MD-231/AF	mL ⁻¹ P NA	MTT	8.1 108 + 17	10.6 + 1.5	Dovomihicin	48 h	dependent Dose-	ΕA	61	2016
		1 1 1AT	71 + 061	C'T + D'CT_		11 04	denendent	41	10	0107
4T1 mammary	NA	TTM	$235.5 \pm$	NA	Curcumin and bortezomib	24 h	Dose-	Alendronate	62	2012
epithelial carcinoma cells	$0.37~{ m ug}~{ m mL}^{-1}$	MTT	$\begin{array}{c} 71.30\\ 151.7 \end{array}$	-1.00 ± 0.11	Paclitaxel	48 h	dependent Dose-	Glutamate	56	2016
) -		4.9				dependent			
MCF-7/ADR	$4.6 \ \mu g \ m L^{-1}$	TTM	~ 210	+27	Doxorubicin	48 h	Dose-	Low-molecular	63	2014
							dependent	weight protamine		

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Table 1 (Contd.)

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Type of cell	line	IC_{50}	assay	Size (nm)	potential (mV)	Active compound	Exposure duratior	relationship	Targeting ligand	Ref.	Year
		NA	MTT	$245.8\pm$	-8.57 ± 0.6	Gold nanorods and doxorubicin	28 h	Dose-	Human serum	50	2019
				7.8				dependent	albumin		
	JC	0.034 ± 0.00085	STM	240 ± 1	-19 ± 5	Paclitaxel and tariquidar	96 h	Dose- denendent	Biotin	64	2009
		NA	STM	200–250	-12.1 ± 0.3	Paclitaxel and P-gp-targeted siRNA	24 h	Dose-	Biotin	65	2010
	T47D	NA	TTM	210 + 10	-13	Daclitaxel	48 h	dependent Dose-	Hiiman seriim	99	2015
					2			dependent	albumin	0	
Lung	A549/T	$0.78 \ \mu g \ m L^{-1}$	TTM	${\sim}210$	+27	Doxorubicin	48 h	Dose-	Low-molecular	63	2014
		-					-	dependent	weight protamine		
	A549	0.34 µg mL ⁻¹	TTM	~ 210	+27	Doxorubicin	48 h	Dose- denendent	Low-molecular weight protamine	63	2014
		$30 \ \mu g \ m L^{-1}$	MTS	$286 \pm$	-45 ± 3.2	Doxorubicin	20 h	Dose-	Cyclo-(1,12)-	67	2009
				10.3				dependent	PenITDGEATDSGC (c1 AB1) nentide		
		NA	MTT	301 ± 10	-37.4 ± 1.4	Doxorubicin	24 h	Dose-	LFC131 peptide	68	2014
								dependent	1		
		0.00330 $\mu g m L^{-1}$	SRB	$108 \pm$	-21.32 ± 1.91	Doxorubicin	48 h	Dose- denendent	Transferrin	69	2015
		NA	STM	200	58.07	Chlorin e6	24 h	Dose-	Hyaluronic acid	70	2017
		1		C				dependent		i	
	A549-Luc	4.12 µg mL	J.I.M	8c	-29.4	Docetaxel	48 h	Dose-	Hyaluronic acid	7	7107
		$0.91~{ m \mug}~{ m mL}^{-1}$	MTT	154	-22.7	Docetaxel	48 h	dependent Dose-	Hyaluronic acid	72	2016
		0						dependent			
	A549-luc-C8	NA	MTT	80	-50	Paclitaxel palmitate	48 h	Dose- denendent	Cetuximab	73	2013
	TFR positive A549	$0.01~\mu{ m g}~{ m mL}^{-1}$	CCK	96–156	NA	Hypocrellin A	8 h	Dose-	Transferrin	74	2017
			E	-				dependent 		,	
	H1299, A549 and H1975	A549 (\sim 0.011 µg mL ⁻¹), H1299 (\sim 0.024 µg mL ⁻¹), H1975 (\sim 0.0017 µg mL ⁻¹)	Trypan blue	217 ± 13.54	$+29.5 \pm 4.04$	Paclitaxel	24 and 48 h	Time- dependent	RGD peptide	12	2017
Colon	Caco-2	$\begin{array}{c} 1.019 \pm 0.233 \ \mu\text{g} \\ \text{mL}^{-1} \end{array}$	TTM	330 ± 3	-3.9 ± 0.3	Paclitaxel	24 h	Dose- dependent	Wheat germ agglutinin	13	2010
		$\begin{array}{l} 0.087\pm0.020 \ \mu\text{g} \\ \text{mL}^{-1} \end{array}$					72 h	Time- dependent			
	CCD-18Co	$\begin{array}{l} 1.007 \pm 0.121 \ \mu\text{g} \\ \text{mL}^{-1} \end{array}$					24 h	Dose- dependent			
		$\begin{array}{c} 0.137 \pm 0.027 \ \mu g \\ m L^{-1} \end{array}$					72 h	Time- dependent			
	Ht-29	$\begin{array}{l} 0.061 \pm 0.021 \ \mu\text{g} \\ \text{mL}^{-1} \end{array}$	TTM	330 ± 3	-3.9 ± 0.3	Paclitaxel	24 h	Dose- dependent	Wheat germ agglutinin	13	2010

Response

Zeta

Cell viability

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Table 1 (Contd.)

