

How Much Useful Radiation Does the Sun Deliver?

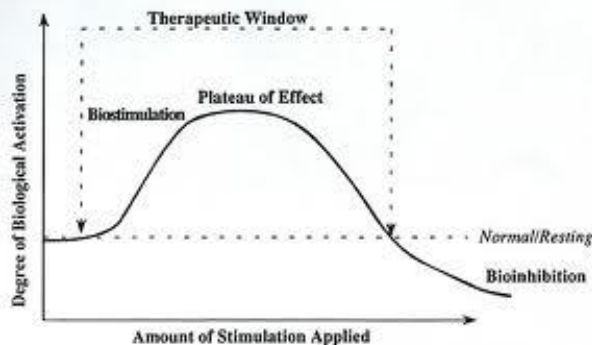
Bryan J. Stephens, PhD

It is important to understand the order of magnitudes involved when it comes to applications in radiation. Far too often do people present generalizations without at least a relative scale. Even when printing graphs of data, people neglect the axis-labels, whether it be through a lack of units or the superposition of two plots that have different units. As such, these graphs lead to inaccurate conclusions about the point attempting to be made.

A prime example of such hand-waving arguments is the ubiquitous citation of the Arndt-Schulz law, which refers to "U" shaped dose response curves for external agents: below a threshold there is no effect, a small amount of something has small effect, a moderate amount has a large effect, and a large amount has either no effect or an adverse effect.

This "law" was originally formulated in the world of pharmacology, has come in and out of favor several times, and now serves as one of the foundations of homeopathy. There is no doubt that there are issues relevant to laser therapy in which this idea applies; the creation of reactive oxygen species (ROS) or free-radicals is an obvious example. Radiation oncology takes special advantage of free-radicals as they are potent DNA breakers; in fact, the hydroxyl radical that comes as a by-product of ionized water accounts for about 2/3 of all radiation induced, mammalian DNA damage (1). In lower levels, however, ROS's serve as cell-signal carriers as well as to induce an endogenous response that leads to an increased long-term defense capacity against exogenous radicals and other foreign toxins.

2-D Visualization of the Arndt-Schultz "Law"



But, it is crucial to remember that this is not a "law" at all, nor is it based on fundamental principles or cellular processes, and so to claim that more than X amount of radiation is inhibitory because the Arndt-Schultz law says so, is completely unfounded.

Virtually all of the empirical investigations that attempt to narrow the optimal treatment parameters have been performed in vitro.

These studies have the advantages that the majority of the parameters can be easily measured and well controlled, and many of the results of these experiments have indeed shown an optimal dose region for biostimulation above which inhibition takes place.

There are, however, inherent limitations in extrapolating these results to conclusions on the effects in bulk tissue, as well as some fundamental shortcomings in the breadth of their investigations.