			Cell							
Type of cell	line	IC_{50}	viability assay	Size (nm)	Zeta potential (mV) Active compound	Exposure duration	Response 1 relationship	Targeting ligand	Ref
		$0.028 \pm 0.008 \ \mu g$	TTM	330 ± 3	-3.9 ± 0.3	Paclitaxel	72 h	Time-	Wheat germ	13
		mL^{-1}					•	dependent	agglutinin	
		NA	TTM	90 ± 1.9	-36.3 ± 4.2	Curcumin	2 + 48 h	Dose-	Ribonucleic acid	75
								dependent	(RNA) Apts against epithelial cell adhesion molecule	
	CT26	NA	TTM	$245.8 \pm$	-8.57 ± 0.6	Gold nanorods and doxorubicin	28 h	Dose-	(EPCAM) Human serum	50
				7.8				dependent	albumin	
	C26	NA	TTM	$210.4 \pm$	$+9.7\pm0.2$	Antimir-21 and epirubicin	72 h	Dose-	MUC1 Apt	55
		$3.67 \ \mu g \ m L^{-1}$	TTM	$\begin{array}{c} 10.14 \\ 102.3 \pm \end{array}$	-13.2 ± 2.4	10-Hydroxy camptothecin (HCPT)	48 h	dependent Dose-	Chondroitin	76
				2.9				dependent	sulphate	
	HCT116	NA	MTT	150 ± 12	$+0.2\pm0.12$	Camptothecin	72 h	Dose- denendent	Conatumumab	77
Stomach	MKN74, MKN74-	NA	MTT	293 ± 15	-20.0 ± 0.4	Paclitaxel	24 and 48 h	Time-	Human anti-human	14
	CD44v6+ and							dependent	CD44v6 Fab,	
Control	GP202	0.051-1		1000		(ninothermoneurled 10 hids 7) octas	4 07		AbD15179	00
DASUIC	17001	TIII SH co.o	1 1 I	400.0 H	0.2 ± 0.62-	vivas (/-euityr-10-iiyutoxycaniipuonieciii)	40 11	Dose- denendent	AUNE	0 0
	MKN28	NA	\mathbf{TTM}	~ 200	NA	Pheophorbide a	2 h	Dose-	Folate	78
								dependent		
Liver	HepG2	$0.78 \ \mu g \ m L^{-1}$	TTM	$138 \pm$	NA	Epirubicin	24 h	Dose-	LFC131 peptide	79
		0.38 µº mL ⁻¹		3.12			48 h	dependent Time-		
		84 0000						dependent		
		$5.4\pm0.21~\mu{ m g}$	\mathbf{TTM}	204	-5.6	Docetaxel	72 h	Dose-	Human serum	80
		mL^{-1}						dependent	albumin	
		$2.338 \ \mu g \ m L^{-1}$	TTM	$111.3 \pm$	-6.17 ± 0.41	Doxorubicin	24 h	Dose-	Biotin	81
		7.6 μg mL $^{-1}$	TTM	$0.3 \\ 209.4$	-16.7	Paclitaxel	48 h	dependent Dose-	Pullulan	25
					0			dependent		L C
		3.1 µg mL	MITT	718.2	-18.2	COMDICTASCAULI A4	48 II	Dose-	runuan	C7
		$\sim 2~\mu { m g}~{ m mL}^{-1}$	TTM	$\textbf{288.4} \pm$	-14.1	Epirubicin and tocotrienols	3 h	dependent Dose-	Asialofetuin	82
		VIV		1.11	ç 7		404	dependent	to non of no 1 dOVD	ŝ
	/-uuf	N A	1 1 IM	1 82. 1 82.	۲-T	201816111D	40 11	denendent	CAUR4 antagomst, AMD3100	60
	SMMC-7721	NA	CCK-8	$1.02 \\ 187.2 \pm$	$^{+28.9}\pm0.3$	Arsenic trioxide (As ₂ O ₃)	24, 48 and 72 h	Time-	Lactobionic acid-	84
				10.6				dependent	modified chitosan	
		NA	CCK-8	$249.1\pm$ 0.1	-28.7 ± 1.1	As_2O_3	24, 48 and 72 h	Time- denendent	Lactose acid	85
Ovarian	NCI/ADR-RES	$0.044\pm0.0026~\mu\text{g}$	MTS	240 ± 1	-19 ± 5	Paclitaxel and tariquidar	96 h	Dose-	Biotin	64
		mL^{-1}				1		dependent		

Ref. Year

Type of cell line SKO ^N			•						Torrating ligand	₽∩f	
SKOV		IC ₅₀	assay	Size (nm)	potential (mV)	Active compound	Exposure duration	on relationship	ומוזע ווואסטויט	1001	Year
	-3	NA	SRB	$213.0 \pm$	-1.3 ± 3.8	Doxorubicin	24 h	Dose-	HER2 antibody	22	2011
		0.062 $\mu g m L^{-1}$	TTM	3.5 $341.8 \pm$	-3.5 ± 5.9	Paclitaxel	3 h	dependent Dose-	TAT peptide	86	2013
		0 073 ± 0 003		86.8 101 € ⊥	r c + 3 8 c	Domestic filibility of CDIONIS	40 cr d 70 b	dependent Timo	(RKKRRQRRR) T up 1 docementido	r L	2000
		mL^{-1} (48 h), 0.027 \pm 0.001 µg mL ⁻¹ (72 h)	IIM	104.0 ⊥ 4.1	₽. 7 ⊥ 0.07-	DOCCEARCE, SILIDILILI ALLO DE DOLAS	40 allu / 2 ll	dependent	hormone	0 4	0107
		$\begin{array}{c} 4.91 \ \mu g \ m L^{-1} \ (24 \ h), \ 1.42 \ \mu g \ m L^{-1} \ (48 \ h) \end{array}$	CCK-8	$\begin{array}{c} 165.61 \pm \\ 13.36 \end{array}$	$+19.59 \pm 1.74$	Cisplatin	24 and 48 h	Time- dependent	Trastuzumab	87	2019
		NA	SRB	210 ± 7	-1.0 ± 0.5	Indocyanine green and doxorubicin	24 h	Dose- dependent	Anti-HER2	88	2014
OCSI	S	$0.000754 \ \mu g \ m L^{-1}$	TTM	294.7	NA	Paclitaxel	24 h	Dose- dependent	FA	18	2017
Cervical Lucil	erase- ssino Hela	$0.65~\mu{ m g~mL}^{-1}$	CellTiter- Glo®	· 207 土 4 461	$+5.29 \pm 1.5$	Anti-luc siRNA	72 h	Dose- denendent	Lipid	89	2012
HeLa	BLUE SILLES	$1.86\pm0.17~\mu{ m g}$	MTT	$190.91 \pm$	-19.3 ± 0.59	Doxorubicin	24 h	Dose-	Folate	90	2018
		mL^{-1}		0.19			- 07	dependent 	-		
		$0.80 \pm 0.06 \ \mu g \ \mathrm{mL}^{-1}$		190.91 ± 0.19	-19.3 ± 0.59		48 h	Time- dependent	Folate		2018
		$1.66\pm0.16~\mu\mathrm{g}$		$194.97 \pm$	-15.4 ± 1.57		24 h	Dose-	RGD peptide (Arg-		2018
		mL^{-1}		1.33				dependent	Gly-Asp)		
		$0.79\pm0.13~\mu{ m gm}$		$194.97 \pm$	-15.4 ± 1.57		48 h	Time-	RGD peptide (Arg-		2018
		mL ⁻¹ 0.61 uc mI ⁻¹	MTT	1.33 151 7 ±	1 00 + 0 11	Doditoval	4 0 P	dependent Dece-	Gly-Asp) Glutamate	99	2016
		TIII 2rd 10.0	1 1 IM	4.9	TT:0 + 00.T_	r auticanci	40 11	dependent	Olutaillate	00	0107
KB-3	1 and KB-V1	$>9.95 \ \mu g \ m L^{-1}$	TTM	$132.4 \pm$	-40.3 ± 6.1	Curcumin	48 h	Dose-	Anti-P-glycoprotein	91	2012
)		1.5				dependent			
KB-V		$0.051 \ \mu g \ m L^{-1}$	TTM	165.4	-37.2	Curcumin	48 h	Dose-	Mouse monoclonal	92	2014
								dependent	anti-P-glycoprotein (P-gp) antibody (APgp; clone F4)		
KB		NA	TTM	198 ± 12	-19.6 ± 1.5	Doxorubicin	48 h	Dose-	FA	61	2016
		$0.0057~\mathrm{\mu g~mL}^{-1}$	SRB	200-250	6+	Docetaxel and SPIONs	48 h	dependent Dose-	Folate-chitosan	19	2017
		-						dependent			
		$2.7 \ \mu g \ m L^{-1}$	TTM	118 ± 3	-8.5 ± 2.4	Doxorubicin	10 h	Dose-	FA	33	2015
HCA.	1	NA	TTM	$175.25 \pm$	-19	Sorafenib	48 h	dependent Dose-	CXCR4 antagonist	83	2015
				1.82				dependent	AMD3100		
Prostate PC3		$0.48 \pm 0.087 \ \mu g$	STM	123 ± 2	-30.5 ± 1.4	Doxorubicin	72 h	Dose-	Transferrin	93	2017
		mL - A			$+5.29\pm1.5$	KIF11 siRNA	72 h	dependent	Lipid	89	2012

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Table 1 (Contd.)

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Review

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Table 1 (Contd.)						
	2	Cell viability	Zeta	-	-	Response
Type of cell line	IC_{50}	assay	Size (nm) potential (mV) Active compound	Exposure dura	tion relationship Tar
		CellTiter	· 207 ±			Dose-
		Glo®	4.461			dependent
	$0.093 \pm 0.016 \ \mu g$	WST-1	$91.2 \pm -60.7 \pm 1.0$	Doxorubicin and irinotecan	240 h	Dose- Hy:

Open Access Article. Published on 03 March 2021. Downloaded on 8/21/2025 2:42:44 PM.