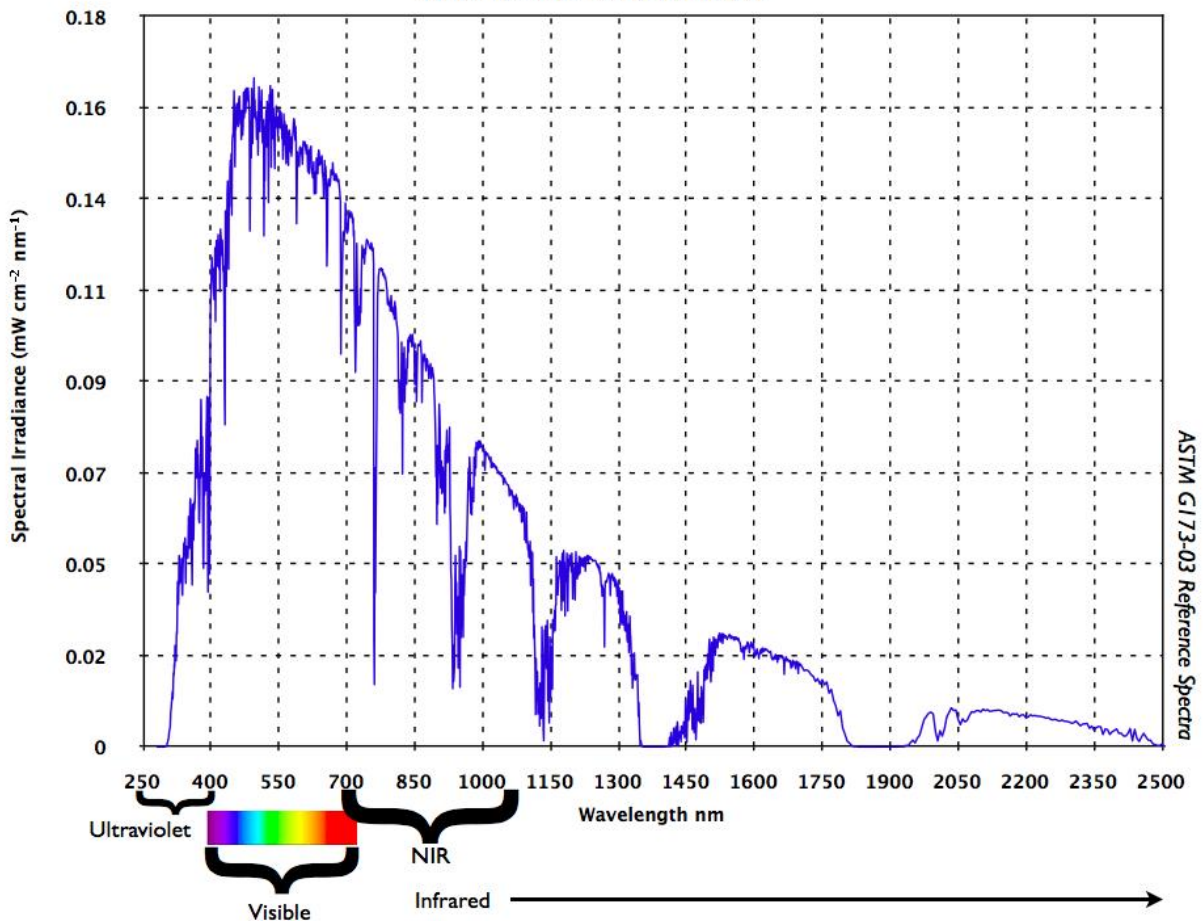
An obvious example is simply the range of doses used and the a priori assumption that there is only one peak in the biostimulatory spectrum.

Tiina Karu, among others, has shown this to be an invalid assumption, and that for a given cell line, there may be several peaks of similar biostimulatory effect separated by several orders of magnitude of doses (2).

So the “U” shaped dose response curve cited by a particular study may illustrate only one of the several potential peaks in a curve, whose full range has not been measured.