1 (Contd.)					
of cell line	IC_{50}	Cell viability assay	Size (nm)	Zeta potential (mV)	Active c
	$0.093 \pm 0.016 \ \mu g$	CellTiter- Glo® WST-1	207 ± 4.461 91.2 \pm	-60.7 ± 1.0	Doxoru
	mL ⁻¹ 0.04 μg mL ⁻¹	SRB	8.1 200–250	6+	Docetax
	$\begin{array}{l} 0.01403 \pm 0.00112 \\ \mu g \ m L^{-1} \ (24 \ h), \\ 0.00579 \pm 0.00109 \\ \mu g \ m L^{-1} \ (48 \ h), \\ 0.00322 \pm 0.00111 \end{array}$	TTM	146.9 ± 8.6	NA	Docetax
PC3M	μg mL ⁻¹ (72 h) NA	CCK-8	$\begin{array}{c} 187.4 \pm \\ 32.7 \end{array}$	NA	Docetax
LNCaP	NA	CellTiter- Glo®	$\begin{array}{c} 207 \pm \\ 4 \ 461 \end{array}$	$+5.29\pm1.5$	KIF11 s
DU145	NA	CellTiter- Glo®	207 ± 4.461	$+5.29 \pm 1.5$	KIF11 s
	<80 $\mu g m L^{-1}$	SRB	206.9	+21.7	Bicaluta

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bicin and irinotecan cel and SPIONs kel and SPIONs

prostate stem cell Hyaluronic acid Folate-chitosan Single-chain dependent dependent Dose- and dependent dependent Dose- and dependent dependent dependent Dose-Dosetime-Dose-Dose-Dosetime-24, 48 and 72 h

RSC Advances 2015 20142012 2012 2016 2013 20162013 2012 2011 2013 20142014100 2011 66 94 89 89 95 2296 97 96 97 97 98 98 antigen antibodies Prostate stem cell antigen antibody cRGDfK peptide HER2 antibody Human holo-transferrin Human holo-AS1411 Apt AS1411 Apt AS1411 Apt AS1411 Apt AS1411 Apt transferrin Anisamide Lipid Lipid FA dependent dependent Dose- and dependent dependent Dose- and dependent dependent dependent dependent dependent dependent Dose-Dose-Dose-Dose-Dose-Dose-Dosetimetime-24, 48 and 72 h 48, 72, 96 h 48, 72, 96 h 120 h 120 h120 h120 h72 h 72 h 24 h48 h48 h 24 h 24 hPaclitaxel and combretastatin A4 Curcumin and gemcitabine Curcumin and gemcitabine Curcumin and gemcitabine Cisplatin and rapamycin Curcumin and SPIONs **Curcumin and SPIONs** el and SPIONs iRNA Bicalutamide iRNA Doxorubicin Bortezomib Bortezomib -11.4 ± 2.3 -1.3 ± 3.8 $200 \pm 10 - 16 \pm 1$ $200\pm 10\ -16\pm 1$ $200 \pm 10 - 16 \pm 1$ +21.7NA NA NA NA NA $213.0 \pm$ 206.9 150150 1501501503.5 blue and blue and Alamar Alamar Alamar Alamar Alamar Presto Presto blue SRB MTS blue blue blue blue SRB SRB SRB

> NA NA

MES-SA/Dx5

Uterine

PANC-1

Pancreas

NA NA

MIA PaCa-2

ΝA NA NA

Ref. Year

relationship Targeting ligand

2015

60

2017 2011

19

48 h

21

S2-013

 $\begin{array}{l} 0.0028 \pm 0.00019 \\ \mu g \ m L^{-1} \end{array}$

Normal hTERT-

PK-1

HPNE

 $0.09~\mu g~m L^{-1}$

NA

B16F10

Skin

A375-luc

Type of cell l	ine	IC ₅₀	Cell viability assay	Size (nm)	Zeta potential (mV)	Active compound	Exposure duration	Response 1 relationship	Targeting ligand	Ref. Yo	ear
			Trypan blue	$\begin{array}{c} 244.1 \pm \\ 4.3 \end{array}$				Dose- dependent			
Umbilical vein	HUVECs	0.0396 $\mu g m L^{-1}$	TTM	209.4	-16.7	Paclitaxel	48 h	Dose- dependent	Pullulan	25 20	016
endothelial		0.0118 $\mu g \mathrm{~mL}^{-1}$	TTM	218.2	-18.2	Combretastatin A4	48 h	Dose- dependent	Pullulan	25 2(016
		NA	TTM	$\begin{array}{c} 175.25 \pm \\ 1.82 \end{array}$	-19	Sorafenib	48 h	Dose- dependent	CXCR4 antagonist, AMD3100	83 2(015
		NA	Trypan blue	$\begin{array}{c} 244.1 \pm \\ 4.3 \end{array}$	-11.4 ± 2.3	Paclitaxel and combretastatin A4	24 h	Dose- dependent	cRGDfK peptide	100 20	011
Oesophageal	0E21	NA	TTM	133	-4.7	Ruthenium-based DNA replication inhibitor and radiosensitizer (Du(rham) (rmuh) ²⁺¹)	24 h	Dose- dependent	hEGF	27 20	018
	OE33	NA	TTM	133	-4.7	(current)(current)) Ruthenium-based DNA replication inhibitor and radiosensitizer (Ru(mben).(fmmh)2*)	24 h	Dose- dependent	hEGF	27 20	018
Bladder	UM-UC-3 and RT- 4	$0.509~\mu{ m g~mL}^{-1}$	WST-1	151 ± 32	NA	Belinostat (NSC726630, PXD101)	72 h	Dose- denendent	Poly(guanidinium oxanorhornene)	101 20	013
Head and neck	UMSCC 22A	NA	TTM	142	-14.6 ± 0.5	Doxorubicin	3 h	Dose- denendent	Anti-EGFR antibody	29 2(017
Kidney	COS-7	NA	MTT	118 ± 3	-8.5 ± 2.4	Doxorubicin	10 h	Dose- dependent	FA	33 2(015

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Table 1 (Contd.)

Review

treatment. PLGA nanoparticles were formed by using a single emulsion evaporation method. The active targeting ligand single-chain prostate stem cell antigen antibodies (scAb_{PSCA}) were conjugated to PLGA *via* a poly(ethylene glycol) linker. Overexpression of prostate stem cell antigen (PSCA), a prostate-specific glycosyl phosphatidylinositol-anchored glycoprotein found in prostate cancer PC3 cells, was the binding site for the scAb_{PSCA}-conjugated nanoparticles.²⁰ Targeted PLGA nanoparticles demonstrated improved cellular uptake and cytotoxicity in PC3 prostate cancer cells exhibited an IC₅₀ of 0.01403 µg mL⁻¹ (24 h), 0.00579 µg mL⁻¹ (48 h) and 0.00322 µg mL⁻¹ (72 h).²¹ Herein, the scAb_{PSCA}-conjugated nanoparticles showed a time-dependent cytotoxicity against prostate cancer PC3 cells.

2.1.11 Uterine. One study reported a comparison of the cytotoxicity and cellular uptake activity of targeted and nontargeted PLGA nanoparticles for delivering doxorubicin against multi-drug resistance in uterine (MES-SA/Dx5) cancer cells. HER2 antibody-conjugated nanoparticles and nontargeted nanoparticles showed higher cellular uptake of doxorubicin than free doxorubicin in MES-SA/Dx5 cancer cells. No significant difference was found regarding cytotoxicity in MES-SA/Dx5 cells for targeted and non-targeted PLGA nanoparticles. This was due to no HER2 receptor overexpression being observed in MES-SA/Dx5 cells. Higher cytotoxicity was observed for both targeted and non-targeted PLGA nanoparticles compared to free doxorubicin, showing suppression of the overexpression of P-glycoprotein in Dx5 cells. HER2 antibodyconjugated nanoparticles were able to overcome the multidrug resistance (MDR) effect in Dx5 cells since cytotoxicity and cellular uptake results at 10 µM extracellular doxorubicin concentration were comparable.22

2.1.12 Pancreas. Bortezomib, a proteasome inhibitor, was loaded into PLGA nanoparticles with poloxamer 407 as an emulsifier against S2-013 pancreatic cancer cells. Surface-modified of the PLGA nanoparticles with transferrin was done to achieve pancreatic cancer cell targeting. Cellular uptake studies have shown high uptake of the targeted PLGA nanoparticles by cancer cells for a sustained release of bortezomib from targeted PLGA nanoparticles. Targeted PLGA nanoparticles showed cytotoxic effects against pancreatic cancer cells with a GI₅₀ of 0.0028 μ g mL⁻¹.²³ Low toxicity to normal pancreatic cells demonstrated that the targeted PLGA nanoparticles enhanced the delivery of bortezomib to S2-013 pancreatic cancer cells.

2.1.13 Skin. nanoparticles containing PLGA dioleoylphosphatidic acid (DOPA) coated cisplatin and rapamycin induced potent cytotoxic effects on A375-luc human melanoma cells with an IC₅₀ of 0.09 µg mL⁻¹.²⁴ This was due to the synergistic effects of rapamycin and cisplatin towards A375-luc human melanoma cells. Rapamycin acts as a mammalian target of rapamycin inhibitors and a sensitizer. DOPA was coated onto cisplatin to achieve compatibility between PLGA and the dual drugs cisplatin and rapamycin. A high anti-proliferative effect was observed in PLGA nanoparticles conjugated with targeting ligand anisamide, which has a high affinity towards sigma receptor membrane-bound proteins that are overexpressed in A375-luc human melanoma cells.

2.1.14 Umbilical vein endothelial. One study reported *in vitro* synergistic effects of paclitaxel or combretastatin A4-loaded charge reversible pullulan-conjugated PLGA nanoparticles formulated with poly(β -amino ester) for the treatment of human umbilical vein endothelial cells (HUVECs). This work revealed IC₅₀s of less than 0.0396 and 0.0118 µg mL⁻¹ for the respective paclitaxel and combretastatin A4-loaded nanoparticles.²⁵ Pullulan-conjugated PLGA nanoparticles had high cytotoxicity activity in HUVECs due to the polysaccharide backbone of pullulan having a high affinity towards the asia-loglycoprotein receptor (ASGPR) in HUVECs.²⁶ The pH sensitivity of the PLGA nanoparticles was attributed to pullulan's cleavage of β -carboxylic amide bond towards changes in pH in the microenvironment of cells.