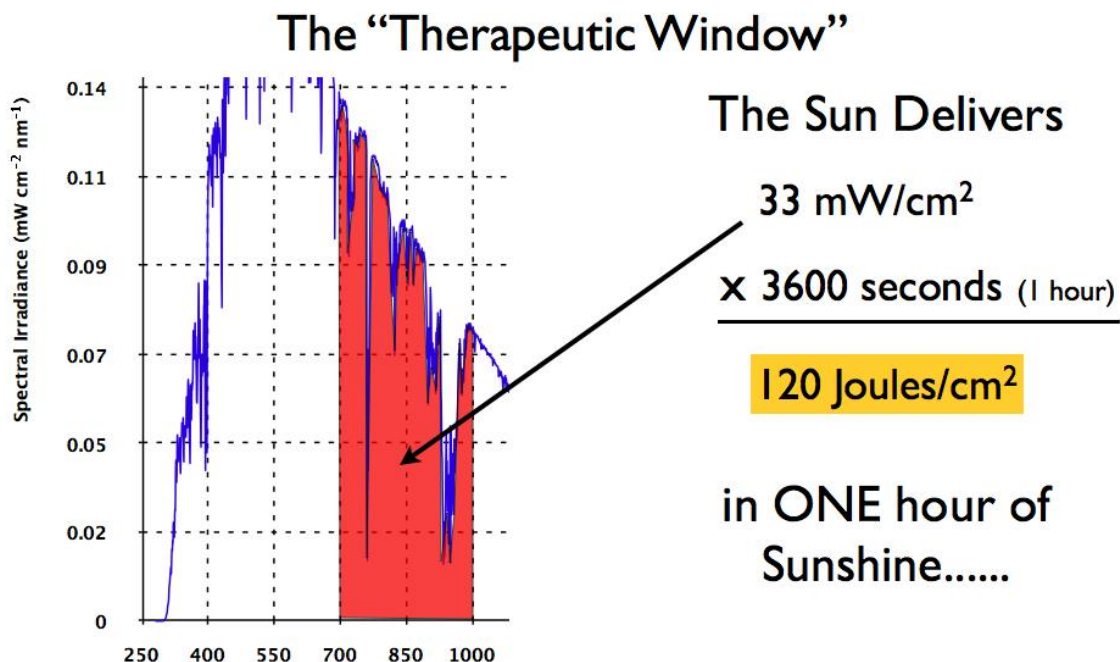
Spectrum of Solar Irradiance

(Power Density at each Wavelength)



To bring some perspective to the amount of radiation delivered during therapy and hopefully shed some light on the increasingly popular “overdosage” concerns, let us examine how much radiation we are exposed to when walking outside.

Figure 1 shows the solar irradiance data recorded by National Renewable Energy Laboratory (3). Surprising to some is the fact that the majority of the radiation we experience from the sun is not in the UV or visible spectrum, but rather in the infrared range.



.....to **every** cm² of your body **SIMULTANEOUSLY**

Note that 120 Joules/cm² would probably **not** fall into the “sweet spot” of the dose-response curve for anyone who cites the Arndt-Schulz “law”, but this is **exactly** what you are exposed to **every** sunny day.

How much though? Table 1 shows the integrated power densities for some relevant wavelength ranges as well as the resultant accumulated doses of each that we are exposed to per hour of sunshine.

Recall that the Class III distinction for lasers includes average power outputs from 5 to 500 milliWatts, and also that this is not a power density, just an output power. Also realize that an Oreo cookie covers an area of about 25 cm². So at the very top end of the Class III capability with this reasonable spot size estimate, the maximal power density deliverable is 20 mW/cm².

You can see from Table 1 that you are exposed to more than that amount of radiation (33 mW/cm²) in the “therapeutic window” (the region in the near infrared (NIR) between the peaks of melanin and water where the most penetration into the body occurs) from the sun than you are from a therapy session with one of these lasers. “But that is a pretty wide spectrum of wavelengths, what about a single wavelength laser?” you ask.

Table 1: Dosages

Wavelength Range	Irradiance (Power Density) $\frac{\text{mW}}{\text{cm}^2}$	Hourly Dosage (Energy Density) $\frac{\text{J}}{\text{cm}^2\text{hr}}$
Total (280 - 4000 nm)	100	360
UV (280 - 400 nm)	6.4	23
Visible (400 - 700 nm)	46	160
Infrared (700 - 4000 nm)	48	170
635 nm \pm 20 nm	5.8	21
800 nm \pm 20 nm*	4.3	16
970 nm \pm 20 nm	2.7	10
“Therapeutic Window” (700 - 1100 nm)	33	120

*Very few people would argue convincingly that 780 or 820 nm radiation has significantly different therapeutic effect from 800 nm, hence the bandwidth listed here.

Ok let’s examine, for example, an 800 nm therapy on a lower-lumbar ailment that is centered on the spine, spans 10 cm (~4 in) wide and 15 cm (~6 in) long, so an area of 150 cm².

Given the same power and spot size as before, segment the 150 cm² lower back into six, equal 25 cm² sections.

If you were to spend 100 seconds on each segment, then in 10 minutes (600 seconds) you would have covered the entire area and delivered 300 Joules of energy evenly across this lower back region**.

In that same ten minutes, in the same lower back region, and with radiation in the same wavelength range, the sun will have delivered 387 Joules of energy (4.3 mW/cm² @800 nm x 150 cm² x 600 seconds)!!!

But again you ask, “How can that be since the power density of this laser is more than the sun at this wavelength?”

The sun delivers this power density to every centimeter regardless of the size of the treatment area simultaneously, whereas the laser is confined to its spot size, so increasing the spot size from this fixed-power-output laser would decrease the power density (not so with the sun, which delivers 127,000,000,000,000 Watts of power to the Earth’s surface).

Take a Walk....Some Say It's Therapeutic



The entire back half of your body will receive about 800,000 Joules of Therapeutic Energy in **ONE HOUR** of sunbathing.

$$120 \text{ J/cm}^2 \times 13,000 \text{ cm}^2 \times 1/2 \text{ your body}$$

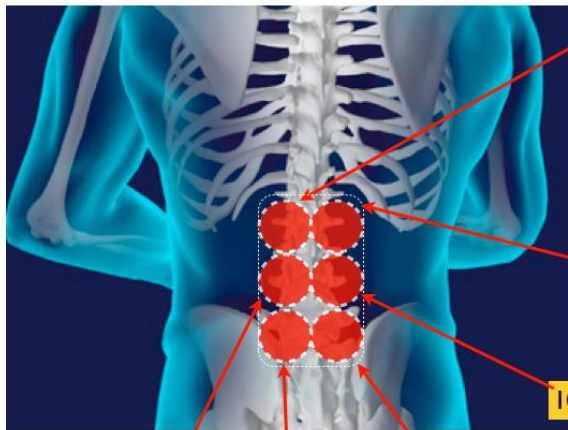
Average Surface Area
of the Human Adult
Body = 1.3 m²

So Much For
“Overdosing” Claims

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UV (ionizing) radiation can break molecular bonds.
It is **not** Infrared radiation that tans/burns your skin.

Example: 800 nm, 500 mW Class IIIb Laser with 25 cm² Spot Size



$$25 \text{ cm}^2 \times 20 \text{ mW/cm}^2 \times 100 \text{ seconds}$$

$$\text{Power Density} = \frac{\text{Output Power } 500 \text{ mW}}{\text{Spot Size } 25 \text{ cm}^2}$$

50 Joules

+ another 100 seconds

+ 100 seconds

+ 100 seconds

+ 100 seconds

100 seconds

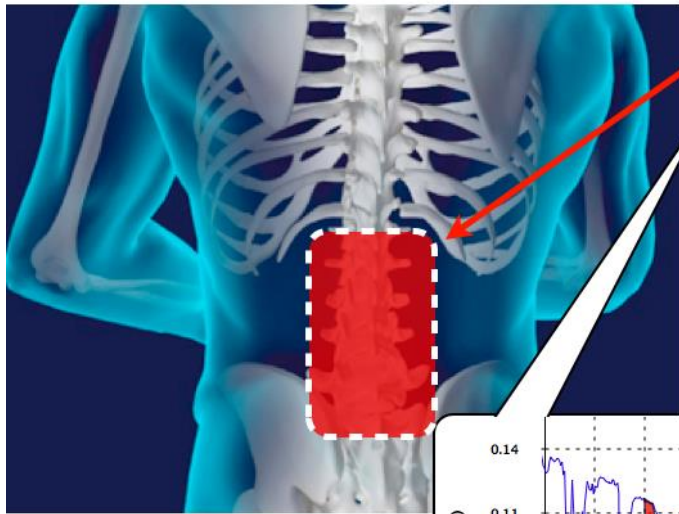
100 seconds

100 seconds



Total Area Covered	150 cm ²
Total Treatment Time	600 seconds = 10 minutes
Total Energy Delivered	300 Joules
Total Dose to Skin	2 J/cm ²

Same Example, But By Laying Down in the Sun



$$\begin{aligned} &150 \text{ cm}^2 \\ &\times \\ &4.3 \text{ mW/cm}^2 \\ &\times \\ &600 \text{ seconds} \\ &387 \text{ Joules} \end{aligned}$$