2.1.15 Esophageal. Surface-modified PLGA nanoparticles with DTPA-hEGF allowed PLGA nanoparticles to attain radiolabeling and targeting towards the EGF receptor (EGFR). DTPA represents diethylenetriaminepentaacetic acid, while hEGF refers to human epidermal growth factor. Surface-modified PLGA nanoparticles were radiolabeled with ¹¹¹In to achieve high affinity to EGFR-overexpressing esophageal cancer cells. The ¹¹¹In radiolabeled PLGA nanoparticles induced radiotoxicity via cellular DNA damage. Ru1 or Ru(phen)₂(tpphz)²⁺ (phen represents 1,10-phenanthroline, while tpphz represents tetrapyridophenazine) is a ruthenium-based DNA replication inhibitor and radiosensitizer. Ru1 was loaded into ¹¹¹In radiolabeled PLGA nanoparticles for DNA damage enhancement. hEGF-PLGA-Ru1 nanoparticles showed remarkable cytotoxicity in EGFR-overexpressing OE21 cells due to the active targeting of the hEGF ligand. However, compared to OE21 cells, lower cytotoxicity was observed in EGFR-normal OE33 cells, with >70% proliferation.²⁷ No IC₅₀ data were reported for the *in vitro* cytotoxicity results of hEGF-PLGA-Ru1 nanoparticles.

2.1.16 Bladder. PLGA nanoparticles were surface-modified with a novel cell-penetrating polymer – poly(guanidinium oxanorbornene) (PGON) – to improve tissue penetration tenfold in mouse bladder and human ureter. PGON is a synthetic polymer that mimics cell-penetrating peptides and possesses low toxicity to normal/cancer cells. PGON PLGA nanoparticles showed a significant enhancement in intracellular uptake of nanoparticles compared to unmodified nanoparticles. Belinostat, a histone deacetylase (HDAC) inhibitor, was loaded into the PGON PLGA nanoparticles to assess their biological activity. In comparison to uncapsulated belinostat, belinostat-loaded nanoparticles exhibited a significantly low IC₅₀ (0.509 μ g mL⁻¹) in cultured bladder cancer cells (UM-UC-3 and RT-4) and sustained hyperacetylation.²⁸

2.1.17 Head and neck. A PLGA/polydopamine core/shell nanoparticle system was designed for light induced cancer thermochemotherapy. Overexpression of the epidermal growth factor receptor (EGFR) drove the high binding of anti-EGFR antibody-conjugated nanoparticles towards head and neck cancer cells. This enhanced cellular uptake of nanoparticles by head and neck cancer cells and induced the conversion of near-infrared light to heat, triggering drug release from the nanoparticles and cancer cell ablation due to the increased

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temperature. The study revealed that PLGA/polydopamine nanoparticles were effective in inhibiting cancer cells at 10 µM doxorubicin concentration when coupled with near-infrared (NIR) irradiation. A doxorubicin concentration of 5 µM or higher was required to achieve the NIR irradiation effect on PLGA/polydopamine nanoparticles in order to produce heat needed for cancer cell ablation and trigger drug release.²⁹

2.1.18 Kidney. Folate-targeted and reduction-triggered PLGA nanoparticles were prepared for targeted delivery of doxorubicin to the COS-7 kidney fibroblast-like cell line. Folatetargeted PLGA nanoparticles were prepared from a PLGA core containing a monolayer soybean lecithin and a reducible outer layer monomethoxy-poly(ethylene glycol)-S-S-hexadecyl (mPEG-S-S-C₁₆). Disulfide bonds (-S-S-) are highly degradable in the reducing environment (high concentration of glutathione) of cancer cells and thus release drugs at the targeted site.³⁰⁻³² FA was conjugated to the mPEG-S-S-C16 outer layer to achieve tumor targeting. No significant difference was observed in the cytotoxicity in FR-negative COS-7 cells for targeted and nontargeted PLGA nanoparticles. This shows that the cellular uptake of folate-targeted PLGA nanoparticles involved a FRmediated endocytosis.33 The study showed a dose-dependent effect where the cytotoxic effect of the nanoparticles was directly proportional to the concentration of doxorubicin, which proves the non-cytotoxicity of the nanoparticles.

2.2 Size and cytotoxicity

The cytotoxicity results show that PLGA nanoparticles induced an anti-proliferative effect as early as 3 h, taking 240 h at most. The particle size of PLGA nanoparticles ranged from 58 to 407 nm, with an average size of 189 nm. It was evident that particles smaller than 100 nm and larger than 300 nm were less commonly prepared, as a certain size is required to carry the load of the drugs and nor bigger size to promote the EPR effect in cancer cells. The IC₅₀ of cytotoxicity of PLGA nanoparticles was plotted against particle size of the PLGA nanoparticles to assess the correlation between particle size and cytotoxicity (Fig. 3). It can be seen that as the particle size increased, the IC_{50} of cytotoxicity also increased, which indicates that smaller nanoparticles induced lower IC50 values and higher cytotoxicity potency. Although the application of corona materials such as



The correlation between particle size and cytotoxicity. Fia. 3

hyaluronic acid increase the particle size, the efficacy of the encapsulated drugs to the desired site was enhanced. This is due to the cancer targeting properties provided by the binding of hyaluronic acid to the PLGA nanoparticles.53,58,60,70,72 Selective targeting enhances the cellular uptake of drugs in cancer cells and reduces the cytotoxic effect of drugs in normal cells. This further justifies that the ideal size and ability of PLGA nanoparticles to selectively deliver drugs to desired site are crucial in developing efficient and safe drug delivery systems. The IC₅₀ values were mostly lower than 10 μ g mL⁻¹, but reached up to 80 $\mu g m L^{-1}$ for FA-conjugated chitosan-functionalized PLGA nanoparticles (CPN) with particle size of 207 nm. This was due to the extremely low entrapment efficiency of bicalutamide in CPN (only about 1%).95