delivered to EVERY cm²

Total Area Covered

SAME = 150 cm²

Total Treatment Time

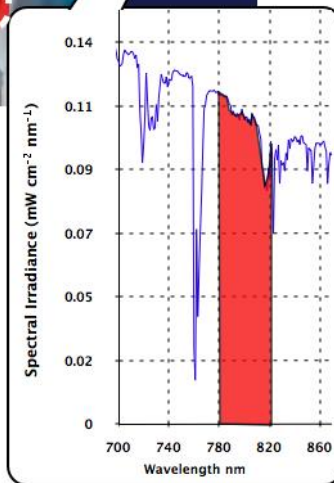
SAME = 10 minutes

Total Energy Delivered

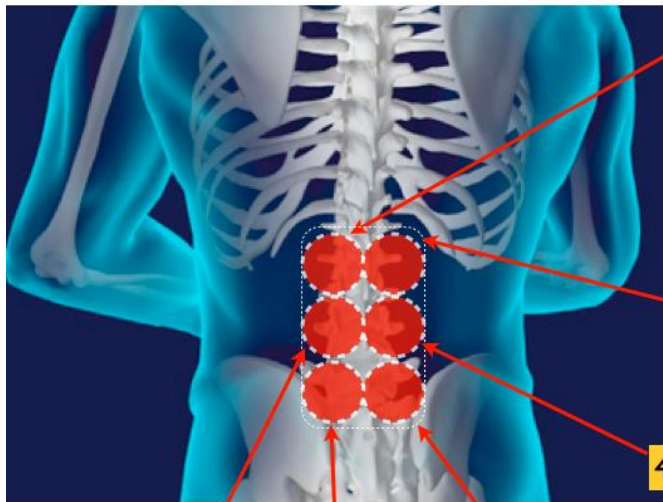
MORE....387 Joules

Total Dose to Skin

MORE....2.6 J/cm²



Now a Class IV laser: 800 nm, 12 W with 25 cm² Spot Size



$$25 \text{ cm}^2 \times 480 \text{ mW/cm}^2 \times 45 \text{ seconds}$$

$$\text{Power Density} = \frac{\text{Output Power } 12,000 \text{ mW}}{\text{Spot Size } 25 \text{ cm}^2}$$

540 Joules

+

another 45 seconds

+

45 seconds

+

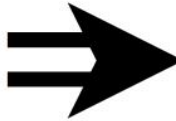
45 seconds

+

45 seconds

+

45 seconds



Total Area Covered

SAME = 150 cm²

Total Treatment Time

270 seconds = 4.5 minutes

Total Energy Delivered

3240 Joules

Total Dose to Skin

21.6 J/cm²

We already discovered that 21 J/cm² is not harmful, but how do we know it is **optimal** for treating the spine???

Where do these Dose Prescriptions Come From?

Chronic Lumbar Pain

Power	Duty cycle	Phase
12.0 W	CW	CW
Wavelength		ISP
800 + 970 nm		Hz
Phase time		CW
00:30		ISP
Treatment time		Hz
00:04:30		ISP
Frequency		CW
		ISP
Preset J	Applied J	CW
3240.0	0.0	
Average power		
12.0 W		

KLASER delete phase

← ISP

4:30

3240 J

12 Hz

CW
ISP

Lumbar Pain (Chronic)	
Biostimulatory Dose	6 J/cm ²
Tx Area	150 cm ²
Energy Desired AT TARGET	900 J
Depth of Target	6 cm
% Intensity Delivered at Target Depth	29%
Energy Necessary at Surface	3240 J

This is in the middle of the range of industry-wide agreed-upon values for biostimulatory dose (energy density)

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Where do these Dose Prescriptions Come From?

Chronic Lumbar Pain		Phase
Power	12.0 W	Duty cycle CW
Wavelength	800 + 970 nm	
Phase time	00:30	Treatment time 00:04:30
Frequency	CW	Applied J 0.0
Preset J	3240.0	Average power 12.0 W



Lumbar Pain (Chronic)	
Biostimulatory Dose	6 J/cm ²
Tx Area	150 cm ²
Energy Desired AT TARGET	900 J
Depth of Target	6 cm
% Intensity Delivered at Target Depth	29%
Energy Necessary at Surface	3240 J

Typical Lumbar Treatments are from L1 through L5 which span approx 10 cm wide by 15 cm long (4 in x 6 in)

Where do these Dose Prescriptions Come From?

Chronic Lumbar Pain

Power	Duty cycle	Phase
12.0 w	CW	CW
Wavelength		ISP
800 + 970 nm		Hz
Phase time		CW
00:30		ISP
Treatment time		Hz
00:04:30		ISP
Frequency		CW
		ISP
Preset J	Applied J	
3240.0	0.0	
Average power		
12.0 w		

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Lumbar Pain (Chronic)	
Biostimulatory Dose	6 J/cm ²
Tx Area	150 cm ²
Energy Desired AT TARGET	900 J
Depth of Target	6 cm
% Intensity Delivered at Target Depth	29%
Energy Necessary at Surface	3240 J

Very simple multiplication to get total Energy. This many Joules will provide biostimulation for the entire ailment.

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Where do these Dose Prescriptions Come From?

Chronic Lumbar Pain		Phase
Power	12.0 w	CW
Duty cycle	CW	ISP
Wavelength	800 + 970 nm	Hz
Phase time	00:30	CW
Treatment time	00:04:30	ISP
Frequency	CW	Hz
Preset J	3240.0	ISP
Applied J	0.0	CW
Average power	12.0 w	

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← [Save] [ISP]



Lumbar Pain (Chronic)	
Biostimulatory Dose	6 J/cm ²
Tx Area	150 cm ²
Energy Desired AT TARGET	900 J
Depth of Target	6 cm
% Intensity Delivered at Target Depth	29%
Energy Necessary at Surface	3240 J

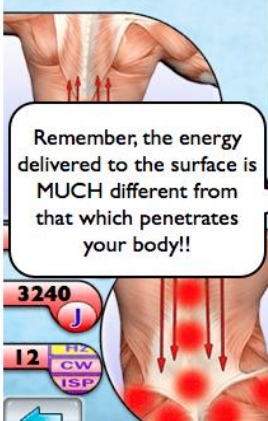
To reach the origin of the pain, the laser must penetrate to the center of the spine. This is the average depth.

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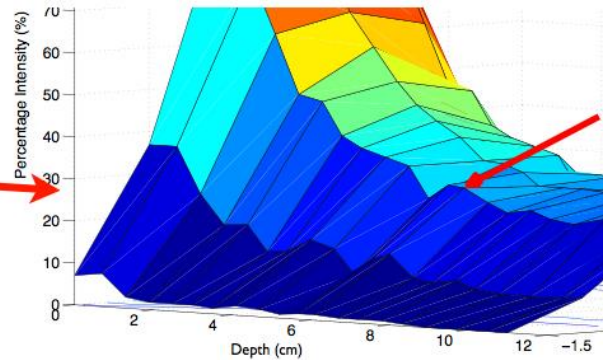
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Where do these Dose Prescriptions Come From?

Chronic Lumbar Pain		Phase
Power	12.0 w	Duty cycle CW
Wavelength	800 + 970 nm	
Phase time	00:30	
Treatment time	00:04:30	
Frequency	CW	
Preset J	3240.0	Applied J 0.0
Average power	12.0 w	



Lumbar Pain (Chronic)	
Biostimulatory Dose	6 J/cm ²
Tx Area	150 cm ²
Energy Desired AT TARGET	900 J
Depth of Target	6 cm
% Intensity Delivered at Target Depth	29%
Energy Necessary at Surface	3240 J



Click here to remind yourself where this figure comes from, and how we know the depth-dose profile of laser radiation INSIDE the body

Where do these Dose Prescriptions Come From?

Chronic Lumbar Pain

Power	Duty cycle	Phase
12.0 W	CW	CW
Wavelength		ISP
800 + 970 nm		Hz
Phase time		CW
00:30		ISP
Treatment time		Hz
00:04:30		ISP
Frequency		CW
		ISP
Preset J	Applied J	CW
3240.0	0.0	
Average power		
12.0 W		

deloto phase

THIS is how a treatment protocol is determined. Not just based on surface dose, but STARTING with enough at the surface to have a therapeutic dose at RELEVANT DEPTHS.

4:30

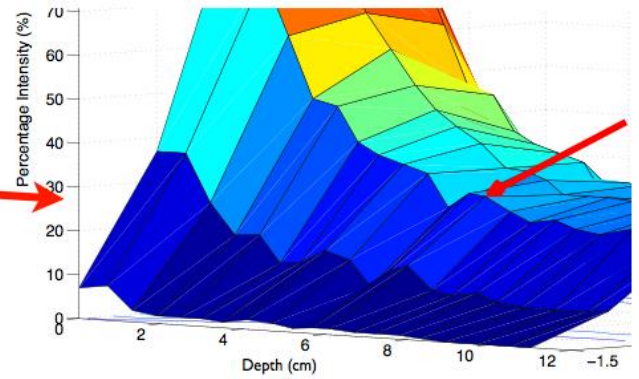
3240 J

12 W CW ISP

Lumbar Pain (Chronic)	
Biostimulatory Dose	6 J/cm ²
Tx Area	150 cm ²
Energy Desired AT TARGET	900 J
Depth of Target	6 cm
% Intensity Delivered at Target Depth	29%
Energy Necessary at Surface	3240 J

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Click here to remind yourself where this figure comes from, and how we know the depth-dose profile of laser radiation INSIDE the body

Where do these Dose Prescriptions Come From?