2.3 Zeta potential and cytotoxicity

A plot of the zeta potential of the PLGA nanoparticles against their cytotoxicity IC₅₀ values can be seen in Fig. 4. It is noticeable that PLGA nanoparticles were predominantly in negative charged because of its nature negatively charge of the carboxyl group end chain in PLGA. PLGA nanoparticles ranging from -13.2 to -19.3 mV showed the lowest IC₅₀ value of 0.00031 μ g mL⁻¹ at -18.9 mV, with an average IC₅₀ value of 1.15 µg mL⁻¹ (n = 20) (ESI data[†]). Surface charge of the particle is defined by the absolute value of zeta potential. Zeta potential is a critical factor in designing a drug delivery system because it defines the stability of the nanoparticles. Interestingly, a former study reported that the cytotoxicity potency of PLGA nanoparticles is directly proportional to the absolute zeta potential.102 This is in agreement with a previous report that an absolute value of zeta potential 20 mV or much lower results in nanoparticles with adequate stability.¹⁰³ The stability of nanoparticles is directly proportional to the absolute value of zeta potential. Since stronger repulsive forces were formed between the nanoparticles with high absolute values of zeta potential, stable nanoparticles with uniform size distributions were produced.104 PLGA is a hydrophobic polymer and can be stabilized by the hydrophilic corona materials such as chitosan.19,47,84 This is because of the absolute zeta potential of PLGA nanoparticles is increasing with the concentration of chitosan and indirectly resulted in increased stability of the PLGA nanoparticles. High



The correlation between zeta potential and cytotoxicity. Fia. 4

stability in nanoparticles ensures that there is no early drug release along the route to the target site, which translates to a higher cytotoxic effect on the targeted site in cancer cells.

3. Discussion

This systematic review provides an overview of the application of different targeting ligands and active compounds/drugs used in PLGA nanoparticles to achieve active targeting for drug delivery to a particular cell line. This can give insight to researchers in regard to the designing of a potential drug delivery nanoparticle system for different types of cell lines. The potential of treating multiple cell lines using a single formulation makes the designation of a drug delivery system become more flexible in terms of its usage. For instance, a drug delivery nanoparticle system involving the encapsulation of paclitaxel and conjugation of transferrin as the targeting ligand can be used to treat several types of cancer cells, including breast and brain cancer cells. This can be explained by the fact that FR is a well-known biomarker that has a high affinity for FA in cancer cells due to its overexpression on several types of cancer cell lines, while paclitaxel has long been recognized as a mitotic inhibitor for treating various types of cancer cells. Both the drug and targeting ligand are suitable for treating breast and cervical cancers within a single formulation; this provides cost efficiency and compatibility to patients. The systematic review gives a summary of the IC50 of cytotoxicity of different types of cancer cells treated with various formulated PLGA nanoparticles, in which the overview of the cytotoxicity of PLGA nanoparticles is better understood. For instance, the exposure time and IC_{50} concentration for selected types of cells could serve as references for other researchers to use in planning and identifying their research interests and protocols, which would make these processes easier and save time.

The cellular uptake of nanoparticles with the presence of targeting ligands provides a specific binding to the target or cancer site without causing any or less harms to the healthy cells. This phenomenon is attracting more interest from researchers due to its safeness and less toxicity being imposed as a result of its specific controlled release of anti-cancer drugs. These statements are in line with the findings of previous studies that reported that the surface conjugation of a targeting ligand in nanoparticles more greatly enhances the cellular uptake of drugs and cytotoxicity potency compared to nonconjugated nanoparticles.12,21,27 For instance, the cell viability for RGD antibody-conjugated nanoparticles (PTX-PLGA-CSNP-RGD, 35.2%) was significantly lower (p < 0.01) than for nonconjugated nanoparticles (PTX-PLGA-CSNP, 45.7%).12 On top of this, 24 h treatment of A549 cells with FluTax-PLGA-CSNP-RGD, on the basis of the fluorescence intensity of fluorescent paclitaxel (FluTax), revealed higher uptake of 28 pg/1 \times 10⁵ cells, compared to PTX-PLGA-CSNP by 28 pg/1 \times 10⁵ cells. The reduced cell viability and higher fluorescence intensity of Flu-Tax in RGD antibody-conjugated nanoparticles demonstrates the selective absorption of paclitaxel through integrin receptormediated endocytosis compared to non-targeted delivery at the same dose.

Identifying the zeta potential and particle size of PLGA nanoparticles is crucial because an ideal nanoparticle size can provide an EPR effect for cancer cells' uptake of drugs, while proper zeta potential can provide nanoparticles with high stability. From this systematic review, it is evident that nanoparticles <300 nm in size and ~20 mV in absolute zeta potential are favorable. This is because a decent size (~200 nm) is required for nanoparticles to load the drugs, while high zeta potential provides a uniform and narrow size distribution, as well as high stability.¹⁰⁵ Since nanoparticles are highly stable, the leakage of drugs is negligible during transportation along the target site, which means greater cytotoxicity potency and cellular uptake of nanoparticles.