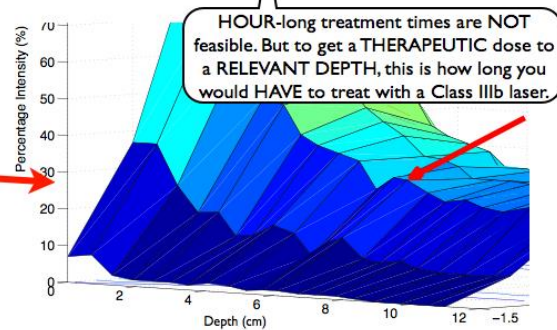
Chronic Lumbar Pain

Power	12.0 W	Duty cycle	CW	Phase	CW
Wavelength	800 + 970 nm				ISP
Phase time	00:30				HZ
Treatment time	00:04:30				CW
Frequency	CW				ISP
Preset J	3240.0	Applied J	0.0		CW
Average power	12.0 W				

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Lumbar Pain (Chronic)	
Biostimulatory Dose	6 J/cm ²
Tx Area	150 cm ²
Energy Desired AT TARGET	900 J
Depth of Target	6 cm
% Intensity Delivered at Target Depth	29%
Energy Necessary at Surface	3240 J

Treatment Time	Class IIIb (ej 200 mW)	K-Laser (12,000 mW)
Seconds	16,100	268
Minutes	268	4.5
Hours	4.5!!!	0.07



[Click here to remind yourself where this figure comes from, and how we know the depth-dose profile of laser radiation INSIDE the body](#)

“What of frequency modulation? Surely that’s worth the money.”

Yes, controlling electronics precisely enough to have clean, square- or triangular-waved pulses can be difficult and slightly expensive to manufacture and program.

This capability is also very important since it has become quite clear to our industry that different conditions and tissue-types respond differently to different modulation frequencies during treatment (4). But at its very heart, this functionality can be accomplished inexpensively by using a \$14 variable speed box fan with different size and shaped blades that chop the beam systematically.

Granted, this is inconvenient, but it would be very difficult to justify paying several thousand dollars just for that feature, especially on a laser whose power density output is dwarfed by the solar irradiance on a sunny day.

“So what is worth the money?” Class IV lasers, by definition, have power output above 500 milliWatts, and there are some on the market that span up to 60 Watts of average power.

Some have fixed spot sizes, some variable, and the power density spans quite a large spectrum.

A 12-Watt laser with the same Oreo cookie spot size delivers a power density of ~ 500 mW/cm², a full 24 times greater than the most powerful Class IIIb laser, never-mind one where the spot size can be narrowed to the size of a nickel (area = 3.5 cm², power density = 3,400 mW/cm²).

Now there is of course a ceiling of power density above which thermal damage is possible (power densities above about 1,200,000 mW/cm² are used for surgical applications) and so therefore there is a fundamental limit of the maximum power of a therapeutic laser (in fact, we have already reached that limit).

But there is no ceiling of dose.

Nonsense? I'm sure a value of 120 J/cm² (from Table 1) would not be in the “sweet spot” of a graph that someone who is quoting the Arndt-Schulz law would use, (in fact, it would most likely fall into the “Inhibitory” ditch) but that dose is literally just a walk in the park.

**Remember, 1000 mW = 1W = 1 Joule per second

References

- 1) Hall, E., Giaccia, A. J., 2006. Radiobiology for the Radiologist, 6th Edition. Lippincott Williams and Wilkins.
- 2) Karu, T.I., Pyatibrat, L.V., and Ryabykh, T.P. 1997. Nonmonotonic Behavior of the Dose Dependence of the Radiation Effect on Cells In Vitro Exposed to Pulsed Laser Radiation at 820nm. Lasers Surg. Med. 21:485-492.
- 3) ASTM Standard G173-03(2008), “Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface,” ASTM International, West Conshohocken, PA, 2008, DOI: 10.1520/G0173-03R08, www.astm.org
- 4) Hashmi, J.T., Huang, Y., Sharma, S.K., Kurup, D.B., De Taboada, L., Carroll, J.D., and Hamblin, M.R., 2010. Lasers Surg. Med., 42:450-466.