Challenges are always present in designing a drug delivery system. Although active targeting of nanoparticles reduces toxicity to normal cells, the conjugation of targeting ligands to the nanoparticles might increase the particle size. This is timeconsuming, as optimization of the preparation step in making nanoparticles of an ideal size is required. In addition, targeting ligand conjugation might also reduce the release of drugs from the nanoparticles due to the probability that the ligand may serve as an external barrier when releasing the drug from the nanoparticles. The process of conjugating targeting ligands onto the surface of nanoparticles often involves a two-step reaction. This two-step reaction may cause leakage or early release of drugs from the nanoparticles due to the involvement of a reaction incubation period as well as sonication to minimize the agglomeration of nanoparticles.

The studies analyzed in this systematic review involved different factors, including length of exposure time, active compounds and targeting ligands used in assessing cytotoxicity assays of PLGA nanoparticles in a single cell line. Comparisons among the available studies for a particular cell line are difficult to make due to the variations in the factors involved. Hence, there is still a lack of ideally designed PLGA nanoparticle drug delivery systems. Moreover, some *in vitro* studies lack proper descriptions for data, such as IC_{50} data for cytotoxicity assays have been used (*e.g.* MTT, MTS, SRB), which may have resulted in variations in cytotoxicity data.¹⁰⁶ Hence, it is difficult to obtain completely accurate results from comparison studies of cytotoxicity for PLGA nanoparticles.

Currently, only 19 drug formulations based on PLGA have been approved by the FDA.¹⁰⁷ This negligible number displays that the development of PLGA formulations is very challenging. Thus far, none of the 19 FDA approved PLGA formulations are based on PLGA nanoparticles as they are mainly composed of PLGA microparticles, solid implant and *in situ* gel. This lacking availability of PLGA nanoformulations further indicates that more evaluations on its efficacy and safety requirements are needed before getting approved for clinical use. Poor drug entrapment efficiency and drug release kinetics from PLGA nanoformulations are the main challenges faced in order to deliver drugs effectively to the target site. For instances, initial burst drug release is the typical issue of low efficacy in designing PLGA nanoformulations. Although PLGA nanoformulations were reported to be safe and selective targeting to the cancer cells in *in vitro* and animal studies, they are insufficient to prove that the same outcomes will be observed in human trials. Safety concerns of a drug delivery system are the top priority when it comes to establish their application.

Nevertheless, challenges still arise along with opportunities. Despite the great challenges, PLGA nanoparticles are still of interest due to its biocompatibility and particularly, an FDA approved material for drug delivery. Over the past few decades, a significant advancement in the development of PLGA nanoparticles for the application of drug delivery has led to the revolution of pharmaceutical industry. The uniqueness of PLGA nanoformulations, specifically their sustained and controlled drug release as well as cancer targeting properties provide the assurance of great potentials as promising nanocarriers. There are still great potentials in PLGA nanoformulations by modifying their physicochemical properties with better understanding of the physiology of the cancer cells and pharmacokinetics of the drug delivery system. In terms of biocompatibility and toxicity in biological systems, the physicochemical properties of PLGA nanoformulations play an important role.¹⁰⁸ Particle size, surface charge and selective targeting properties of PLGA nanoformulations are critical benchmarks to consider when it comes to efficacy. The potential of these state-of-the-art innovations and strategies to develop PLGA nanoformulations are contributing to the advancement of cancer treatment. Nevertheless, intensive evaluations for pharmacokinetics, biodistribution and toxicity are essential before progressing PLGA nanoformulations into clinical studies.

4. Conclusions

In conclusion, PLGA nanoparticles with active targeting properties have higher cytotoxicity and cellular uptake of drugs compared to non-targeting nanoparticles, regardless of the types of cells studied. The size and zeta potential of PLGA nanoparticles play a crucial role in defining the resulting cytotoxicity. Therefore, in future studies, greater focus should be placed on assessing the pharmacodynamic, pharmacokinetic and toxicokinetic profiles of the drug delivery system using cancer-targeting PLGA nanoparticles. In addition, although the listed PLGA nanoparticles exhibited the potency of pharmacological actions based on the in vitro data, there was a lack of in vivo data for many of them. This raises concerns regarding efficacy and safety of usage in the application of PLGA nanoparticles in human trials. Therefore, more relevant in vivo data on the efficacy and toxicity of PLGA nanoparticles are desired before human clinical trials should be commenced, as a pharmaceutical formulation can only be considered successful when both safety of usage and efficacy are guaranteed.

Author contributions

Hock Ing Chiu: methodology, validation, formal analysis, investigation, writing – original draft, writing – review & editing, visualization, project administration. Nozlena Abdul Samad:

data curation, formal analysis, investigation Lizhen Fang: data curation, formal analysis, investigation. Vuanghao Lim: conceptualization, methodology, validation, formal analysis, writing – review & editing, supervision, project administration, funding acquisition.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This research was funded by the Fundamental Research Grant Scheme (FRGS, 203.CIPPT.6711684) from the Ministry of Higher Education, Malaysia. Hock Ing Chiu would like to express his appreciation to USM for providing him the USM Fellowship Scheme.

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